UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
**United States Patent and Trademark Office**
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

| APPLICATION NO. | ISSUE DATE | PATENT NO. | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 10/10/2017 | 9784449 | | 1025 |

23497 7590 09/20/2017

JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

# ISSUE NOTIFICATION

The projected patent number and issue date are specified above.

**Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)**
(application filed on or after May 29, 2000)

The Patent Term Adjustment is 539 day(s). Any patent to issue from the above-identified application will include an indication of the adjustment on the front page.

If a Continued Prosecution Application (CPA) was filed in the above-identified application, the filing date that determines Patent Term Adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) WEB site (http://pair.uspto.gov).

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Application Assistance Unit (AAU) of the Office of Data Management (ODM) at (571)-272-4200.

APPLICANT(s) (Please see PAIR WEB site http://pair.uspto.gov for additional applicants):

Jed Margolin, VC Highlands, NV;

# PART B - FEE(S) TRANSMITTAL

**Complete and send this form, together with applicable fee(s), to: Mail** **Mail Stop ISSUE FEE**
**Commissioner for Patents**
**P.O. Box 1450**
**Alexandria, Virginia 22313-1450**
**or Fax (571)-273-2885**

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

23497 7590 08/07/2017
JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

**Certificate of Mailing or Transmission**

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being facsimile transmitted to the USPTO (571) 273-2885, on the date indicated below.

| |
|---|
| (Depositor's name) |
| (Signature) |
| (Date) |

| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

TITLE OF INVENTION: Flame Sensing System

| APPLN. TYPE | ENTITY STATUS | ISSUE FEE DUE | PUBLICATION FEE DUE | PREV. PAID ISSUE FEE | TOTAL FEE(S) DUE | DATE DUE |
|---|---|---|---|---|---|---|
| nonprovisional | SMALL | $480 | $0 | $0 | $480 | 11/07/2017 |

| EXAMINER | ART UNIT | CLASS-SUBCLASS |
|---|---|---|
| WU, ZHEN Y | 2685 | 340-577000 |

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).
   - ☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.
   - ☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list
   (1) The names of up to 3 registered patent attorneys or agents OR, alternatively,
   (2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.
   1 ____________
   2 ____________
   3 ____________

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document has been filed for recordation as set forth in 37 CFR 3.11. Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) : ☐ Individual ☐ Corporation or other private group entity ☐ Government

4a. The following fee(s) are submitted:
- ☒ Issue Fee
- ☒ Publication Fee (No small entity discount permitted)
- ☒ Advance Order - # of Copies 5

4b. Payment of Fee(s): **(Please first reapply any previously paid issue fee shown above)**
- ☐ A check is enclosed.
- ☒ Payment by credit card. ~~Form PTO-2038 is attached.~~ Paid through EFS
- ☐ The director is hereby authorized to charge the required fee(s), any deficiency, or credits any overpayment, to Deposit Account Number ____________ (enclose an extra copy of this form).

5. **Change in Entity Status** (from status indicated above)
- ☐ Applicant certifying micro entity status. See 37 CFR 1.29
- ☐ Applicant asserting small entity status. See 37 CFR 1.27
- ☐ Applicant changing to regular undiscounted fee status.

NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.

NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.

NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature *Jed Margolin* Date 8/8/2017

Typed or printed name Jed Margolin Registration No. ____________



PTOL-85 Part B (10-13) Approved for use through 10/31/2013. OMB 0651-0033 U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

# Electronic Patent Application Fee Transmittal

| | |
|---|---|
| **Application Number:** | 14316489 |
| **Filing Date:** | 26-Jun-2014 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Filer:** | Jed Margolin |
| **Attorney Docket Number:** | |

Filed as Small Entity

**Filing Fees for** **Utility under 35 USC 111(a)**

| Description | Fee Code | Quantity | Amount | Sub-Total in USD($) |
|---|---|---|---|---|
| **Basic Filing:** | | | | |
| **Pages:** | | | | |
| **Claims:** | | | | |
| **Miscellaneous-Filing:** | | | | |
| **Petition:** | | | | |
| **Patent-Appeals-and-Interference:** | | | | |
| **Post-Allowance-and-Post-Issuance:** | | | | |
| UTILITY APPL ISSUE FEE | 2501 | 1 | 480 | 480 |

| Description | Fee Code | Quantity | Amount | Sub-Total in USD($) |
|---|---|---|---|---|
| **Extension-of-Time:** | | | | |
| **Miscellaneous:** | | | | |
| Printed copy of patent - no color | 8001 | 5 | 3 | 15 |
| | **Total in USD ($)** | | | **495** |

# Electronic Acknowledgement Receipt

| | |
|---|---|
| **EFS ID:** | 30023998 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 08-AUG-2017 |
| **Filing Date:** | 26-JUN-2014 |
| **Time Stamp:** | 22:44:57 |
| **Application Type:** | Utility under 35 USC 111(a) |

## Payment information:

| | |
|---|---|
| Submitted with Payment | yes |
| Payment Type | CARD |
| Payment was successfully received in RAM | $495 |
| RAM confirmation Number | 080917INTEFSW22484800 |
| Deposit Account | |
| Authorized User | |

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

## File Listing:

| Document Number | Document Description | File Name | File Size(Bytes)/ Message Digest | Multi Part /.zip | Pages (if appl.) |
|---|---|---|---|---|---|
| 1 | Issue Fee Payment (PTO-85B) | flame_fee_partb.pdf | 156757<br>78d1afaef650503f0f9744d56831d9a20397 7f96 | no | 1 |
| **Warnings:** | | | | | |
| **Information:** | | | | | |
| 2 | Fee Worksheet (SB06) | fee-info.pdf | 31350<br>952ea3d036fd414ed4c779e81557330afd2f 4434 | no | 2 |
| **Warnings:** | | | | | |
| **Information:** | | | | | |
| | | | **Total Files Size (in bytes):** | 188107 | |

**This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.**

**<u>New Applications Under 35 U.S.C. 111</u>**

**If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.**

**<u>National Stage of an International Application under 35 U.S.C. 371</u>**

**If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.**

**<u>New International Application Filed with the USPTO as a Receiving Office</u>**

**If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.**

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

# NOTICE OF ALLOWANCE AND FEE(S) DUE

23497 7590 08/07/2017
JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

| EXAMINER | |
|---|---|
| WU, ZHEN Y | |
| ART UNIT | PAPER NUMBER |
| 2685 | |

DATE MAILED: 08/07/2017

| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

TITLE OF INVENTION: Flame Sensing System

| APPLN. TYPE | ENTITY STATUS | ISSUE FEE DUE | PUBLICATION FEE DUE | PREV. PAID ISSUE FEE | TOTAL FEE(S) DUE | DATE DUE |
|---|---|---|---|---|---|---|
| nonprovisional | SMALL | $480 | $0 | $0 | $480 | 11/07/2017 |

**THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED. THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.**

**THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED. SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE DOES NOT REFLECT A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE IN THIS APPLICATION. IF AN ISSUE FEE HAS PREVIOUSLY BEEN PAID IN THIS APPLICATION (AS SHOWN ABOVE), THE RETURN OF PART B OF THIS FORM WILL BE CONSIDERED A REQUEST TO REAPPLY THE PREVIOUSLY PAID ISSUE FEE TOWARD THE ISSUE FEE NOW DUE.**

**HOW TO REPLY TO THIS NOTICE:**

I. Review the ENTITY STATUS shown above. If the ENTITY STATUS is shown as SMALL or MICRO, verify whether entitlement to that entity status still applies.

If the ENTITY STATUS is the same as shown above, pay the TOTAL FEE(S) DUE shown above.

If the ENTITY STATUS is changed from that shown above, on PART B - FEE(S) TRANSMITTAL, complete section number 5 titled "Change in Entity Status (from status indicated above)".

For purposes of this notice, small entity fees are 1/2 the amount of undiscounted fees, and micro entity fees are 1/2 the amount of small entity fees.

II. PART B - FEE(S) TRANSMITTAL, or its equivalent, must be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed and an extra copy of the form should be submitted. If an equivalent of Part B is filed, a request to reapply a previously paid issue fee must be clearly made, and delays in processing may occur due to the difficulty in recognizing the paper as an equivalent of Part B.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Mail Stop ISSUE FEE unless advised to the contrary.

**IMPORTANT REMINDER: Utility patents issuing on applications filed on or after Dec. 12, 1980 may require payment of maintenance fees. It is patentee's responsibility to ensure timely payment of maintenance fees when due.**

# PART B - FEE(S) TRANSMITTAL

**Complete and send this form, together with applicable fee(s), to: Mail** **Mail Stop ISSUE FEE**
**Commissioner for Patents**
**P.O. Box 1450**
**Alexandria, Virginia 22313-1450**
**or Fax (571)-273-2885**

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CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

23497 7590 08/07/2017

JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

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**Certificate of Mailing or Transmission**

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(Depositor's name)

(Signature)

(Date)

| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

TITLE OF INVENTION: Flame Sensing System

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|---|---|---|---|---|---|---|
| nonprovisional | SMALL | $480 | $0 | $0 | $480 | 11/07/2017 |

| EXAMINER | ART UNIT | CLASS-SUBCLASS |
|---|---|---|
| WU, ZHEN Y | 2685 | 340-577000 |

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).
   - ☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.
   - ☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

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   (1) The names of up to 3 registered patent attorneys or agents OR, alternatively,
   (2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.
   1________________
   2________________
   3________________

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document has been filed for recordation as set forth in 37 CFR 3.11. Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) : ☐ Individual ☐ Corporation or other private group entity ☐ Government

4a. The following fee(s) are submitted:
- ☐ Issue Fee
- ☐ Publication Fee (No small entity discount permitted)
- ☐ Advance Order - # of Copies ____________

4b. Payment of Fee(s): **(Please first reapply any previously paid issue fee shown above)**
- ☐ A check is enclosed.
- ☐ Payment by credit card. Form PTO-2038 is attached.
- ☐ The director is hereby authorized to charge the required fee(s), any deficiency, or credits any overpayment, to Deposit Account Number ________ (enclose an extra copy of this form).

5. **Change in Entity Status** (from status indicated above)
- ☐ Applicant certifying micro entity status. See 37 CFR 1.29 — NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.
- ☐ Applicant asserting small entity status. See 37 CFR 1.27 — NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.
- ☐ Applicant changing to regular undiscounted fee status. — NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature ________________ Date ________________

Typed or printed name ________________ Registration No. ________________

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
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| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
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| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

23497 7590 08/07/2017
JED MARGOLIN
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RENO, NV 89521-7430

| EXAMINER | |
|---|---|
| WU, ZHEN Y | |

| ART UNIT | PAPER NUMBER |
|---|---|
| 2685 | |

DATE MAILED: 08/07/2017

**Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)**
(Applications filed on or after May 29, 2000)

The Office has discontinued providing a Patent Term Adjustment (PTA) calculation with the Notice of Allowance.

Section 1(h)(2) of the AIA Technical Corrections Act amended 35 U.S.C. 154(b)(3)(B)(i) to eliminate the requirement that the Office provide a patent term adjustment determination with the notice of allowance. See Revisions to Patent Term Adjustment, 78 Fed. Reg. 19416, 19417 (Apr. 1, 2013). Therefore, the Office is no longer providing an initial patent term adjustment determination with the notice of allowance. The Office will continue to provide a patent term adjustment determination with the Issue Notification Letter that is mailed to applicant approximately three weeks prior to the issue date of the patent, and will include the patent term adjustment on the patent. Any request for reconsideration of the patent term adjustment determination (or reinstatement of patent term adjustment) should follow the process outlined in 37 CFR 1.705.

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at 1-(888)-786-0101 or (571)-272-4200.

## OMB Clearance and PRA Burden Statement for PTOL-85 Part B

The Paperwork Reduction Act (PRA) of 1995 requires Federal agencies to obtain Office of Management and Budget approval before requesting most types of information from the public. When OMB approves an agency request to collect information from the public, OMB (i) provides a valid OMB Control Number and expiration date for the agency to display on the instrument that will be used to collect the information and (ii) requires the agency to inform the public about the OMB Control Number's legal significance in accordance with 5 CFR 1320.5(b).

The information collected by PTOL-85 Part B is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450. Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

## Privacy Act Statement

**The Privacy Act of 1974 (P.L. 93-579)** requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

| **Notice of Allowability** | **Application No.**<br>14/316,489 | **Applicant(s)**<br>MARGOLIN, JED | |
|---|---|---|---|
| | **Examiner**<br>ZHEN Y. WU | **Art Unit**<br>2685 | **AIA (First Inventor to File) Status**<br>Yes |

***-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--***

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1. ☒ This communication is responsive to 05/15/2017.
   ☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on______.
2. ☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.
3. ☒ The allowed claim(s) is/are 1-18. As a result of the allowed claim(s), you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.
4. ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

   **Certified copies:**

   a) ☐ All b) ☐ Some *c) ☐ None of the:
   1. ☐ Certified copies of the priority documents have been received.
   2. ☐ Certified copies of the priority documents have been received in Application No. ______ .
   3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

   * Certified copies not received: _____.

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file a reply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application.
**THIS THREE-MONTH PERIOD IS NOT EXTENDABLE**.

5. ☐ CORRECTED DRAWINGS ( as "replacement sheets") must be submitted.
   ☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No./Mail Date _____.

   **Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the front (not the back) of each sheet. Replacement sheet(s) should be labeled as such in the header according to 37 CFR 1.121(d).**
6. ☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

**Attachment(s)**

1. ☒ Notice of References Cited (PTO-892)
2. ☐ Information Disclosure Statements (PTO/SB/08), Paper No./Mail Date _____
3. ☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material
4. ☐ Interview Summary (PTO-413), Paper No./Mail Date _____ .
5. ☐ Examiner's Amendment/Comment
6. ☒ Examiner's Statement of Reasons for Allowance
7. ☐ Other _____.

/ZHEN Y WU/
Examiner, Art Unit 2685

### ***Allowable Subject Matter***

The following is an examiner's statement of reasons for allowance: Claims 1-18 are indicated to be allowable as the closet prior art by Haupenthal (Pat. No.: US 6,486,486 B1) does not teach or fairly suggest the applicant's claimed invention. The distinguishing elements of the claim "**d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame; e. a harmonic signal detector having an input connected to the output of said high impedance buffer; f. an indicator connected to the output of said harmonic signal detector; whereas g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.**" as recited in claim 1 and similarly presented in claim 12, "**said flame from said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a first mixing signal at the sum of the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform as well as a second mixing signal at the difference between the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform,**" as recited claim 6 and similarly presented in claim 15, and "**a. providing two signal sources to said flame using a flame rod; b. using flame rectification to cause said two signal**

**sources to mix; c. providing a signal detector to detect a mixing signal produced by said two signal sources; and d. providing an indicator to indicate the results of said signal detector.**" as recited claim 18 are allowable subject matter. The various claimed limitations mentioned in the claims are not taught or suggested by the prior art taken either singly or in combination, with emphasize that it is each claim, taken as a whole, including the interrelationships and interconnections between various claimed elements make them allowable over the prior art of record.

Any comments considered necessary by applicant must be submitted no later than the payment of the issue fee and, to avoid processing delays, should preferably accompany the issue fee. Such submissions should be clearly labeled "Comments on Statement of Reasons for Allowance.".

***Conclusion***

Any inquiry concerning this communication or earlier communications from the examiner should be directed to ZHEN Y. WU whose telephone number is (571)272-5711. The examiner can normally be reached on Monday to Friday, 8AM - 5PM, Alternate Friday, EST.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Hai Phan can be reached on (571) - 272-6338. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/ZHEN Y WU/
Examiner, Art Unit 2685

| *Notice of References Cited* | Application/Control No. 14/316,489 | Applicant(s)/Patent Under Reexamination MARGOLIN, JED | |
|---|---|---|---|
| | Examiner ZHEN Y. WU | Art Unit 2685 | Page 1 of 1 |

**U.S. PATENT DOCUMENTS**

| * | | Document Number Country Code-Number-Kind Code | Date MM-YYYY | Name | CPC Classification | US Classification |
|---|---|---|---|---|---|---|
| * | A | US-5,051,590 A | 09-1991 | Kern; Mark T. | G08B17/12 | 250/227.14 |
| * | B | US-5,300,836 A | 04-1994 | Cha; Soo Y. | C22C33/0207 | 327/113 |
| * | C | US-5,547,369 A | 08-1996 | Sohma; Kenichi | F23M11/045 | 340/577 |
| * | D | US-6,486,486 B1 | 11-2002 | Haupenthal; Karl-Friedrich | F23N5/082 | 250/554 |
| * | E | US-6,501,383 B1 | 12-2002 | Haupenthal; Karl-Friedrich | F23N5/123 | 340/577 |
| * | F | US-2012/0280134 A1 | 11-2012 | DIEBOLD; Alexander | F23N5/082 | 250/372 |
| * | G | US-2014/0085503 A1 | 03-2014 | Su; Wen-Yueh | G03B7/16 | 348/223.1 |
| * | H | US-2014/0162197 A1 | 06-2014 | KRICHTAFOVITCH; IGOR A. | F23C99/001 | 431/2 |
| * | I | US-2015/0362177 A1 | 12-2015 | KRICHTAFOVITCH; IGOR A. | F23C99/001 | 431/8 |
| | J | US- | | | | |
| | K | US- | | | | |
| | L | US- | | | | |
| | M | US- | | | | |

**FOREIGN PATENT DOCUMENTS**

| * | | Document Number Country Code-Number-Kind Code | Date MM-YYYY | Country | Name | CPC Classification |
|---|---|---|---|---|---|---|
| | N | | | | | |
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| | P | | | | | |
| | Q | | | | | |
| | R | | | | | |
| | S | | | | | |
| | T | | | | | |

**NON-PATENT DOCUMENTS**

| * | | Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages) |
|---|---|---|
| | U | |
| | V | |
| | W | |
| | X | |

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

| Search Notes | Application/Control No.<br>14316489 | Applicant(s)/Patent Under Reexamination<br>MARGOLIN, JED |
|---|---|---|
| | Examiner<br>ZHEN Y WU | Art Unit<br>2685 |

## CPC- SEARCHED

| Symbol | Date | Examiner |
|---|---|---|
| F23N 5/123, 2023/42, 2023/10 | 1/17/2017 | ZYW |
| G08B 17/125 | 1/17/2017 | ZYW |
| Y02T 50/677 | 5/4/2017 | ZYW |

## CPC COMBINATION SETS - SEARCHED

| Symbol | Date | Examiner |
|---|---|---|
| | | |

## US CLASSIFICATION SEARCHED

| Class | Subclass | Date | Examiner |
|---|---|---|---|
| 340 | 577 | 1/17/2017 | ZYW |

* See search history printout included with this form or the SEARCH NOTES box below to determine the scope of the search.

## SEARCH NOTES

| Search Notes | Date | Examiner |
|---|---|---|
| All CPC and USPC classifications listed were searched in combination with keywords in EAST | 1/17/2017 | ZYW |
| Inventor and assignee searches double patenting | 1/17/2017 | ZYW |
| NPL searches (eg. Google, Google scholar) | 1/17/2017 | ZYW |
| Consulted with SPE Hai Phan with claim and allowable subject matter | 1/17/2017 | ZYW |
| Updated searches | 5/4/2017 | ZYW |
| Inteference searches (text and class) | 8/3/2017 | ZYW |
| Updated searches | 8/3/2017 | ZYW |
| Consulted with SPE Hai Phan with claim and allowable subject matter | 8/3/2017 | ZYW |

## INTERFERENCE SEARCH

| | |
|---|---|
| /ZHEN Y WU/<br>Examiner.Art Unit 2685 | |

| US Class/ CPC Symbol | US Subclass / CPC Group | Date | Examiner |
|---|---|---|---|
| 340 | 577 | 8/3/2017 | ZYW |
| F23N | 5/123, 2023/42, 2023/10 | 8/3/2017 | ZYW |
| G08B | 17/125 | 8/3/2017 | ZYW |
| Y02T | 50/677 | 8/3/2017 | ZYW |

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| /ZHEN Y WU/<br>Examiner.Art Unit 2685 | |

| *Index of Claims* | Application/Control No.<br>14316489 | Applicant(s)/Patent Under Reexamination<br>MARGOLIN, JED |
|---|---|---|
| | Examiner<br>ZHEN Y WU | Art Unit<br>2685 |

| ✓ | Rejected | - | Cancelled | N | Non-Elected | A | Appeal |
|---|---|---|---|---|---|---|---|
| = | Allowed | ÷ | Restricted | I | Interference | O | Objected |

☒ Claims renumbered in the same order as presented by applicant ☐ CPA ☐ T.D. ☐ R.1.47

| CLAIM | | DATE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Final | Original | 01/17/2017 | 05/04/2017 | 08/03/2017 | | | | | | |
| | 1 | ✓ | ✓ | = | | | | | | |
| | 2 | ✓ | ✓ | = | | | | | | |
| | 3 | ✓ | ✓ | = | | | | | | |
| | 4 | O | O | = | | | | | | |
| | 5 | O | O | = | | | | | | |
| | 6 | N | = | = | | | | | | |
| | 7 | N | = | = | | | | | | |
| | 8 | N | = | = | | | | | | |
| | 9 | N | = | = | | | | | | |
| | 10 | N | = | = | | | | | | |
| | 11 | N | = | = | | | | | | |
| | 12 | ✓ | ✓ | = | | | | | | |
| | 13 | ✓ | ✓ | = | | | | | | |
| | 14 | ✓ | ✓ | = | | | | | | |
| | 15 | N | = | = | | | | | | |
| | 16 | N | = | = | | | | | | |
| | 17 | N | = | = | | | | | | |
| | 18 | N | ✓ | = | | | | | | |

**EAST Search History**

**EAST Search History (Prior Art)**

| Ref # | Hits | Search Query | DBs | Default Operator | Plurals | Time Stamp |
|---|---|---|---|---|---|---|
| L1 | 1 | (Margolin near2 jed) and (flame with burner).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/08/02 16:01 |
| L2 | 103 | mixing with flame with signal | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/08/02 16:02 |
| L3 | 75 | mix$3 near10 flame near10 signal | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/08/02 16:02 |
| L4 | 13 | mix$3 near10 flame near10 signals | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:03 |
| L5 | 44 | mix$3 near10 fire near10 signals | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:06 |
| L6 | 1473 | determin$3 with (fire or flame) with signals | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:07 |
| L7 | 33 | determin$3 near10 (fire or flame) near10 two near4 signals | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:07 |
| L8 | 896 | determin$3 near10 (fire or flame) | US-PGPUB; | AND | OFF | 2017/08/02 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | near10 signals | USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | 16:17 |
| L9 | 15 | determin$3 near10 (fire or flame) near10 signals near through | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:17 |
| L10 | 38 | determin$3 near10 (fire or flame) near10 signals near10 through | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:17 |
| L11 | 4411 | 340/577.ccls. F23N5/123 G08B17/125 F23N2023/10 F23N2023/42 Y02T50/677 | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/08/02 16:39 |
| L12 | 646 | L11 and (flame or fire) near6 detection | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/08/02 16:39 |
| L13 | 243 | detect$3 near10 (fire or flame) near10 signals near10 through | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:40 |
| L14 | 684 | (transmit or send) with signal with through with (fire or flame) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:41 |
| L15 | 267 | (transmit or send) near8 signal near8 through near8 (fire or flame) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/08/02 16:41 |
| L16 | 160 | (transmit or send) near8 signal near8 through near8 (fire or flame) and @ad<"20140626" | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; | AND | OFF | 2017/08/02 16:41 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | IBM_TDB | | | |
| L19 | 4 | "5547369".pn. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/08/02 16:44 |
| L20 | 3 | "20140085503".pn. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/08/02 16:45 |
| L37 | 18 | (flame signal rod (harmonic or mixing) ).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/08/02 17:24 |
| L38 | 4 | (flame signal rod (harmonic or mixing)).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | SAME | ON | 2017/08/02 17:24 |
| L39 | 5 | (flame signal rod (harmonic or mix$3)).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | SAME | ON | 2017/08/02 17:25 |
| S2 | 1 | (Margolin near jed).in. and (flame with burner).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 16:05 |
| S4 | 23 | ("1077628" \| "1688126" \| "2112736" \| "2136256" \| "2709799" \| "2804608" \| "3301307" \| "3956080" \| "0307031" \| "4082493" \| "4317487" \| "6404342" \| "8310801" \| "0803684").PN. | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 16:13 |
| S6 | 3 | detect$3 near8 harmonic near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:20 |
| S7 | 89 | sens$3 near4 (resistance or resistivit$3) near4 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; | AND | ON | 2016/09/26 22:20 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | IBM_TDB | | | |
| S8 | 2 | (sens$3 or detect$3) with harmonic with distortion with flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:21 |
| S9 | 2 | harmonic near distortion near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S10 | 2 | harmonic near distortion near8 flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S11 | 3 | harmonic near distortion near8 fire | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S12 | 14399 | signal with flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:31 |
| S13 | 256 | two near2 signals with flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:31 |
| S14 | 38 | two near2 signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:32 |
| S15 | 94 | appl$3 with signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:36 |
| S16 | 59 | appl$3 near8 signals near8 flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:37 |
| S17 | 1 | "6486486".pn. | US-PGPUB; USPAT; USOCR | AND | ON | 2017/04/19 12:25 |
| S18 | 2 | "6486486".pn. or "6501383".pn. | US-PGPUB; USPAT; USOCR | AND | ON | 2017/04/19 12:26 |
| S19 | 4323 | 340/577.ccls. F23N5/123 G08B17/125 F23N2023/10 | US-PGPUB; USPAT; | OR | ON | 2017/04/19 12:46 |

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|---|---|---|---|---|---|---|
| | | F23N2023/42 Y02T50/677 | USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S20 | 1 | S19 and harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:47 |
| S21 | 29 | S19 and mixing with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:47 |
| S22 | 1838298 | S19 and mixing with signal (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:47 |
| S23 | 8 | S19 and mixing with signal with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:47 |
| S24 | 14 | S19 and combin$4 with signal with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:48 |
| S25 | 158 | ("1077628" \| "6486486" \| "4082493" \| "6404342" \| "1688126" \| "2804608" \| "8310801" \| "2136256" \| "4317487" \| "2112736" \| "2709799" \| "3956080" \| "0803684" \| "3301307" \| "0307031" \| "20080266000" \| "6501383").PN. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:49 |
| S26 | 26 | ("1077628" \| "6486486" \| "4082493" \| "6404342" \| "1688126" \| "2804608" \| "8310801" \| "2136256" \| "4317487" \| "2112736" \| "2709799" \| "3956080" \| "0803684" \| "3301307" \| "0307031" \| "20080266000" \| "6501383").PN. | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 12:49 |
| S27 | 2 | detect$3 near8 harmonic near8 (flame or fire) and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:00 |
| S28 | 0 | S26 and (combin$3 or mix$3) with signal | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:01 |
| S29 | 4 | S26 and (harmonic) with signal | US-PGPUB; | OR | ON | 2017/04/19 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | USPAT; USOCR | | | 13:01 |
| S30 | 4 | harmonic near3 distortion near8 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:04 |
| S31 | 5 | harmonic near3 distortion near8 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 13:04 |
| S32 | 977 | two near2 signals with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 13:06 |
| S33 | 287 | two near2 signals with (flame or fire) with detect$3 with signal | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 13:06 |
| S34 | 111 | two near2 signals with (flame or fire) with detect$3 with signal | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:07 |
| S35 | 148 | signal with flame near2 rod | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:12 |
| S36 | 2 | signal with flame near2 rod and harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:13 |
| S37 | 5 | signal with flame near2 rod with mix$3 | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:13 |
| S38 | 14 | mixing with signal with through with (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:26 |
| S39 | 1 | flame near2 rectification with signal with mix$3 | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:30 |
| S40 | 572 | apply with signal with (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S41 | 352 | apply near10 signal near10 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S42 | 2071 | appl$3 near10 signal near10 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S43 | 234 | appl$3 near10 signal near10 through with (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S45 | 147 | appl$3 near10 signal near10 through with (flame or fire) and | US-PGPUB; USPAT; | OR | ON | 2017/04/19 13:49 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | @ad< "20140530" | USOCR | | | |
| S46 | 26 | appl$3 near10 signal near10 through with (flame or fire) and burner and @ad< "20140530" | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:50 |
| S47 | 36 | (Margolin near2 Jed).in. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/04/19 18:11 |
| S48 | 1 | S47 and (flame with harmonic).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/04/19 18:11 |
| S49 | 1 | S47 and (flame with mixing with signal).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/04/19 18:12 |
| S50 | 145 | flame near2 rod with electrode | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:15 |
| S51 | 133 | flame near2 rod with electrode and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:15 |
| S52 | 3 | flame near2 rod with electrode with signal and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S54 | 82708 | phase near2 locked near2 loop | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S55 | 38475 | phase near2 locked near2 loop with frequency | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S56 | 389 | phase near2 locked near2 loop with frequency with harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S57 | 1 | phase near2 locked near2 loop with frequency with harmonic and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:17 |
| S58 | 0 | phase near2 locked near2 loop with frequency with harmonic with burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:17 |
| S59 | 23 | phase near2 locked near2 loop with frequency with harmonic with tuned | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:18 |
| S60 | 2 | harmonic near2 detector near10 clock near10 synchronous | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:21 |

**EAST Search History (Interference)**

| Ref # | Hits | Search Query | DBs | Default Operator | Plurals | Time Stamp |
|---|---|---|---|---|---|---|
| L21 | 2292177 | (flame signal mixing).clm. | US-PGPUB; USPAT | OR | ON | 2017/08/02 17:03 |
| L22 | 23 | (flame signal mixing).clm. | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:04 |
| L23 | 11 | (flame signal mixing).clm. | US-PGPUB; USPAT | WITH | ON | 2017/08/02 17:04 |
| L24 | 8 | (flame signal harmonic).clm. | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:07 |
| L25 | 4 | (flame signal harmonic).clm. | US-PGPUB; USPAT | WITH | ON | 2017/08/02 17:08 |
| L26 | 568 | 340/577.ccls. F23N5/123 G08B17/125 F23N2023/10 F23N2023/42 Y02T50/677 | US-PGPUB; USPAT | OR | ON | 2017/08/02 17:20 |
| L27 | 507 | l26 and (flame signal) | US-PGPUB; USPAT | OR | ON | 2017/08/02 17:21 |
| L28 | 151 | l26 and (flame signal) | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:21 |
| L29 | 1 | l26 and (flame harmonic) | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:21 |
| L30 | 19 | l26 and (flame with (harmonic or mixing)) | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:22 |
| L31 | 1 | l26 and (flame with (harmonic or mixing)).clm. | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:22 |
| L32 | 1843 | (flame with (harmonic or mixing)).clm. | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:22 |
| L33 | 30 | (flame signal (harmonic or mixing) ).clm. | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:22 |
| L34 | 4 | (flame signal rod (harmonic or mixing) ).clm. | US-PGPUB; USPAT | SAME | ON | 2017/08/02 17:23 |
| L35 | 1 | (flame signal rod (harmonic or mixing) ).clm. | US-PGPUB; USPAT | WITH | ON | 2017/08/02 17:23 |
| L36 | 18 | (flame signal rod (harmonic or mixing) ).clm. | US-PGPUB; USPAT | AND | ON | 2017/08/02 17:23 |

**8/2/2017 5:25:22 PM**
**C:\Users\zwu1\Documents\EAST\Workspaces\14316489 (Flame Sensing system).wsp**

| *Issue Classification* | Application/Control No. | Applicant(s)/Patent Under Reexamination |
|---|---|---|
| | 14316489 | MARGOLIN, JED |
| | **Examiner** | **Art Unit** |
| | ZHEN Y WU | 2685 |

| CPC | | | | | | |
|---|---|---|---|---|---|---|
| **Symbol** | | | | | **Type** | **Version** |
| F23N | | 5 | / | 123 | F | 2013-01-01 |
| F23N | | 2023 | / | 10 | A | 2013-01-01 |
| F23N | | 2023 | / | 42 | A | 2013-01-01 |
| G08B | | 17 | / | 125 | I | 2013-01-01 |
| Y02T | | 50 | / | 677 | A | 2013-01-01 |
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| CPC Combination Sets | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Symbol** | | | | | **Type** | **Set** | **Ranking** | **Version** |
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| | | **Total Claims Allowed:** | |
|---|---|---|---|
| (Assistant Examiner) | (Date) | 18 | |
| /ZHEN Y WU/<br>Examiner.Art Unit 2685<br>(Primary Examiner) | 08/03/2017<br>(Date) | O.G. Print Claim(s)<br>1 | O.G. Print Figure<br>1 |

| *Issue Classification* | Application/Control No. | Applicant(s)/Patent Under Reexamination |
|---|---|---|
| | 14316489 | MARGOLIN, JED |
| | **Examiner** | **Art Unit** |
| | ZHEN Y WU | 2685 |

| US ORIGINAL CLASSIFICATION | | INTERNATIONAL CLASSIFICATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CLASS | SUBCLASS | CLAIMED | | | | | NON-CLAIMED | | | | | |
| 340 | 577 | G | 0 | 8 | B | 17 / 12 (2006.01.01) | | | | | | |

| CROSS REFERENCE(S) | | | | | |
|---|---|---|---|---|---|
| CLASS | SUBCLASS (ONE SUBCLASS PER BLOCK) | | | | |

| | | |
|---|---|---|
| (Assistant Examiner) | (Date) | **Total Claims Allowed:** 18 |
| /ZHEN Y WU/<br>Examiner.Art Unit 2685<br>(Primary Examiner) | 08/03/2017<br>(Date) | O.G. Print Claim(s): 1 / O.G. Print Figure: 1 |

| *Issue Classification* | Application/Control No. | Applicant(s)/Patent Under Reexamination |
|---|---|---|
| | 14316489 | MARGOLIN, JED |
| | **Examiner** | **Art Unit** |
| | ZHEN Y WU | 2685 |

☒ **Claims renumbered in the same order as presented by applicant** ☐ **CPA** ☐ **T.D.** ☐ **R.1.47**

| Final | Original | Final | Original | Final | Original | Final | Original | Final | Original | Final | Original | Final | Original | Final | Original |
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| (Assistant Examiner) | (Date) | **Total Claims Allowed:** 18 | |
| /ZHEN Y WU/<br>Examiner.Art Unit 2685<br><br>(Primary Examiner) | 08/03/2017<br><br>(Date) | O.G. Print Claim(s)<br>1 | O.G. Print Figure<br>1 |

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of Jed Margolin
Serial No.: 14/316,489
Filed: 06/26/2014
For: Flame Sensing System

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

This is in response to the Office Action mailed 05/11/2017.

**1.** As a result of Applicant's Petition to Withdraw Restriction Requirement filed 01/25/2017 (the details of which are in Applicant's Response of 02/04/2017) the Examiner called Applicant on 02/03/2017 and left a message saying said he would vacate his Office Action of 01/19/2017 and that he would examine all of Applicant's claims. However, there is no indication in the PAIR Transaction History or File Wrapper that the Examiner vacated his Office Action of 01/19/2017. If Applicant had not filed his Response to the Office Action on 02/04/2017 Applicant's application would have been considered abandoned on 04/19/2017.

In addition, in the current Office Action, although the Examiner checked the box under **Status** saying that the current Office Action is responsive to Applicant's communications filed 02/04/2017 he did not respond to it.

He really should have read it. In it Applicant politely and respectfully showed that, in the Office Action of 01/19/2017 the Examiner had materially misquoted Applicant's Claim 1. His rejection of Claim 1 resulted in the rejection of several other claims. The Examiner violated MPEP 2143.03:

**2143.03 All Claim Limitations Must Be Considered [R-08.2012]**

> "All words in a claim must be considered in judging the patentability of that claim against the prior art." *In re Wilson,* 424 F.2d 1382, 1385, 165 USPQ 494, 496 (CCPA 1970).
> ....

The claims are the legal definition of the invention. Since the Examiner misquoted Claim 1 in a material way he had not examined Applicant's invention claimed in Claim 1.

**2.** In the Examiner's Office Action mailed 05/11/2017 he again rejected Claims 1, 2 and 12 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1).

His rejection is identical to his rejection in the Office Action mailed 01/19/2017 including his material misquoting of Applicant's Claim 1. Therefore, Applicant's response here will be identical to his response filed 02/04/2017.

**3.** The Examiner has again rejected Claims 3, 13 and 14 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).

Again, his current rejection of Claims 3, 13, and 14 is identical to his rejection of these claims in his Office Action of 01/19/2017. Therefore, Applicant will again show that the Examiner's rejection is in error.

**4.** Claims 4 and 5 were objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

**5.** The Examiner has allowed Claims 6-11 and 15-l7. Applicant thanks the Examiner for that.

**6.** However, the Examiner has rejected Claim 18 using two references which, neither singly nor together have any possible relevance to Applicant's invention. Nonetheless Applicant has amended Claim 18 to make it clear to the Examiner that the two signal sources are provided to the flame using a flame rod (Flame Rod 3 in Figure 89) which neither reference uses. Also, neither reference uses flame rectification.

Applicant's remarks begin on page 10.

The claims begin on page 4.

Respectfully submitted,

/Jed Margolin/ Date: May 15, 2017

Jed Margolin

Jed Margolin
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775-847-7845

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## Claims

1. (Original) A system for detecting the presence of a flame comprising:

   a. a combustion burner;

   b. a flame rod;

   c. a signal source having a selected waveform connected to said flame rod;

   d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

   e. a harmonic signal detector having an input connected to the output of said high impedance buffer;

   f. an indicator connected to the output of said harmonic signal detector;

whereas

   g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and

   h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.

2. (Original) The system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

3. (Original) The system of claim 1 whereby said harmonic signal detector comprises a phase locked loop tuned to the frequency of said harmonic signal.

4. (Original) The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising:

   a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

   b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

5. (Original) The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

6. (Original) A system for detecting the presence of a flame comprising:

a. a combustion burner;

b. a flame rod;

c. a first signal source having a selected waveform connected to said flame rod;

d. a second signal source having a selected waveform connected to said flame rod;

e. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

f. a signal detector having an input connected to the output of said high impedance buffer;

g. an indicator connected to the output of said signal detector;

whereas

h. said flame from said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a first mixing signal at the sum of the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform as well as a second mixing signal at the difference between the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform, and

i. said signal detector is configured to detect said first mixing signal or said second mixing signal and indicate the results on said indicator.

7. (Original) The system of claim 6 whereby said signal detector comprises a phase locked loop tuned to said first mixing frequency or to said second mixing frequency.

8. Original) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, and a reference signal having the same frequency as said first mixing signal or said second mixing signal, and said signal detector comprises a simple synchronous detector comprising:

a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

9. (Original) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, a first reference signal having the same frequency as said first mixing signal or said second mixing signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

10. (Original) The system of claim 6 whereby said first signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

11. (Original) The system of claim 6 whereby said second signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

12. (Original) A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a signal source having a selected waveform introduced to said flame rod;
d. providing a high impedance buffer to buffer a flame rod signal from said flame rod;
e. providing a harmonic signal detector to receive the output of said high impedance buffer;
f. providing an indicator to receive the output of said harmonic signal detector;

whereas

g. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said signal source having a selected waveform to produce harmonics of the fundamental frequency of said selected waveform,
h. said harmonic signal detector is used to detect the presence of at least one of said harmonics of said selected waveform and indicate the presence of said at least one of said harmonics of said selected waveform on said indicator, and
i. said presence of said at least one of said harmonics of said selected waveform is proof of the presence of said flame.

13. (Original) The method of claim 12 where said step of providing a harmonic signal detector comprises providing a phase locked loop.

14. (Original) The method of claim 12 where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

15. (Original) A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a first signal source having a selected waveform introduced to said flame rod;
d. providing a second signal source having a selected waveform introduced to said flame rod;
e. providing a high impedance buffer to buffer a flame rod signal from said flame rod;
f. providing a signal detector to receive the output of said high impedance buffer;
g. providing an indicator to receive the output of said signal detector;

whereas

h. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a sum signal at the sum frequency of said first signal source and said second signal source and a difference signal at the difference frequency of said first signal source and said second signal source,
i. said signal detector is used to detect the presence of said sum signal or said difference signal and indicate the presence of said sum signal or said difference signal on said indicator, and
j. said presence of said sum signal or said difference signal is proof of the presence of said flame.

16. (Original) The method of claim 15 where said step of providing a signal detector comprises providing a phase locked loop.

17. (Original) The method of claim 15 where said step of providing a signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

18. (Amended) A method for detecting the presence of a flame comprising the steps of:

a. providing two signal sources to said flame using a flame rod;

b. using flame rectification to cause said two signal sources to mix;

c. providing a signal detector to detect a mixing signal produced by said two signal sources; and

d. providing an indicator to indicate the results of said signal detector.

**Applicant's Remarks**

**A.** The Examiner rejected Claims 1, 2 and 12 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No. US 6,501,383 B1) in view of Haupenthal (Pat. No. US 6,486,486 B1).

The Examiner rejected Claims 3, 13 and 14 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).

Applicant will begin by showing what Haupenthal '383 and Haupenthal '486 actually teach and what they do not teach.

## I. Haupenthal '383

In Haupenthal '383 he is concerned that in a flame sensing system using flame rectification to produce a DC voltage, a component (such as a capacitor) in the filter section could fail so that the system could indicate the presence of a flame when there isn't one.

In Haupenthal's description of prior art:

> 2. Description of the Prior Art
>
> Monitoring gas flames frequently entails the use of flame monitors which utilize the rectifier effect of the flame, that is to say which operate on the basis of what is known as the ionization principle. In that procedure an ac voltage is applied between two electrodes. The volume which is filled by the flame depends on the instantaneous output of the burner. The direct current which can be produced can be very low at a low level of burner output and if the geometry of the electrodes is not the optimum, while the alternating current can be substantially greater in dependence on the capacitance of the sensor line. The flame signal amplifier must therefore be capable of filtering off the low direct current component in the overall sensor circuit current, without the alternating current being able to simulate a flame signal as a result of the inevitable rectifier effects in the amplifier input. Therefore the magnitude of the direct current component gives a measurement in respect of the intensity of the flame, in which respect the absence of a flame corresponds to the intensity of zero, the detection of which must be established reliably and very close to real time in order to avoid unburnt gas or oil from flowing out into the burner chamber.

{Emphasis added}

But:

> In principle filtering of the direct current component can be implemented by an evaluation circuit which is connected upstream of the flame signal amplifier, such as for example a low

> pass filter with a sufficiently low limit frequency. If however the filter capability of the low pass filter is lost, for example because of a failure of a filter capacitor, the alternating current could simulate the presence of a flame, even when the flame is not present.

{Emphasis added}

Note the emphasis on "direct current" and "direct current component". Applicant's invention does not use flame rectification to produce a direct current, a practice which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

Haupenthal proposes to solve the problem caused by the failure of a filter as follows:

> Therefore the object of the present invention is to provide a method and an apparatus for monitoring a flame which serves as a flame monitoring method and circuit respectively, the response sensitivity of which is substantially improved in comparison with the state of the art without detracting from compatibility for line capacitance, whose switch-off capability can be periodically checked during burner operation and also supplies an output signal representing a measurement in respect of flame intensity. The invention further seeks to provide that the method ensures continuous checking of the monitoring action.
>
> According to a first aspect of the present invention, there is provided a method of monitoring a flame, wherein: in dependence on the presence or intensity of the flame there is produced from a first electrical signal a second electrical signal of different magnitude, the second electrical signal is applied to an evaluation circuit and converted into a first output signal, and the evaluation circuit is acted upon by a monitoring signal which upon failure of the evaluation circuit leads to a second output signal.

{Emphasis added}

Unfortunately, this is so vague that we are required to decipher what he means by "a first electrical signal" and "a second electrical signal".

But then he says:

> The method according to the invention of monitoring a flame makes use of the known principle that in dependence on the presence or the intensity of the flame there is produced from a first electrical signal (for example an ac voltage signal) a second electrical signal of different magnitude (for example a dc signal) (I.sub.F) . A preferred embodiment uses ionization electrodes or ultraviolet sensors with series-connected diode which in dependence on flame intensity supply a corresponding dc signal. No dc signal is produced when the flame is extinguished. The second electrical signal (I.sub.F) is detected by an evaluation circuit to which the ionization electrodes or the ultraviolet sensors are connected, and converted into a first output signal (A), wherein conversion is effected by various further circuit elements in such a

way that differently dynamic output signals are obtained, depending on the respective flame intensity involved. Therefore with changing flame intensities the output signal (A) is an output signal which changes in terms of its dynamics.

{Emphasis added}

The first electrical signal may be an AC voltage signal and the second electrical may be a DC signal, and the first electrical signal (an AC signal) produces the second electrical signal (a DC signal).

Since Haupenthal is concerned that in a flame sensing system using flame rectification to produce a DC voltage a component (such as a capacitor) in the filter section could fail so that the system could indicate the presence of a flame when there isn't one, the first electrical signal is the AC applied to the flame sensor (which is subject to flame rectification) and the second electrical signal is the dc voltage produced by filtering. However, in addition, "A preferred embodiment uses ionization electrodes or ultraviolet sensors"

Unless the "or" is a mistranslation of the original German (or a typo) and Haupenthal really does mean "or" and not "and" then his patent is for two different inventions, both of which were already known at the time he filed his application. There are:

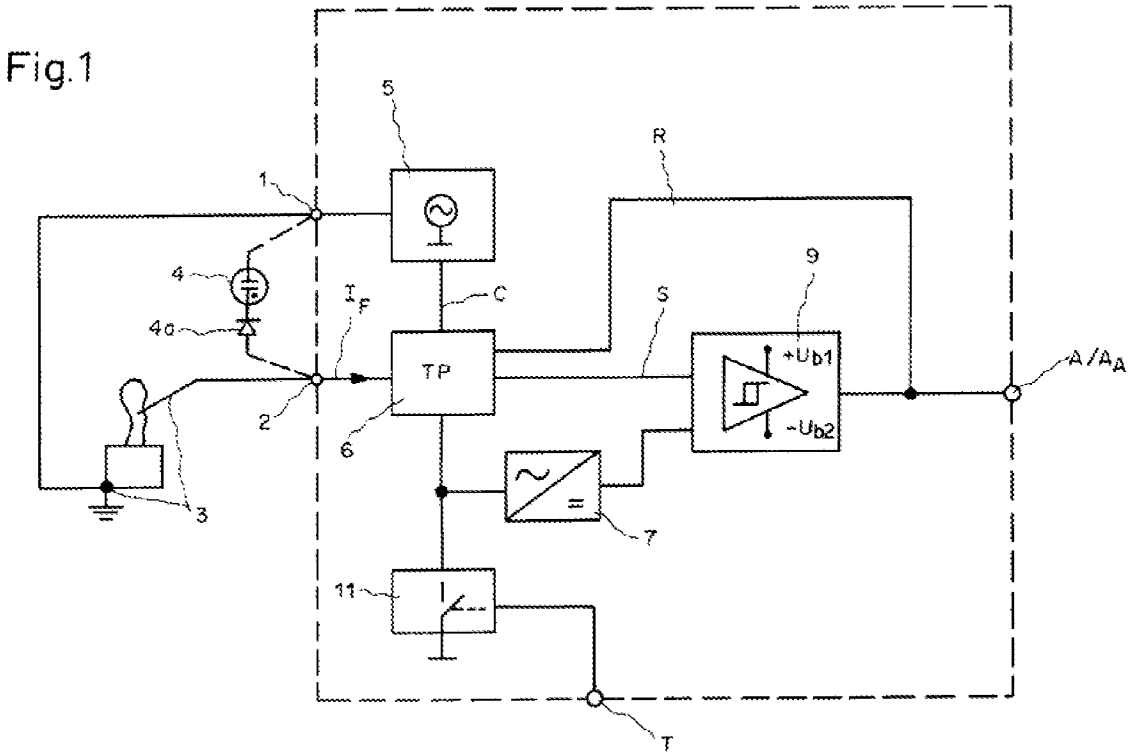
1. Flame rectification of an AC voltage which after filtering provides a DC voltage. U.S. Patent 2,112,736 **Flame Detector** issued March 29, 1938 to William D. Cockrell, assigned to General Electric *{Applicant's IDS Cite 2}*. This patent teaches using flame rectification for providing flame proof. Cockrell Figure 1 shows an embodiment using one electrode (22) with the burner (2) used as the return. See Page 1, left column, line 41 - Page 2, right column, line 15.

2. A UV sensor that detects the UV radiation produced by a flame.

From Haupenthal DESCRIPTION OF THE PREFERRED EMBODIMENT:

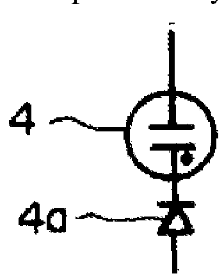
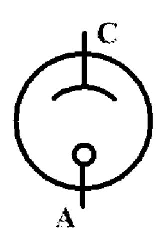
FIG. 1 is a diagrammatic view of a preferred embodiment of apparatus according to the invention. <u>Ionization electrodes 3 or ultraviolet sensors 4,4a</u> are supplied by way of a connecting terminal 1 with the ac voltage signal from a suitable source 5 and supply the signal which is generated by the flame and on which an unwanted alternating current signal is superimposed to the terminal 2 at which an evaluation circuit 6, here a filter member, detects the direct current signal I.sub.F. The control signal S is passed to the trigger stage 9 which outputs the output signal A, A.sub.A. A reset line R serves to reset the evaluation circuit 6 so that an oscillating signal appears at the output of the trigger stage 9. If the evaluation circuit 6 comprises a low pass member TP with capacitor C1 and resistor R1, it has to be regularly reset.

Here is Haupenthal Figure 1:




Components 4 and 4a are characterized as “ultraviolet sensors 4,4a” and their (or its) output is added to the signal produced by flame rectification which come from component 3 (a flame electrode and the body of the combustion burner) so Haupenthal must mean flame rectification **<u>and</u>** the use of a UV sensor.

The UV sensor that Hauphenthal uses appears to be a UV phototube.

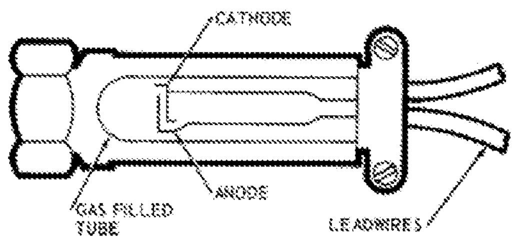
| Haupenthal’s symbol | Standard symbol for a phototube |
|---|---|
|   |   |

See *Ref. 1:* **Phototubes** by Hamamatsu, Figure 2 page 6.

From Column 5, lines 5 -10:

> The flame monitoring circuit is fed in bipolar mode by two operating voltages +Ub1 and -Ub2 defined with respect to a reference potential m. It has two terminals 1 and 2 which can be connected either to two ionization electrodes 3 or to the two terminals of an ultraviolet sensor comprising a gas-filled ultraviolet cell 4 and a diode 4a connected in series therewith.

This is a phototube:




From *Ref. 2*: **Phototube** at Wikipedia:

> A phototube or photoelectric cell is a type of gas-filled or vacuum tube that is sensitive to light. Such a tube is more correctly called a 'photoemissive cell' to distinguish it from photovoltaic or photoconductive cells. Phototubes were previously more widely used but are now replaced in many applications by solid state photodetectors. The photomultiplier tube is one of the most sensitive light detectors, and is still widely used in physics research.

and

> Phototubes operate according to the photoelectric effect: Incoming photons strike a photocathode, knocking electrons out of its surface, which are attracted to an anode. Thus current is dependent on the frequency and intensity of incoming photons. Unlike photomultiplier tubes, no amplification takes place, so the current through the device is typically of the order of a few microamperes.[1]
>
> The light wavelength range over which the device is sensitive depends on the material used for the photoemissive cathode. A caesium-antimony cathode gives a device that is very sensitive in the violet to ultra-violet region with sensitivity falling off to blindness to red light. Caesium on oxidised silver gives a cathode that is most sensitive to infra-red to red light, falling off towards blue, where the sensitivity is low but not zero.[2]

The use of an ultraviolet sensor to detect the presence of a flame goes back to at least 1977 in U.S. Patent 4,039,844 **Flame monitoring system** issued August 2, 1977 to MacDonald (*Ref. 3*). From Column 6, lines 6 - 27:

> In operation, the burner 16A in proper operation provides a flame condition with fluctuating components in zone 22A. The sensor circuit 70 senses that fluctuating component and steady

> state components in zone 24 of flame 20 as well as in background radiation and produces an AC signal which coupled by capacitor 76 to the band pass amplifier 80 which amplifies that AC signal. As long as that AC signal above a minimum threshold is present, filter 128 periodically causes comparator 136 to trigger one shot 148 to produce a forty microsecond pulse at output terminal 178. Those output pulses are compatible with operating circuitry designed to respond to an <u>ultraviolet flame sensor,</u> for example. Should the magnitude of the output signal from the band pass amplifier fall sufficiently to switch comparator 198, however, the pulse generating circuit is clamped off and the threshold level is shifted by the feedback loop of comparator 198 to require a substantially greater magnitude of flame signal at terminal 62' to reinitiate the generation of output pulses at terminal 178 than was required to maintain application of those pulses at that terminal.

{Emphasis added}

What we learn from this is that the ultraviolet produced by a flame contains fluctuating components. MacDonald separates these fluctuating components from the DC component and uses them as flame proof.

These fluctuating components are also an important part of U.S. Patent 5,073,769 **Flame detector using a discrete fourier transform to process amplitude samples from a flame signal** issued December 17, 1991 to Kompelien (*Ref. 4*). From Column 1, lines 5 - 21:

> In fuel burners such as furnaces where the main burner is lit by a pilot burner, it is necessary for obvious reasons to assure that the pilot burner is lit before the main burner fuel valve is opened. This is true whether a standing pilot or intermittent pilot is involved. While there are many different types of sensing operations which can reliably detect presence of a pilot flame, one which is preferred senses the flicker frequency of typical pilot flames. This flicker is a periodic variation of the intensity or amplitude of the infrared, visible, or ultraviolet radiation produced by the burning of the fuel sustaining the pilot flame. The flicker frequency of this radiation in most cases has a component in the range of 13-17 hz. This characteristic is fairly independent of the fuel and the size of the pilot flame.

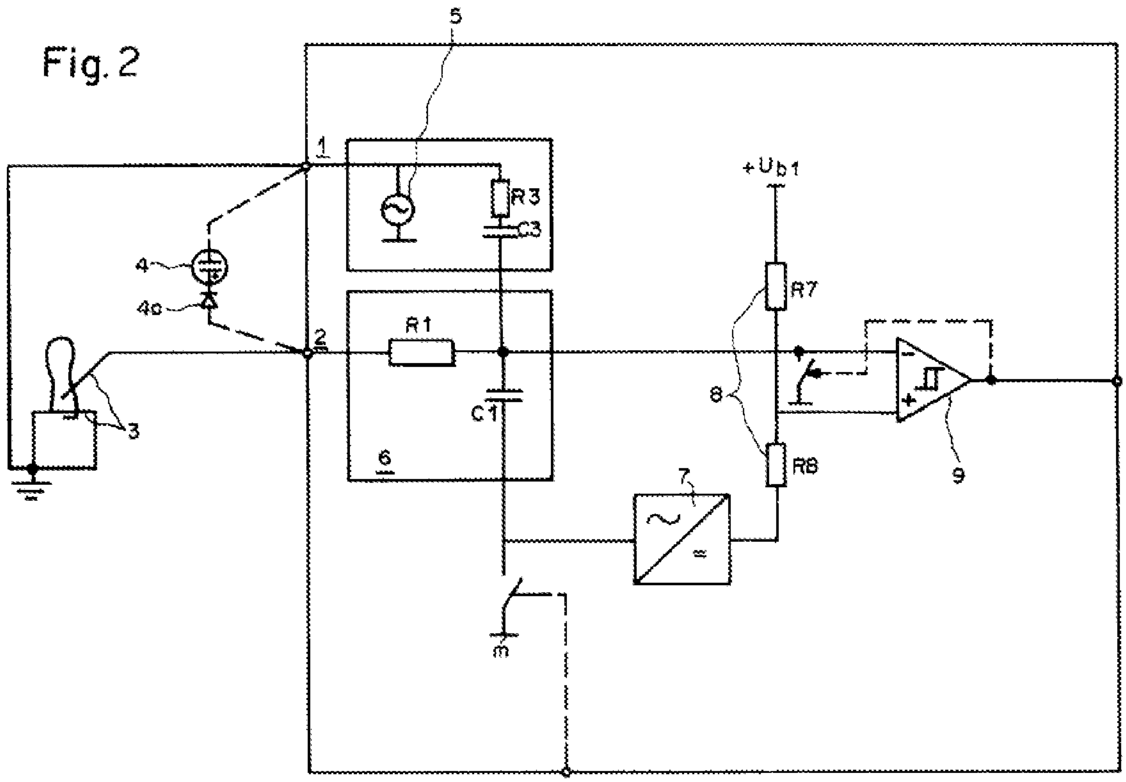
However, Haupenthal's Figure 5 does not appear to have accounted for the 13-17 Hz undulation. Haupenthal states:

> The flame begins to burn at the time t.sub.1, and it is possible to see a direct current signal which rises to the time t.sub.2. Until t.sub.3 the flame intensity remains constant and then falls to t.sub.4 in order there to remain at a lower level in order finally to rise again from the time t.sub.5 and remain at a higher level from time t.sub.6.

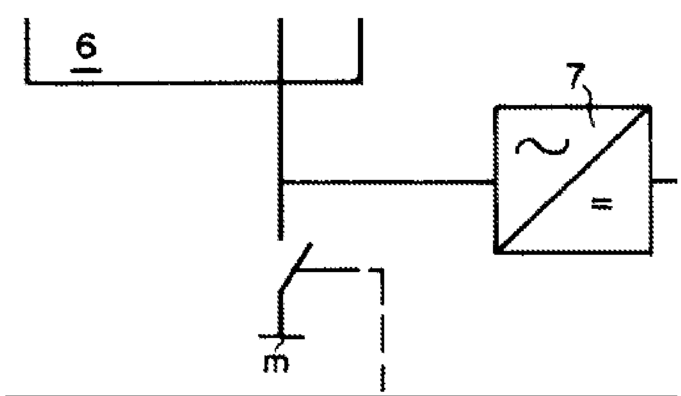
Haupenthal's UV Sensor is connected in parallel with the flame rod and combustion burner so the current through the UV Sensor is added to the current produced by flame rectification.

There is a problem with Haupenthal's circuit. AC source (5) is grounded to circuit ground (m) - which is also known as circuit common. This is shown in Haupenthal Figure 2. (He left it out of Figure 1 even though it is the same part of the circuit.)

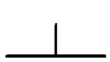
Fig. 2




Since it might not be apparent where circuit ground (m) is this is a zoomed in picture:

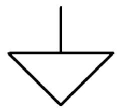



Haupenthal uses the symbol



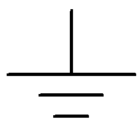
to indicate circuit ground.

Another symbol that is commonly used for circuit ground is:



There does not seem to be an international standard for circuit ground.

However, there is an international electrical symbol for earth ground: IEC 5017.



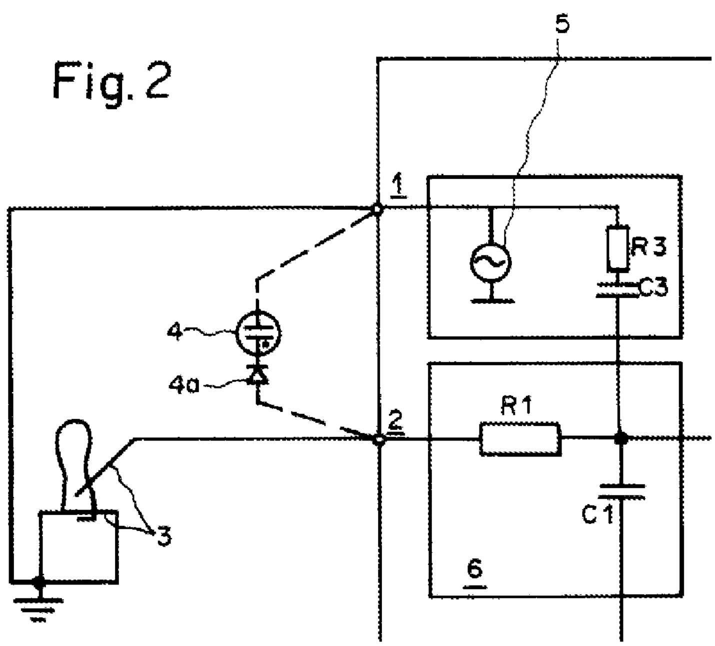
For the ANSI/IEC standard for the symbol see *Ref. 5*. It is characterized as:

1) A direct conducting connection to the earth or body of water that is a part thereof.

The problem is that while one side of AC source (5) is connected to circuit common (m) the hot side terminal (1) is connected to earth ground. This is because the combustion burner must be directly attached to the furnace cabinet which must be grounded to earth ground for safety reasons (it is an exposed metal surface). Another reason the furnace cabinet must be connected to earth ground is that this is a gas furnace, and the gas line must be grounded to earth ground.

This shows that the AC source (5) hot terminal (1) is connected to earth ground.

Fig. 2



If AC source (5) were the AC Mains this would short the AC Mains hot to earth ground producing large ground currents. This cannot be allowed to happen.

Suppose AC source (5) is isolated from the Mains. This would work if the circuit ground (m) were kept isolated from earth ground. If it isn't, then AC source (5) would be shorted out.

But remember that Haupenthal's flame sensor is for a furnace. The furnace will be controlled by a thermostat. The thermostat will need to be located somewhere other than the furnace. Otherwise the heat from the furnace will affect the thermostat readings. And who wants the temperature of their bedroom determined by the temperature in their garage where the furnace might be located?

The thermostat will probably be connected to the furnace by a cable of wires. This means that care must be taken so that no internal conducting part of the thermostat can come into contact with earth ground either directly or through a person. It is unlikely that any safety organization would approve a furnace using Haupenthal's flame sensor.

Be that as it may, Haupenthal's invention uses flame rectification to convert an AC voltage to a DC voltage which is augmented by an ultraviolet flame sensor.

Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

## II. Haupenthal '486

Haupenthal '486 is for a flame sensor that detects the ultraviolet radiation produced by a flame. Haupenthal does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is no flame rod. There is no selected signal. The only things that '486 has in common with Applicant's invention are:

They are both flame sensors; and

Both use the word "harmonics" somewhere.

They achieve their results by completely different means.

Haupenthal is concerned that lighting sources powered by the Mains could be picked up by the UV sensor and cause the UV sensor to report the presence of a flame when there isn't one.

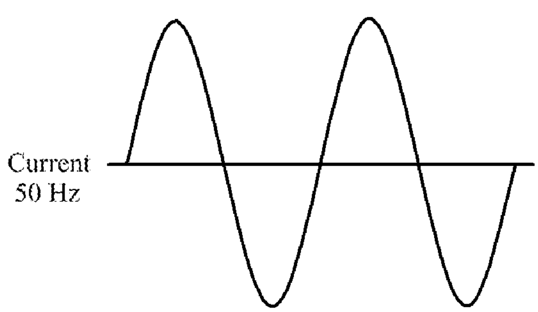
When could this happen? Isn't the combustion compartment sealed? The answer is that there are times when the furnace covers must be removed such as for diagnosing furnace problems.

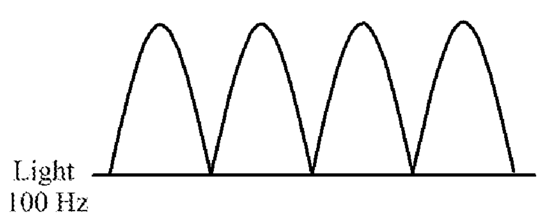
Haupenthal states (Column 2, line 20 - 27):

> The object of the present invention is to provide a flame monitoring system and a method of monitoring a flame, which has immunity in relation to mains frequency-harmonic input signals with a very low level of flame signal information loss and which is suitable for use in relation to burners in a continuous mode of operation.

At the time Haupenthal made his invention (priority comes from around 1998) the major sources of artificial lighting were incandescent lights and fluorescent lights powered by the Mains.

The light produced by an incandescent bulb does not care about the polarity of the current so a Mains current of 50 Hz (which is the Mains frequency in Europe where Haupenthal made his invention) would produce light at twice the Mains frequency, which would be 100 Hz.



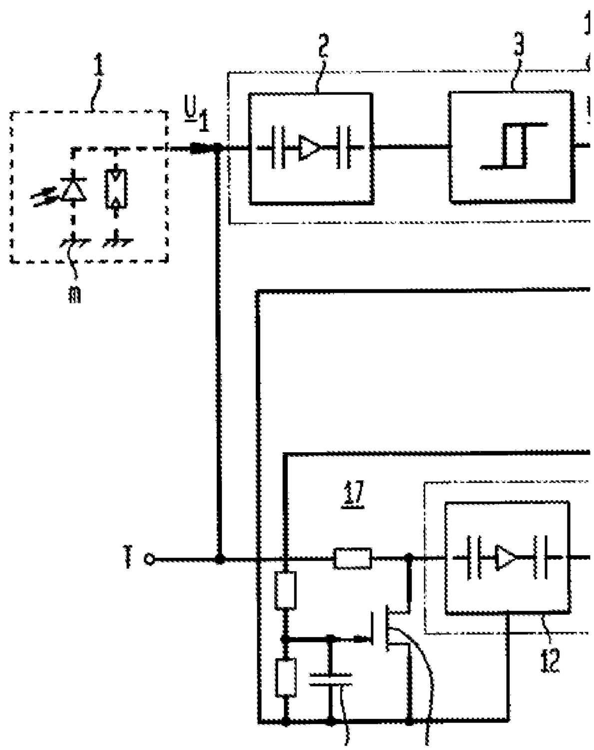




Incandescent bulbs have a large amount of thermal inertia so the light output will be more-or-less steady and not as shown.

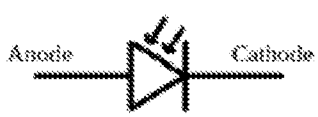
However, fluorescent lights have no thermal inertial so the light output will be as shown.

This is the source of the "mains frequency-harmonic input signals".

Here is the front end of Haupenthal's system showing the UV sensor 1. (Figure 1)




Haupenthal is using the standard symbol for a photodiode.




See *Ref. 6:* **Photodiode** from Wikipedia.

The UV Sensor is labeled "**1**". Input "**T**" is an input for a test signal. From Column 6, lines 5 - 8:

> FIG. 1 also shows a control input, by way of which a test signal T can be superimposed on the signal voltage U.sub.1. Such a test signal T is for example a 100 Hz signal which simulates a light source operated with alternating current.

{Emphasis added}

Further, from Column 2, lines 20 - 59:

> In accordance with a first aspect of the invention, there is provided a flame monitoring system comprising: a flame sensor which converts the radiation emanating from a flame into a flame signal; a flame signal amplifier which converts the flame signal into an output signal; and a frequency-selective arrangement which detects the presence of mains frequency-harmonic

signals in the flame signal; wherein: the frequency-selective arrangement activates the flame signal amplifier when there are no mains frequency-harmonic signals in the flame signal; and the frequency-selective arrangement deactivates the flame signal amplifier when there is a flame signal with mains frequency-harmonic signals or no flame signal or a test signal.

In accordance with a second aspect of the invention, there is provided a method of monitoring a flame, comprising: converting radiation emanating from the flame into a flame signal which is converted into an output signal; and detecting the presence of mains frequency-harmonic signals in the flame signal by using a frequency-selective arrangement; wherein: the flame signal is converted into an output signal when there are no mains frequency-harmonic signals in the flame signal; and the flame signal is converted into a zero signal where there is a flame signal with mains frequency-harmonic signals or no flame signal or a test signal.

In both aspects the flame signal amplifier is activated when there are no mains frequency harmonics (from ambient lighting) and is deactivated when there are mains frequency harmonics (from ambient lighting).

Haupenthal does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is no flame rod. There is no selected signal.

Applicant observes that both incandescent and fluorescent bulbs produce little or no ultraviolet energy. If they did, they would be considered hazardous. (There are fluorescent bulbs designed to produce ultraviolet energy for specific purposes like germocidal lamps but they are not used for general lighting.)

Applicant also observes that fluorescent bulbs using an electronic ballast operate at ultrasonic frequencies. This includes modern compact fluorescent lights (CFLs). Haupenthal's invention would not work as intended with these lights.

It is possible that Haupenthal was working with a general light sensor instead of one that was responsive only to ultraviolet.

The result is that Haupenthal '486 is for a flame sensor that detects the ultraviolet radiation produced by a flame. He detects the second harmonic of the mains power caused by ambient lighting operating at the mains power frequency (and whose operation effectively doubles the frequency of the mains power) and disables the flame sensor when this second harmonic is detected by the ultraviolet sensor. Haupenthal does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is not even a flame rod.

Combining Haupenthal '383 with Haupenthal '486 results in a flame sensing system that:

1. Uses flame rectification to produce a DC voltage when a flame is present;
2. Also uses an ultraviolet sensor to detect the ultraviolet light from the flame; and
3. Turns off the flame sensor when the ultraviolet sensor detects ambient light operating at the Mains power frequency.

Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

And when Haupenthal detects his harmonic it means his ultraviolet sensor might be being fooled by ambient light so the flame might be bad. When Applicant detects his harmonic it means the flame is good.

**B.** For the above reasons the Examiner's rejection of Applicant's claims 1, 2 and 12 is not supportable. The Examiner's reasons are as follows:

> Claims 1, 2 and 12 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1).
>
> Regarding claim 1, Haupenthal (383) teaches a **system for detecting the presence of a flame comprising:**
>
> **a. a combustion burner** (Fig. 1);
>
> **b. a flame rod** (Fig. 1, ionization electrodes 3);
>
> **c. a signal source having a selected waveform connected to said flame rod** (Fig. 1, signal source having an ac waveform is connected to the electrode);
>
> **d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame** (Fig. 1, and Col. 4, lines 36-50,
>
> > "Ionization electrodes 3 or ultraviolet sensors 4, 4a are supplied by way of a connecting terminal 1 with the ac voltage signal from a suitable source 5 and supply the signal which is generated by the flame and on which an unwanted alternating current signal is superimposed to the terminal 2 at which an evaluation circuit 6, here a filter member, detects the direct current signal I.sub.F.");

As Applicant has noted Haupental (383) shows a series path through the combustion burner requiring unsafe grounding practices while Applicant uses a parallel path which allows standard (and safe) grounding practices to be used.

But the real story is that Haupenthal (383) uses flame rectification to produce a direct current, which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

The Examiner continues:

> **e. a signal detector having an input connected to the output of said high impedance buffer** (Fig. 1, evaluation circuit 6);

The Examiner has misquoted Applicant's claim 1(e) which actually says:

**e. a harmonic signal detector having an input connected to the output of said high impedance buffer;**

Haupenthal's Fig. 1 (383) evaluation circuit 6 is not a harmonic signal detector. The word "harmonic" does not appear anywhere in Haupenthal (383). Haupental uses flame rectification to produce a direct current, which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components. Haupenthal's indicator indicates the presence of a direct current produced by flame rectification. Applicant's indicator indicates the presence of either a harmonic of a selected waveform caused by flame rectification or sum and difference frequency components produced when flame rectification causes two selected waveforms to mix.

The Examiner continues:

**f. an indicator connected to the output of said signal detector** (Abstract:

> "The direct current signal (I.sub.F) is detected by an evaluation circuit (6) and converted into a first output signal (A), wherein conversion is effected by various further circuit elements (7, 9, 10) in such a way that differently changing output signals (A.sub.1, A.sub.2) are obtained depending on the respective flame intensity. ".

Indicate the intensity of the flame);

The Examiner has misquoted Applicant's claim 1(f) which actually says:

**f. an indicator connected to the output of said harmonic signal detector;**

Haupental uses flame rectification to produce a direct current, which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components. Haupenthal's indicator indicates the presence of a direct current produced by flame rectification. Applicant's indicator indicates the presence of either a harmonic of a selected waveform caused by flame rectification or sum and difference frequency components produced when flame rectification causes two selected waveforms to mix.

The Examiner continues:

**whereas**

**g. said flame from said combustion burner causes distortion of said signal source having a selected waveform producing a a distorted signal** (Fig. 5, Col. 7 lines 18-28,

> "The uppermost diagram shows the direct current signal I.sub.F on which the alternating current signal is superimposed, in which case the alternating current signal is only shown in part for the sake of enhanced clarity.".

The ac source signal is distorted by the direct current generated by the flame), and

The Examiner has misquoted Applicant's claim 1(g) which actually says:

> **g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and**

As Applicant has explained, he does not use flame rectification to produce a direct current signal. The Examiner's assertion that "The ac source signal is distorted by the direct current generated by the flame" is an interesting conjecture but is not relevant here. Is the Examiner referring to the flame battery referred to in Applicant's specification paragraph 029 ?

> Figure 1 shows a representative Combustion Burner 1, Flame 2, and Flame Rod 3. Figure 2 is a representative electrical model of the electrical properties of Figure 1. Experiments will show that this is an AC model and that the flame battery is an integral part of Flame Diode D (23).

Although the flame does generate a small current by itself (the flame battery) which is probably part of the process that produces flame rectification, the use of flame rectification requires an external current in order to produce its effect.

And the alternating current that is superimposed on the direct current signal I.sub.F comes from coupling capacitance in Haupenthal's sensor lines. From Column 5, lines 33 - 40:

> Only a direct current flows in the sensor circuit between the ionization electrodes 3 because of the rectifying effect of the flame or in the ultraviolet cell 4 because of the diode 4a, more specifically only when the flame is actually burning. However an unwanted alternating current also constantly flows between the terminals 1 and 2, because of the inevitable capacitance of the sensor lines, and that alternating current is superimposed on the direct current.

Since Applicant's invention detects the presence of either a harmonic of a selected waveform caused by flame rectification (or sum and difference frequency components produced when flame rectification causes two selected waveforms to mix) it is already relatively insensitive to any capacitive coupling between the sensor line and ground, which is Applicant's return current path between the combustion burner and the flame rod. Any effect that capacitive coupling between the sensor line and ground has on the DC produced by flame rectification is irrelevant because Applicant does not use the DC produced by flame rectification. In addition, the capacitance between Haupenthal's sensor lines is a linear capacitance and does not introduce distortion.

The Examiner continues:

> **h. said signal detector is configured to detect said distorted signal and indicate the results on said indicator** (Fig. 5. Col. 7 line 29-43, detect flame intensity according to the dc component of the superimposed waveform).

The Examiner has misquoted Applicant's claim 1(h) which actually says:

> **h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.**

Applicant 's indicator does not detect flame intensity according to the DC component of the superimposed waveform. Applicant's indicator indicates the presence of either a harmonic of a selected waveform caused by flame rectification or the sum and/or difference frequency components produced when flame rectification causes two selected waveforms to mix.

The Examiner has omitted words and substituted his own words for the claim filed by Applicant. This is in violation of MPEP 2143.03.

> **2143.03 All Claim Limitations Must Be Considered [R-08.2012]**
>
> "All words in a claim must be considered in judging the patentability of that claim against the prior art." *In re Wilson,* 424 F.2d 1382, 1385, 165 USPQ 494, 496 (CCPA 1970). If an independent claim is nonobvious under 35 U.S.C. 103, then any claim depending therefrom is nonobvious. *In re Fine,* 837 F.2d 1071, 5 USPQ2d 1596 (Fed. Cir. 1988).

By materially misquoting Applicant's claim 1 the Examiner has made an improper rejection. Since the Examiner's rejection of claims 2 and 12 are based on his rejection of claim 1 his rejection of claims 2 and 12 is improper as well.

The Examiner continues:

> Haupenthal (383) teaches a flame monitoring system that detects flame intensity according to the dc current generated by the flame superimposed on the ac source signal instead of the **harmonic** distortion of the ac source signal.

> However, in the same field of flame monitoring system, Haupenthal (486) teaches a system that detects the harmonic frequency signal by the flame. See Abstract,
>
> > "A frequency-selective arrangement (6, 17, 18, 19) detects the presence of mains frequency-harmonic signals in the flame signal (U.sub.1) and activates the flame signal amplifier (40) when there are no mains frequency-harmonic signals in the flame signal (U.sub.1) and deactivates the flame signal amplifier (40) when there is a flame signal (U.sub.1) with periodic signals or no flames signal (U.sub.l) or a test signal (T) .".
>
> Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)'s evaluation circuit with Haupenthal (486)'s harmonic detection system to detect harmonic distortion to accurately detect the presence of a flame.

As Applicant has shown in his discussion of Haupenthal '486, the '486 patent is for a flame sensor that detects the ultraviolet radiation produced by a flame. It does not detect harmonics produced by the flame. Haupenthal is concerned that lighting sources powered by the Mains could be picked up by the UV sensor and cause the UV flame sensor to report the presence of a flame when there isn't one. At the time Haupenthal made his invention (priority comes from around 1998) the major sources of artificial lighting were incandescent lights and fluorescent lights powered by the Mains. The light produced by incandescent bulbs and fluorescent lights does not care about the polarity of the current so a Mains current of 50 Hz (which is the Mains frequency in Europe where Haupenthal made his invention) would produce light at twice the Mains frequency, which would be 100 Hz. It is the Mains frequency harmonic produced by ambient light that '486 is designed to detect. When it detects this harmonic it deactivates the flame sensor.

Haupenthal '486 does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is no flame rod. There is no selected signal. The only things that '486 has in common with Applicant's invention is that:

They are both flame sensors; and

Both use the word "harmonic" somewhere.

They achieve their results by completely different means.

The Examiner finishes the section with:

> <u>Regarding claim 2,</u> Haupenthal (383) in the combination teaches **the system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave** (Fig. 1, ac

voltage source. The ac voltage source is low distortion compare to the superimposed voltage).

Regarding claim 12, recite limitation similar to claim 1. Therefore, claim 12 is rejected with the same rationale and claim 1.

In the Examiner's statement that "The ac voltage source is low distortion compare to the superimposed voltage" Haupenthal's term "superimposed voltage" means the voltage produced by capacitive coupling between Haupenthal's sensor lines. From Column 5, lines 33 - 40:

> Only a direct current flows in the sensor circuit between the ionization electrodes 3 because of the rectifying effect of the flame or in the ultraviolet cell 4 because of the diode 4a, more specifically only when the flame is actually burning. However an unwanted alternating current also constantly flows between the terminals 1 and 2, because of the inevitable capacitance of the sensor lines, and that alternating current is superimposed on the direct current.

The superimposed voltage is a voltage that comes from Haupenthal's AC source (5) through capacitive coupling in the sensor lines. It will have the same percentage of presumed distortion that may be present in AC source (5). It cannot be lower or higher. Therefore the assertion that "The ac voltage source is low distortion compare to the superimposed voltage" is untrue.

Besides, Applicant's claim 2 is a dependent claim that is dependent on claim 1.

Applicant quotes MPEP 2143.03:

> **2143.03 All Claim Limitations Must Be Considered [R-08.2012]**
>
> "All words in a claim must be considered in judging the patentability of that claim against the prior art." *In re Wilson,* 424 F.2d 1382, 1385, 165 USPQ 494, 496 (CCPA 1970). If an independent claim is nonobvious under 35 U.S.C. 103, then any claim depending therefrom is nonobvious. *In re Fine,* 837 F.2d 1071, 5 USPQ2d 1596 (Fed. Cir. 1988).

Applicant has shown that the Examiner's rejection of claim 1 is in error and that claim 1 should be allowed. Therefore, claim 2 must be allowed. And since the Examiner's rejection of claim 1 is in error, so is the Examiner's rejection of claim 12.

**<u>C.</u>** The Examiner rejected Claims 3, 13 and 14 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).

> Claims 3, 13 and 14 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).
>
> <u>Regarding claim 3,</u> Haupenthal (486) in the combination teaches **the system of claim 1 whereby said harmonic signal detector comprises a** detectors to detect harmonic but fails to expressly teach a **phase locked loop tuned to the frequency of said harmonic signal.**
>
> However, in the same field of harmonic detection system, Ngo teaches a phase locked loop that is tuned to a harmonic frequency. See para [0005], "Based on an input reference signal, a digital frequency multiplier circuit utilizes a voltage controlled oscillator (VCO), which is tuned to a harmonic of the input frequency signal, along with a frequency divider and a phase-locked loop (PLL) to generate a desired output frequency.".
>
> Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (486)'s harmonic detector with Ngo's phase locked loop to detect a desired harmonic frequency that would accurately detect the presence of a flame.
>
> <u>Regarding claim 13,</u> recite limitation similar to claim 3. Therefore, claim 13 is rejected with the same rationale and claim 3.
>
> <u>Regarding claim 14,</u> the combination teaches **the method of claim 12** but fails to teach **where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.**
>
> However, in the same field of harmonic detection system, Ngo teaches an external clock signal and a control circuit to align the internal signal with external clock signal. See Abstract,
>
>> "The DCC generates an internal feedback signal. The phase detector detects a phase difference between the internal feedback signal and an external reference clock signal. Coupled between the phase detector and the DCC, the control circuit adjusts the DCC to align the internal feedback signal with the external reference clock signal after a phase difference between the internal feedback signal and the external reference clock signal has been detected.".
>
> Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)'s harmonic detector with a clock and a synchronous detector to synchronous various signals to produce an accurate result.

Applicant again quotes MPEP 2143.03:

> **2143.03 All Claim Limitations Must Be Considered [R-08.2012]**
>
> "All words in a claim must be considered in judging the patentability of that claim against the prior art." *In re Wilson,* 424 F.2d 1382, 1385, 165 USPQ 494, 496 (CCPA 1970). If an independent claim is nonobvious under 35 U.S.C. 103, then any claim depending therefrom is nonobvious. *In re Fine,* 837 F.2d 1071, 5 USPQ2d 1596 (Fed. Cir. 1988).

**1.** Applicant's claim 3 is a dependent claim that is dependent on claim 1. As such, claim 3 contains all of the limitations of claim 1. Applicant has shown that Haupenthal '383 and '486 are irrelevant to Applicant's invention so that claim 1 should be allowed. Thus claim 3 must also be allowed.

Applicant's claim 13 is a dependent claim that is dependent on claim 12. As such, claim 13 contains all of the limitations of claim 12. Applicant has shown that Haupenthal '383 and '486 are irrelevant to Applicant's invention so that claim 12 should be allowed. Thus claim 13 must also be allowed.

Applicant's claim 14 is a dependent claim that is dependent on claim 12. As such, claim 14 contains all of the limitations of claim 12. Applicant has shown that Haupenthal '383 and '486 are irrelevant to Applicant's invention so that claim 12 should be allowed. Thus claim 14 must also be allowed.

Furthermore, claim 14 provides that a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector. This is not a phase locked loop described by Ngo. It is a synchronous detector.

**2.** Ngo (Pub. No.: US 2008/0266000) is for a digitally controlled phase-locked loop. From paragraph 7:

> [0007] In accordance with a preferred embodiment of the present invention, a digital frequency multiplier circuit includes a digitally controlled oscillator (DCO), a phase detector and a control circuit. The DCO generates an internal feedback signal. The phase detector detects a phase difference between the internal feedback signal and an external reference clock signal. Coupled between the phase detector and the DCO, the control circuit adjusts the DCO to align the internal feedback signal with the external reference clock signal after a phase difference between the internal feedback signal and the external reference clock signal has been detected. The control circuit also locks a modulation frequency of the DCO and monitors the state of the digital frequency multiplier circuit in order to maintain the lock.

See Ngo Figure 1.

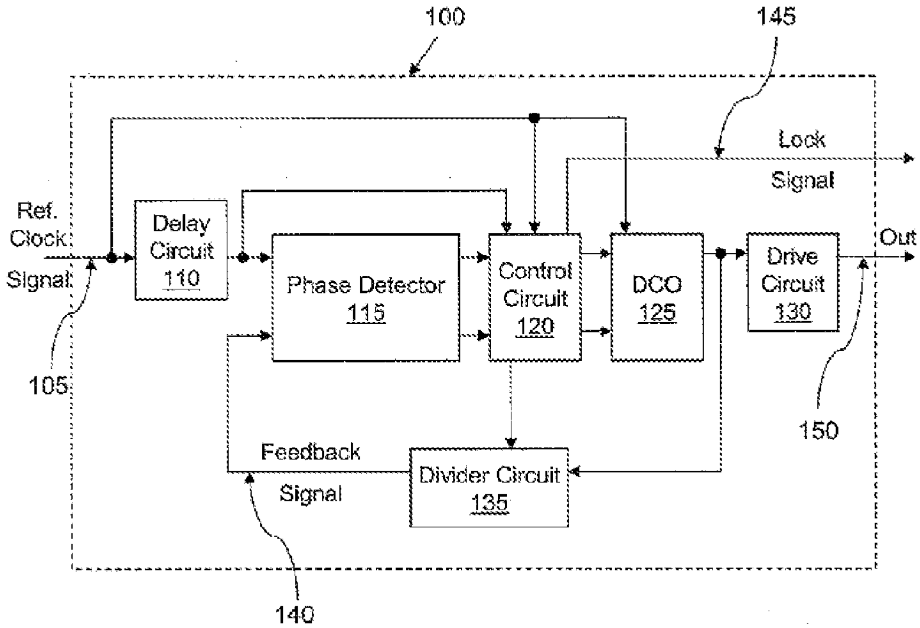



**FIG. 1**

__a.__ The divider (135) is in the feedback loop in order to act as a frequency multiplier. Thus, the output of Ngo's PLL is tuned to a multiple of the input reference.

__b.__ Instead of controlling the frequency of the oscillator with an analog VCO Ngo uses a digitally controlled oscillator (DCO 125).

__c.__ Ngo produces two outputs: a signal that is the reference clock multiplied by a digitally selected ratio and a lock signal that indicates that the output signal is being produced at a selected multiple of the input reference signal.

Applicant's use of a PLL is only to detect an input signal at a particular frequency and produce a lock signal when that input signal is detected, not to produce a multiple of the frequency of the input reference signal. As such Ngo's PLL would be a poor choice to use as Applicant's PLL.

__d.__ As noted, claims 3 and 13 are dependent claims. Applicant does not claim to have invented the phase locked loop. The principles of the phase locked loop were described in 1932, in a paper by Henri de Bellescize, in the French journal L'Onde Électrique. See *Ref. 7.*

A good explanation of the modern phase locked loop can be found in Technical Report No. 32-427 **Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques** by A.J.

Viterbi, published by the Jet Propulsion Laboratory, March 29, 1963 in the section **I. Introduction** (*Ref. 8*, PDF page 5).

Also as noted, claim 14 is a dependent claim that provides for the step of using a synchronous detector. Applicant does not claim to have invented the synchronous detector. Synchronous detectors have been used since the early 20th century.

For the above reasons the Examiner's rejection of dependent claims 3, 13, and 14 is not supportable, is contrary to MPEP 2143.03, and must be withdrawn.

**D.** Claims 4 and 5 were objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

The Examiner's rejection of claim 1 does not hold up to scrutiny of his references and by misquoting Applicant's base claim his rejection is improper. Therefore dependent claims 4 and 5 must be allowed under MPEP 2143.03 .

**E1.** The Examiner rejected Claim 18 as follows:

> Claim 18 is rejected under 35 U.S.C. 103 as being unpatentable over Sohma (Pat. No.: 5,547,369) in view of Su (Pub. No.: US 2014/0085503 Al).
>
> Regarding claim 18, Sohma teaches a **method for detecting the presence of a flame** (Fig. 1 and Col. 3 lines 13-33, determines the properties of a flame) **comprising the steps of:**
>
> **c. providing a signal detector to detect a mixing signal produced by said two signal sources** (Fig. **1, a** camera is used to detect the mixing of light signals); **and**
>
> **d. providing an indicator to indicate the results of said signal detector** (Col.3 lines 25-27,"a camera which photographs flames; display means for displaying a picture of the flames by using an output signal from the camera;").

Sohma fails to expressly teach **providing two signal sources to said flame** and **using flame rectification to cause said two signal sources to mix.**

However, in the same field of photo-shooting, Su teaches lights are mixed together from different lights sources, such as the lights sources are mixed with the flame and detected by the camera. See para [0005], "While taking photos, the ambient light while photo-shooting may be a mixture combining lights from different sources (such as natural light, fluorescent tubes, incandescent light bulb, etc.). Lights from different sources may have individual spectral characteristics, such that the ambient light mixed from them may have a different color temperature.".

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Sohma's flame detection system with various ambient lights sources to be mixed with the flame to produce a higher quality picture.

**<u>Applicant responds</u>**

Applicant will begin by showing what Sohma '369 and Su '503 actually teach and what they do not teach.

**<u>E2.</u>** The title of Sohma '369 is **Camera, Spectrum Analysis, and Combustion Evaluation Apparatus Employing Them**. This teaches a camera system for performing a spectral analysis of a flame and using that information for adjusting the feed rate and mix of air and fuel in order to produce maximum combustion efficiency. See Column 3, lines 20 - 33:

> In the eleventh aspect of the present invention, there is provided a combustion system comprising a burner which burns a mixture consisting of fuel and air; feed means for feeding the fuel and the air to the burner; adjustment means for adjusting a feed rate of at least one of the fuel and the air which are to be fed to the burner; a camera which photographs flames; display means for displaying a picture of the flames by using an output signal from the camera; arithmetic means for obtaining a physical quantity for evaluating a combustion property of the flames by using the output signal from the camera; and control means for controlling the adjustment means in accordance with the physical quantity obtained by the arithmetic means.

It does this using a camera containing a plurality of photosensors divided into groups where each group of photosensors is sensitive to a specific wavelength and where the specific wavelengths do not overlap. See Column 2 lines 19 - 35:

> In the fourth aspect of the present invention, there is provided a camera comprising a plurality of photosensors which are disposed on an imaging face thereof, and which separately deliver respective photodetection signals; the photosensors including at least one photosensor selected from the group of photosensors consisting of a first photosensor whose detection wavelength range includes an emission wavelength of a CH radical, but does not include emission wavelengths of a $C_2$ radical and an OH radical; a second photosensor whose detection wavelength range includes the emission wavelength of the $C_2$ radical, but does not include the emission wavelengths of the CH radical and the OH radical; and a third photosensor whose detection wavelength range includes the emission wavelength of the OH radical, but does not include the emission wavelengths of the CH radical and the $C_2$ radical.

The CH, $C_2$, and OH radicals are part of the intermediate products of combustion which is discussed by the current Applicant in his specification paragraphs 014 - 015, Figure 14, and IDS Cite 12.

Since the wavelengths used by the groups of sensors are not at RBG wavelengths, the RGB signals are synthesized in order to provide a standard picture of the flame. See Column 2, lines 58 - 62:

> In the seventh aspect of the present invention, there is provided a spectrum analysis system comprising the camera defined in the fourth aspect of the invention; and synthesis means for synthesizing R (red), G (green) and B (blue) signals using an output signal from the camera.

Sohma does not teach:

**a.** providing two signal sources to said flame using a flame rod;

Sohma does not provide two signal sources. Sohma uses a camera to look at the flame. Sohma does not use a flame rod. (Applicant amended the claim to make it clearer to the Examiner. The use of a flame rod was already inherent by providing two signals to the flame.)

**b.** using flame rectification to cause said two signal sources to mix;

Sohma does not use flame rectification. He can't, he doesn't have a flame rod. And he does not provide two signals to the flame rod he doesn't have.

**c.** providing a signal detector to detect a mixing signal produced by said two signal sources; and

Sohma does not detect a mixing signal produced by two signal sources because he does not produce two signal sources. And, very importantly, the Examiner is not using the term "mixing" as Applicant defined it in his Paragraph 002:

> The term "mixer" means a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. The terms "mixing" and "to mix" mean using a mixer. When two signals are mixed in this manner it is also called heterodyning.

And in Paragraph 042:

> In this experiment the flame rectifier is used as a mixer. A mixer is a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. See IDS Cite 30 (Horowitz).

The Examiner is not even using the term "mix" the way Sohma uses it:

Sohma Claim 16:

> 16. A combustion system, comprising:
> a burner which burns a mixture consisting of fuel and air;
> ...

Sohma Claim 35:

> 35. A combustion system comprising:
> a burner for burning a mixture of fuel and air to produce flames;
> ...

Sohma Column 3, lines 30 - 33:

> In the eleventh aspect of the present invention, there is provided a combustion system comprising a burner which burns a mixture consisting of fuel and air; feed means for feeding the fuel and the air to the burner; ...

It is common that, in different fields of science and engineering, the same term is used but has different meanings. The term "mix" is one of them. It can have the meaning that Applicant defined, which is not his own personal definition but is used in Communications Engineering. See IDS Cite 30 (Horowitz). In Audio Engineering the term "mix" means to add signals together, such as in done in an audio mixer. In Combustion Engineering it means to add two substances together such as air and fuel, which is how Sohma uses it.

Applicant's invention encompasses several different fields of science and engineering such as:

1. Physics;
2. Plasma Physics;
3. Chemistry;
4. Chemical Engineering;
5. Combustion Engineering;
6. Electrical Engineering;
7. Communications Engineering;

There may be more.

In a few cases it was necessary for Applicant to use the term "mix" in a way that is commonly used in a particular field other than Communications Engineering. In those few cases it is clear from the context how the word is being used, such as Paragraph 013:

> We should discuss temperature. The temperature of a gas is a measure of the average kinetic energy of the gas molecules as they collide with each other and with the walls of the container. If the container walls are rigid the molecules will bounce off. With a flame the walls are the atmosphere, and the boundary between the flame and the atmosphere is a function of atmospheric pressure. The collisions between the molecules in the flame and the molecules in the atmosphere produce diffusion. It is this diffusion that makes diffusion flames possible. An example of a diffusion flame is the flame produced by a wax candle. The other type of flame is called a premixed flame and is where the oxidizer (the oxygen in the atmosphere) is **mixed** with the fuel before combustion. Premixed flames produce a more stoichiometric mixture than diffusion flames, so they burn more completely (and hotter). For this reason most furnaces use premixed flames.

{Emphasis added}

And, finally:

**d.** providing an indicator to indicate the results of said signal detector.

Sohma's signal detector is an imaging sensor (Column 1, lines 44 - 67). Applicant's signal detector is a circuit that detects the sum and/or difference signals produced by flame rectification. See, as an example, Applicant's Paragraph 066.

**E3.** Su '503 (**Mobile Communication Apparatus and Flashlight Controlling Method**) is also about a camera. Su teaches the use of several LEDs of different spectral bands (wavelengths or colors) where the proportion of light produced by the different color LEDs is adjusted to compensate for different color temperatures in a scene, generally caused by the conditions of ambient light. See Su Paragraph 053:

> [0053] Based on aforesaid embodiments, the invention provides a mobile communication apparatus and a flashlight controlling method thereof. A flashlight module of the mobile communication apparatus includes several light-emitting units corresponding to different spectrum bands respectively. The mobile communication apparatus senses the ambient color temperature (e.g., the ambient color temperature can be obtained by capturing a preview image, generating a white-balance information from the preview image, and determining the ambient color temperature from the white-balance information) at first, and then drives the plural light-emitting units with different intensity proportions according to the ambient color temperature, such that a mixed light formed by the light-emitting units may have a color temperature approaching to the ambient color temperature. Therefore, the objects under the flashlight projection may have the same color temperature as the objects of background, and the flashlight module may fulfill the brightness-enhancement function.

Su does not use flame rectification. Su does not use a flame rod. Su mixes his light from the different LEDs using the photometric meaning which means to add them. If Su were to point his camera at a flame his colors would not heterodyne, creating new colors at the sum and difference frequencies of his lights.

**E4.** Applicant's detailed response to Examiner's rejection of Claim 18:

**Examiner:**

> Claim 18 is rejected under 35 U.S.C. 103 as being unpatentable over Sohma (Pat. No.: 5,547,369) in view of Su (Pub. No.: US 2014/0085503 Al).
>
> Regarding claim 18, Sohma teaches a **method for detecting the presence of a flame** (Fig. 1 and Col. 3 lines 13-33, determines the properties of a flame) **comprising the steps of:**
>
> **c. providing a signal detector to detect a mixing signal produced by said two signal sources** (Fig. 1, a camera is used to detect the mixing of light signals); **and**

**Applicant:**

As shown above Sohma does not produce two signal sources.

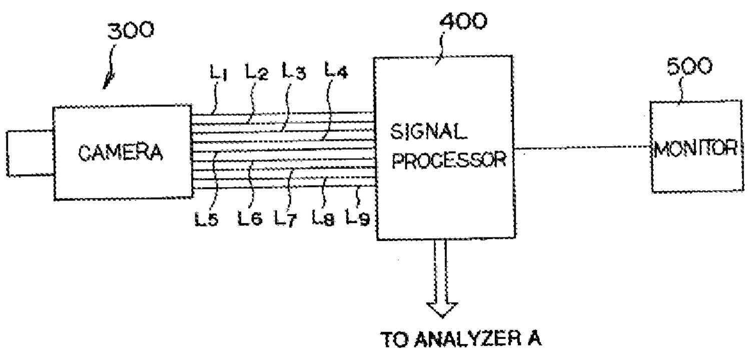
Examiner's characterization of Sohma Fig. 1 is misleading.

Sohma Column 4, lines 12 - 14:

> FIG. 1 is a block diagram showing the general construction of a spectrum analysis system according to the present invention;

Sohma Fig. 1 is reproduced below:

FIG. 1




It shows a Camera 300 sending signals to Signal Processor 400 which sends signals to Monitor 500 and to Analyzer A.

Sohma explains his Fig. 1 in Column 5, line 8 - Column 6, line 2:

> A spectrum analysis system embodying the present invention will now be described. The spectrum analysis system in this embodiment has the feature that a single camera can be used for observing a light component(s) of a desired wavelength(s) and simultaneously for obtaining an ordinary color picture.
>
> As illustrated in FIG. 1, the spectrum analysis system includes a camera 300, a signal processor 400 and a monitor 500.
>
> A CCD (charge-coupled device) photosensor section of the camera 300 is shown on an enlarged scale in FIG. 2. The camera 300 has one photosensitive unit P(ijj) constituted by nine photosensors S.sub.1 .about.S.sub.9. As illustrated in FIG. 3(b), the detection wavelength ranges of the photosensors S.sub.1 .about.S.sub.9 substantially do not overlap one another. On the other hand, in a case where the detection wavelength ranges of the nine photosensors S.sub.1 .about.S.sub.9 are collectively viewed, they cover substantially the whole visible radiation region. For comparison's sake, the outlines of the relative detection sensitivity curves of a conventional camera are illustrated in FIG. 3(c). As seen by comparing the graphs of FIGS. 3(b) and 3(c), the detection wavelength ranges of the photosensors S.sub.1 .about.S.sub.3 lie within the detection wavelength range of a photosensor for blue light (B) in the conventional camera. The detection wavelength ranges of the photosensors S.sub.4 .about.S.sub.6 lie within the detection wavelength range of a photosensor for green light (G) in the conventional camera. The detection wavelength ranges of the photosensors S.sub.7 .about.S.sub.9 lie within the detection wavelength range of a photosensor for red light (R) in the conventional camera. The adjustments of such detection wavelength ranges can be made by altering the light transmission characteristics of a filter/filters which is/are disposed in the photosensor section. The light

transmission characteristics can be altered by, for example, forming stacked filters having different characteristics or using unequal film thicknesses or different compositions for the individual filters.

Referring back to FIG. 1, the camera 300 is furnished with output signal lines L.sub.1 .about.L.sub.9 which are provided in correspondence with the photosensors S.sub.1 .about.S.sub.9. Thus, the detection signals of the respective photosensors S.sub.1 .about.S.sub.9 can be delivered to the signal processor 400 independently of one another for every photosensitive unit. Needless to say, however, even when the nine output signal lines themselves are not independently led to the signal processor 400, the signal components of the photosensors may be output in a separable state. Since the arrangements of circuits, etc., for realizing such independent outputs are not, per se, especially restricted, they shall be omitted from the description here.

The signal processor 400 has functions such as synthesizing the output signals from the respective photosensors S.sub.1 .about.S.sub.9 and arithmetically processing them as required. Also, this processor 400 has the function of supplying the monitor 500 or any other analyzer A with the output signals of the camera 300 directly or after the synthesis or arithmetic processing thereof. By the way, "separation means" or similar terms and "synthesis means" mentioned in the appended claims are implemented by the signal processor 400.

The monitor 500 is an ordinary color monitor (or a monochromatic monitor).

A camera inherently responds to the mixing (adding) of light signals because wherever light signals coincide they add. Applicant has explained that his use of the term “mix” does not mean “add”. See above in numerous places. Sohma’s signals, produced by a flame, are not Applicant’s two signal sources.

**Examiner:**

**d. providing an indicator to indicate the results of said signal detector**

(Col.3 lines 25-27,”a camera which photographs flames; display means for displaying a picture of the flames by using an output signal from the camera;”).

**Applicant:**

Applicant’s signal detector is not a camera. It does not display a picture of the flame. Applicant’s signal detector detects the sum and/or different signals produced when flame rectification causes Applicant’s two signal sources to mix using Applicant’s definition of the term “mix” which has already been explained several times.

Besides, the Examiner has conceded that:

> Sohma fails to expressly teach **providing two signal sources to said flame** and **using flame rectification to cause said two signal sources to mix.**

**Examiner:**

> However, in the same field of photo-shooting, Su teaches lights are mixed together from different lights sources, such as the lights sources are mixed with the flame and detected by the camera. See para [0005], "While taking photos, the ambient light while photo-shooting may be a mixture combining lights from different sources (such as natural light, fluorescent tubes, incandescent light bulb, etc.). Lights from different sources may have individual spectral characteristics, such that the ambient light mixed from them may have a different color temperature.".

Applicant does not detect light from different light sources. Not ambient light, not any kind of light. Applicant does not add light from different light sources which is Su's meaning of the term "mix". Su does not use flame rectification. Su does not use a flame rod. There is no support for the Examiner's statement, " Su teaches lights are mixed together from different lights sources, **such as the lights sources are mixed with the flame and detected by the camera**" in Su Paragraph 0005 or, indeed, anywhere in Su. Su never once uses the word "flame" in his application. The Examiner has made up this statement. Besides, if Su were to point his camera at a flame his colors would not heterodyne, creating new colors at the sum and difference frequencies of his lights.

**Examiner:**

> Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Sohma's flame detection system with various ambient lights sources to be mixed with the flame to produce a higher quality picture.

Neither Sohma nor Su teach:

a. providing two signal sources to said flame using a flame rod;

b. using flame rectification to cause said two signal sources to mix;

c. providing a signal detector to detect a mixing signal produced by said two signal sources; and

d. providing an indicator to indicate the results of said signal detector.

Neither Sohma nor Su teach providing two signal sources to a flame.

Neither Sohma nor Su teach the use of flame rectification.

Neither Sohma nor Su teach the use of a signal detector to detect a mixing signal produced by the two signal sources where the two signal sources are mixed using Applicant's definition of the term "mix". [Applicant amended the claim to make it clearer to the Examiner. The use of a flame rod was already inherent by providing two signals to the flame.]

Since neither Sohma nor Su teach Applicant's signal detector they cannot provide an indicator for it.

Sohma's camera uses an image sensor containing a plurality of photosensors divided into groups where each group of photosensors is sensitive to a specific wavelength and where the specific wavelengths do not overlap. The specific wavelengths are for detecting CH, $C_2$, and OH radicals which are part of the intermediate products of combustion. This allows him to perform a spectral analysis of the flame and use that information for adjusting the feed rate and mix of air and fuel in order to produce maximum combustion efficiency. Adding Su's RBG lights would either have no effect on the picture (because the RBG wavelengths are different from the ones that Sohma's image sensor is designed to detect) or would wash it out. Adding Su's lights to Sohma would not produce a higher quality picture. Besides, Applicant's invention is not a camera.

**F. Conclusion**

For the above reasons Applicant requests an allowance of all of his claims as amended.

**G. Addendum**

The Examiner has already committed serious misconduct by materially misquoting Claim 1 in order to make his rejection seem reasonable under BRI, even after it was politely and respectfully brought to his attention in Applicant's Response filed 02/04/2017.

And in rejecting Claim 18 the Examiner has shown either complete ignorance of Applicant's invention or appalling bad faith.

Applicant respectfully requests that the Examiner act responsibly from this point forward.

**References**

Ref. 1 - **Phototubes** by Hamamatsu; from http://www.hamamatsu.com/resources/pdf/etd/Phototubes_TPT1001E.pdf

Ref. 2 - **Phototube**; Wikipedia; from https://en.wikipedia.org/wiki/Phototube

Ref. 3 - U.S. Patent 4,039,844 **Flame monitoring system** issued August 2, 1977 to MacDonald.

Ref. 4 - U.S. Patent 5,073,769 **Flame detector using a discrete fourier transform to process amplitude samples from a flame signal** issued December 17, 1991 to Kompelien

Ref. 5 - ANSI/IEC Standard symbol for Earth Ground

Ref. 6 - **Photodiode** from Wikipedia; from https://en.wikipedia.org/wiki/Photodiode

Ref. 7 - Phase Locked Loop; Wikipedia; History; from https://en.wikipedia.org/wiki/Phase-locked_loop#History

Ref. 8 - Technical Report No. 32-427 **Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques** by A.J. Viterbi, published by the Jet Propulsion Laboratory, March 29, 1963 in the section **I. Introduction** (*Ref. 11*, PDF page 5). from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19630005005.pdf

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# References

References

# Reference 1

Reference 1

# Phototubes

HAMAMATSU
PHOTON IS OUR BUSINESS

# ■FEATURES AND APPLICATIONS

## FEATURES

| | |
|---|---|
| High sensitivity and high stability | High sensitivity and high stability make phototubes very useful in chemical and medical analytical instruments which require high reliability. |
| Wide dynamic range | Phototubes feature a wide dynamic range from several picoamperes to several microamperes, providing signal output with excellent linearity. |
| Superior temperature stability | Phototubes show virtually no fluctuation with changes in the ambient temperature. |
| Large photosensitive area | Compared to semiconductor sensors, phototubes offer larger photosensitive area. |
| Low voltage operation | Phototubes are designed to operate at a low voltage. |

## SPECTRAL RESPONSE RANGE AND APPLICATIONS

| Spectral Range | Photocathode | Window Material | Spectral Response | | Typical Applications | Applicable Phototube Type No. |
|---|---|---|---|---|---|---|
| Spectral response in vacuum UV region only | Cs-I | $MgF_2$ | 115 nm to 200 nm | ① | Vacuum UV spectrophotometer | R1187 |
| | | Quartz | 160 nm to 200 nm | ② | | R5764 |
| Vacuum UV region only | Diamond | $MgF_2$ | 115 nm to 220 nm | ③ | 172 nm monitor for excimer lamp | R6800U-26 |
| | | Quartz | 160 nm to 220 nm | ④ | 185 nm monitor for sterilizing mercury lamp | R6800U-16 |
| Solar blind spectral response | Au (single metal) | Quartz | 160 nm to 240 nm | ⑤ | 185 nm monitor for sterilizing mercury lamp | R4044 |
| | Cs-Te | Quartz | 160 nm to 350 nm | ⑥ | Monitor for 185 nm, 254 nm mercury line spectrum | R765, R6800U-11 |
| | | UV glass | 185 nm to 350 nm | ⑦ | Ozone monitor | R1107, R1228, R6800U-01 |
| Wide spectral response from UV to infrared | Sb-Cs | UV glass | 185 nm to 650 nm | ⑧ | Spectrophotometer | R840, R727 |
| | | Borosilicate | 300 nm to 650 nm | ⑨ | Blood analyzer | R414 |

# ■GLOSSARY OF TERMS

**●Spectral response characteristic:**
When light (photons) enters the photocathode, it is converted into electrons emitting from the photocathode at a certain ratio. This ratio depends on the wavelength of incident light. The relationship between the ratio and the wavelength is called spectral response characteristic.

**●Peak wavelength:**
The wavelength gives the maximum sensitivity to the photocathode. In this catalog, the peak wavelength for radiant sensitivity (A/W) is listed.

**●Absolute maximum ratings:**
The limiting values of the operating and environmental conditions applied to a phototube. Any conditions shall not exceed these ratings even instantaneously.

**●Anode supply voltage:**
The voltage applied across the anode and the cathode. Normally, the cathode is used at ground potential, so the anode supply voltage equals the potential difference between the anode and ground.

**●Peak cathode current:**
The peak current that can be allowed from the cathode when it is of pulse waveform.

**●Average cathode current:**
The average current that can be allowed from the cathode. Normally, it is the average for 30 seconds.

**●Average cathode current density:**
The average cathode current per unit surface area on the photocathode.

**●Luminous sensitivity:**
The ratio of photocurrent in amperes (A) flowing in the photocathode to the incident luminous flux in lumens (lm).

$$\text{Luminous sensitivity (A/lm)} = \frac{\text{Current (A)}}{\text{Luminous flux (lm)}}$$

**●Radiant sensitivity:**
The ratio of photocurrent in amperes (A) flowing in the photocathode to the intensity of the incident light in watts (W).

$$\text{Radiant sensitivity (A/W)} = \frac{\text{Current (A)}}{\text{Light intensity (W)}}$$

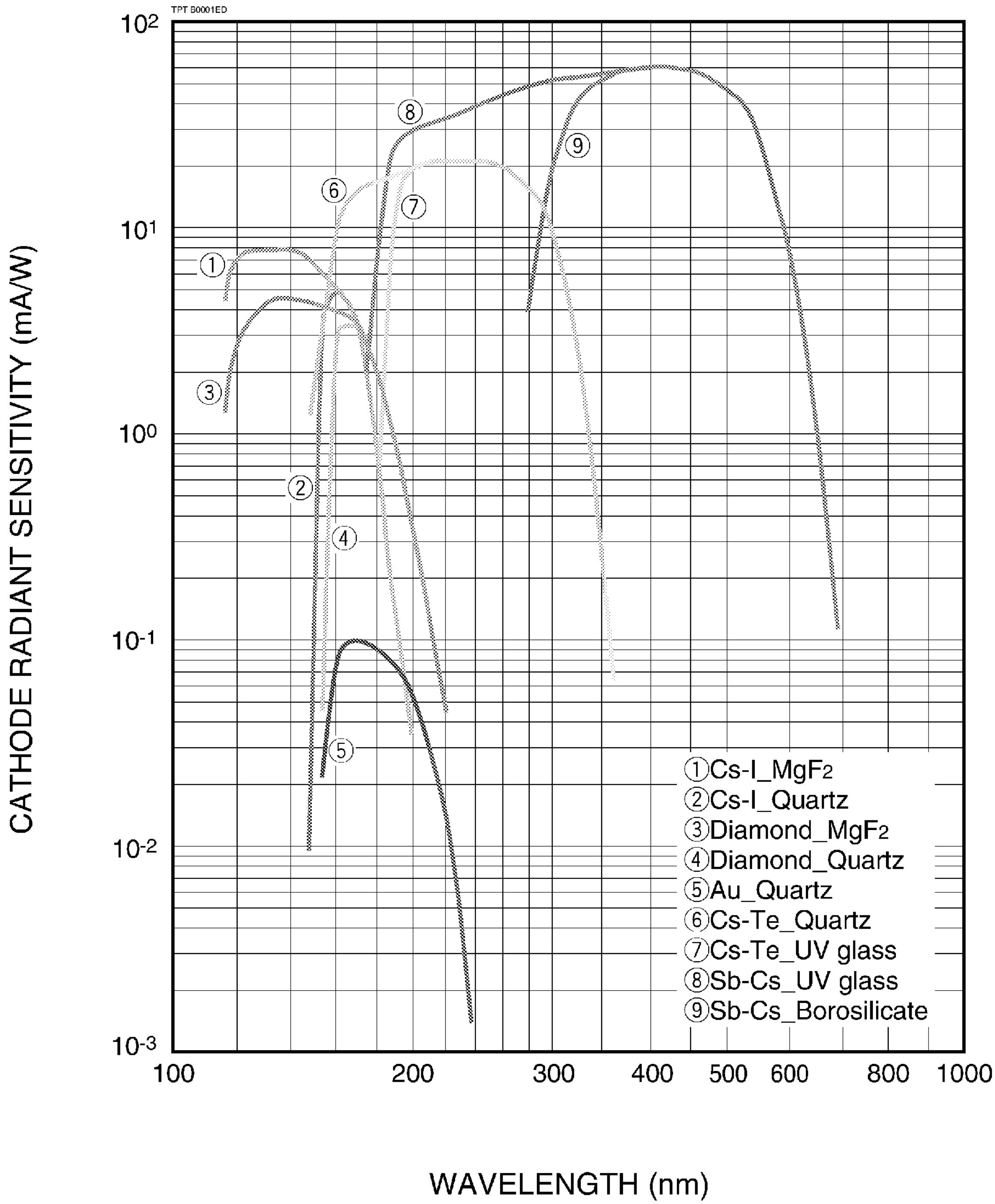
**●Dark Current:**
The current flowing between the anode and the cathode when light is removed.

**●Interelectrode capacitance:**
The electrostatic capacitance between the anode and the cathode.

**●Recommended operating voltage:**
The lifetime of a phototube tends to become shortened as the supply voltage increases. The supply voltage should be made as low as possible as compared to the maximum ratings, in order to lengthen useful life. However, if the supply voltage is too low, the voltagecurrent characteristics fall outside the saturation region, and undersirable phenomena such as hysteresis (Note 1) may occur. Considering these effects, the recommended operating voltage for each type of phototube is listed in this catalog.

(Note 1) Hysteresis: The temporary instability in output signal when light is applied to a phototube, showing "overshoot" or "undershoot" without being proportional to light input.

■SPECTRAL RESPONSE CHARACTERISTICS



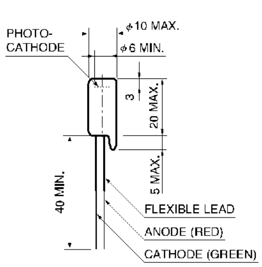
## ■CHARACTERISTICS

| Type No. | Ⓐ Spectral Response (nm) | Peak Wave-length (nm) | Outline Diagram No. | Tube Diameter (mm) | Photocathode Area Min. (mm) | Input Window Material | Absolute Maximum Ratings: Anode Supply Voltage (V) | Peak Cathode Current (µA) | Ⓑ Average Cathode Current Density (µA/cm²) | Average Cathode Current (µA) | Ⓒ Ambient Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **●GLASS BULB TYPE** | | | | | | | | | | | |
| **For Vacuum UV (Cs-I Photocathode)** | | | | | | | | | | | |
| R1187 | 115 to 200 | 130 | ❸ | φ15 | φ8 | $MgF_2$ | 100 | 1 | 0.5 | 0.1 | -80 to +50 |
| R5764 | 160 to 200 | 161 | ❸ | φ15 | φ8 | Quartz | 100 | 1 | 0.5 | 0.1 | -80 to +50 |
| **For UV / High Power (Au Single Metal Photocathode)** | | | | | | | | | | | |
| R4044 | 160 to 240 | 185 | ❸ | φ15 | φ8 | Quartz | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| **For UV / General Purpose (Cs-Te Photocathode)** | | | | | | | | | | | |
| R1107 | 185 to 350 | 240 | ❶ | φ10 | φ6 | UV glass | 100 | 0.5 | 5 | 0.15 | -80 to +50 |
| R765 | 160 to 350 | 240 | ❷ | φ15 | φ8 | Quartz | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| R1228 | 185 to 350 | 240 | ❷ | φ15 | φ8 | UV glass | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| **For UV to Visible (Sb-Cs Photocathode)** | | | | | | | | | | | |
| R414 | 300 to 650 | 400 | ❶ | φ10 | φ6 | Borosilicate glass | 100 | 1 | 5 | 0.3 | -80 to +50 |
| R840 | 185 to 650 | 340 | ❷ | φ15 | φ8 | UV glass | 100 | 2 | 5 | 0.5 | -80 to +50 |
| R727 | 185 to 650 | 340 | ❹ | φ20 | φ15 | UV glass | 100 | 6 | 5 | 2 | -80 to +50 |
| **●METAL PACKAGE TYPE** | | | | | | | | | | | |
| **For Vacuum UV (Diamond Photocathode)** | | | | | | | | | | | |
| R6800U-26 | 115 to 220 | 135 | ❺ | φ16 | φ6 | $MgF_2$ | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| R6800U-16 | 160 to 220 | 165 | ❺ | φ16 | φ6 | Quartz | 100 | 10 | 50 | 4 | -80 to +50 |
| **For UV / General Purpose (Cs-Te Photocathode)** | | | | | | | | | | | |
| R6800U-11 | 160 to 350 | 240 | ❻ | φ16 | φ8 | Quartz | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| R6800U-01 | 185 to 350 | 240 | ❼ | φ16 | φ8 | UV glass | 100 | 1.2 | 5 | 0.4 | -80 to +50 |

**NOTE:** ⒶSee spectral response characteristics on page 2. ⒷOutput current averaged over 1 second time interval. The whole photocathode is uniformly illuminated. ⒸWhen a tube is operated below -35 °C see page 6, "Caution".

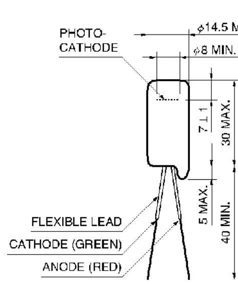
## ■DIMENSIONAL OUTLINES (Unit: mm)

**❶ R414, R1107**




TPT A0002EA

**❷ R765, R1228, R840**

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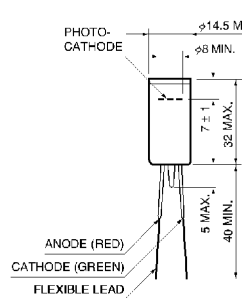
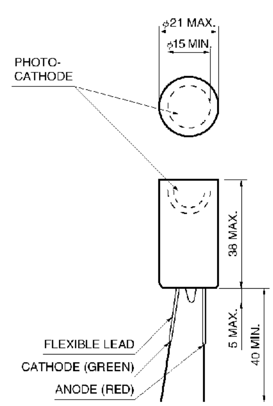
**❸ R5764, R4044, R1187**




TPT A0014EC

**❹ R727**

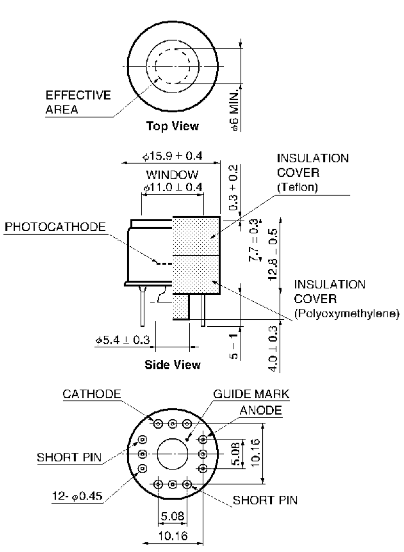



TPT A0006EB

| Characteristics at 25 °C | | | | | | | | | | | Type No. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Luminous Sensitivity ❶ | | Radiant Sensitivity | | | | | | Dark Current | Recommended Operating Voltage | Interelectrode Capacitance | |
| | | 122 nm | | 254 nm | | Pt Peak ❺ | | | | | |
| Typ. (µA/lm) | Min. (µA/lm) | Typ. (mA/W) | Min. (mA/W) | Typ. (mA/W) | Min. (mA/W) | Typ. (mA/W) | Min. (mA/W) | Max. (pA) | (V) | (pF) | |
| — | | 8 | 2 | — | | — | | 2 | 15 | 2.4 | R1187 |
| — | | — | | — | | 5 | 1 | 2 | 15 | 2.4 | R5764 |
| — | | — | | — | | 0.1 | 0.02 | 1 | 15 | 2.4 | R4044 |
| — | | — | | 15 | 10 | — | | 2 | 15 | 2.0 | R1107 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 2.4 | R765 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 2.4 | R1228 |
| 80 | 40 | — | | — | | — | | 5 | 15 | 2.0 | R414 |
| 80 | 40 | — | | — | | — | | 2 | 15 | 2.4 | R840 |
| 110 | 40 | — | | — | | — | | 2 | 15 | 2.0 | R727 |
| — | | 3 | 1 | — | | — | | 1 | 15 | 3 | R6800U-26 |
| — | | — | | — | | 3 | 1 | 1 | 15 | 3 | R6800U-16 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 3 | R6800U-11 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 3 | R6800U-01 |

❶The photocurrent from the photocathode per incident light flux ($10^{-5}$ to $10^{-2}$ lumens) from a tungsten filament lamp operated at a distribution temperature of 2856 K. ❺See peak wavelength.

### ❺ R6800U-16, -26

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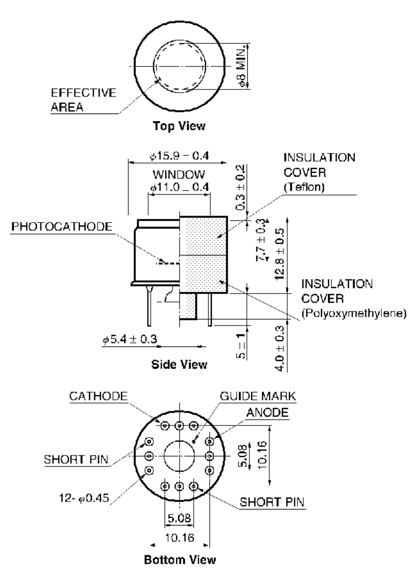
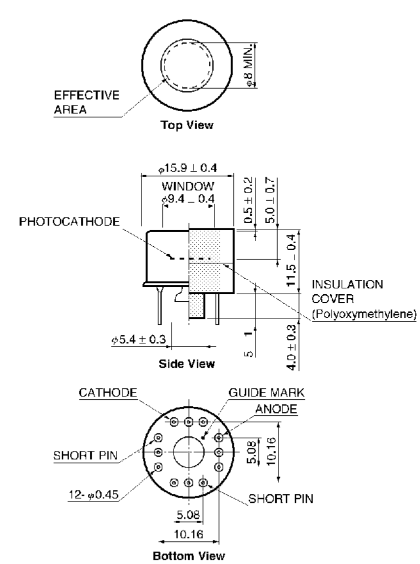
### ❻ R6800U-11




TPT A0045EB

### ❼ R6800U-01




TPT A0022EC



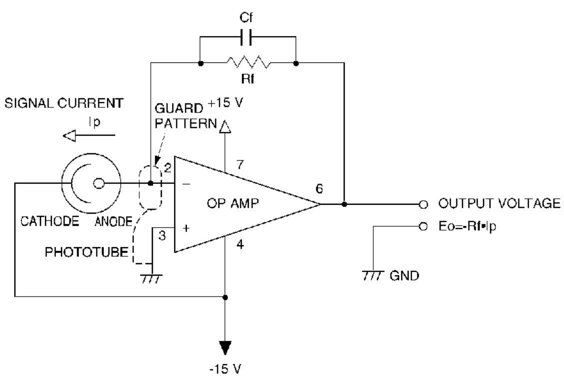
NOTE: Don't use pins excepting ANODE and CATHODE pins.

# ■EXAMPLE OF OPERATING CIRCUITS

## OPERATING CIRCUITS FOR PHOTOTUBES

Figure 1 shows an operating circuit example using the phototube bias voltage also for the power to an operational amplifier. The feedback resistance Rf should be chosen so that the output voltage becomes 0.1 V to 1 V. Cf must be placed for stable operation and should be between 10 pF and 100 pF. It is recommended to use a low-bias, low-offset-current FET input operational amplifier. For the input terminal (pin 2), a guard pattern should be provided on the printed circuit board or a stand-off terminal made of Teflon should be used.

Figure 1: When Pulse / Minus Powers Are Available

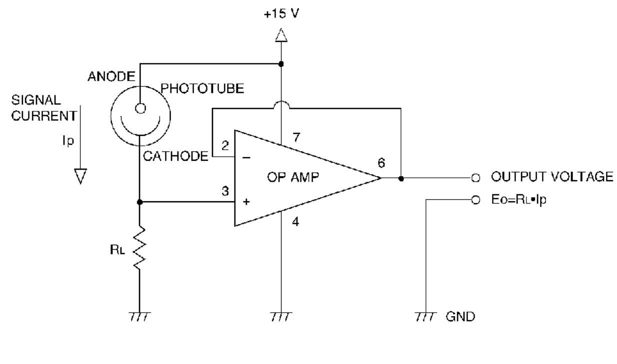



(Inverting current-voltage conversion circuit)

TPT C0001EC

Figure 2 shows an operating circuit in which a low-impedance voltage is output from an operation amplifier after the signal current has been converted into a voltage through the road resistance RL. The operational amplifier should be a low-bias, low-offset-current type which can be operated on a single power.

Figure 2: Operating Circuit Operating on Signal Power




(Impedance conversion circuit)

TPT C0002EC

**NOTE:** The operational amplifiers that can be used in these circuits differ in such factors as operating temperature range, bias current, phase compensation, and offset adjustment method, depending on the type used. Please refer to the catalog or data sheet available from the manufacturer.
Sample circuits listed in this catalog introduce typical applications and do not cover any guarantee of the circuit design. No patent rights are granted to any of the circuits described herein.

## ■ ⚠ CAUTIONS

● **Maximum ratings**
Always operate the phototube within the maximum rating listed in this catalog.

● **The light input surface area should be as large as possible**
The output current available from a phototube is determined by the maximum average cathode current and maximum average cathode current density. If the light input surface area is small, even if the output current is below the maximum average cathode current, the maximum average cathode current density may be exceeded. Therefore, the light input surface area should be as large as possible to decrease the cathode current per unit surface area. This is important also, from the standpoint of photocathode uniformity (i.e., variation in sensitivity with respect to incident light position).

● **Handle tubes with extreme care**
Phototubes have evacuated glass envelopes. Allowing the glass to be scratched or to be subjected to shock can cause cracks. Extreme care should be taken in handling, especially for tubes with graded sealing of synthetic silica.

● **Avoid mechanical vibration**
Mechanical vibration can cause microphonic noise (sensitivity fluctuation caused by vibration of the electrode.) and variation in sensitivity caused by displacement of the incident light position.

● **keep faceplate and base clean**
Do not touch the faceplate and base with bare hands. Dirt and fingerprints on the faceplate cause loss of transmittance and dirt on the base may cause ohmic leakage. Should they become soiled, wipe it clean using alcohol.

● **Avoid direct sunlight and other high-intensity light**
Avoid subjecting the phototube to direct sunlight or other high-intensity light, as this can adversely affect the photocathode, causing not only loss of sensitivity but instability as well.

● **Handling of tubes with a glass base**
A glass base (also called button stem) is weak, so care should be taken in handling this type of tube.

● **Cooling of tubes**
When cooling a phototube, the photocathode section is usually cooled. However, if you suppose that the base is also cooled down to -35 °C or below, please consult our sales office in advance.

● **Helium permeation through silica bulb**
Helium will permeate through the silica bulb, leading to an increase in noise. Avoid operating or storing tubes in an environment where helium is present.

Data and specifications listed in this catalog are subject to change due to product improvement and other factors. Before specifying any of the types in your production equipment, please consult our sales office.

## ■WARRANTY

In general, Hamamatsu products listed in this catalog are warranted for a period of one year from time of delivery. This warranty is limited to replacement for the defective product. Note, however, that this warranty will not apply to failures caused by natural calamity or misuse.

## ■CE MARKING

This catalog contains products which are subject to CE Marking of European Union Directives. For further details, please consult Hamamatsu sales offices.

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TPT 1001E10
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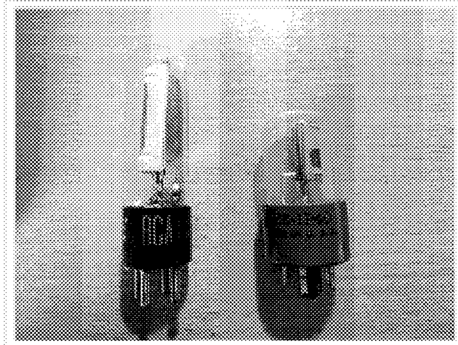
# Reference 2

Reference 2

# Phototube

From Wikipedia, the free encyclopedia

A **phototube** or photoelectric cell is a type of gas-filled or vacuum tube that is sensitive to light. Such a tube is more correctly called a 'photoemissive cell' to distinguish it from photovoltaic or photoconductive cells. Phototubes were previously more widely used but are now replaced in many applications by solid state photodetectors. The photomultiplier tube is one of the most sensitive light detectors, and is still widely used in physics research.


Two different types of phototubes

## Operating principles

Phototubes operate according to the photoelectric effect: Incoming photons strike a photocathode, knocking electrons out of its surface, which are attracted to an anode. Thus current is dependent on the frequency and intensity of incoming photons. Unlike photomultiplier tubes, no amplification takes place, so the current through the device is typically of the order of a few microamperes.[1]

The light wavelength range over which the device is sensitive depends on the material used for the photoemissive cathode. A caesium-antimony cathode gives a device that is very sensitive in the violet to ultra-violet region with sensitivity falling off to blindness to red light. Caesium on oxidised silver gives a cathode that is most sensitive to infra-red to red light, falling off towards blue, where the sensitivity is low but not zero.[2]

Vacuum devices have a near constant anode current for a given level of illumination relative to anode voltage. Gas filled devices are more sensitive but the frequency response to modulated illumination falls off at lower frequencies compared to the vacuum devices. The frequency response of vacuum devices is generally limited by the transit time of the electrons from cathode to anode.

## Applications

One major application of the phototube was the reading of optical sound tracks for projected films. Phototubes were used in a variety of light-sensing applications until they were superseded by photoresistors and photodiodes.

## References

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# Reference 3

Reference 3

# United States Patent [19]

**MacDonald**

[11] **4,039,844**

[45] **Aug. 2, 1977**


[54] **FLAME MONITORING SYSTEM**


[75] Inventor: **Malcolm F. MacDonald,** Chelmsford, Mass.

[73] Assignee: **Electronics Corporation of America,** Cambridge, Mass.



[21] Appl. No.: **560,569**

[22] Filed: **Mar. 20, 1975**

[51] **Int. Cl.**[2] .......... **G01N 21/58**

[52] **U.S. Cl.** .......... **250/554;** 250/214 AG; 250/214 RC; 340/228.2

[58] **Field of Search** ........ 250/206, 554, 214, 214 AG, 250/214 RC; 340/228.1, 228.2; 23/254 EF


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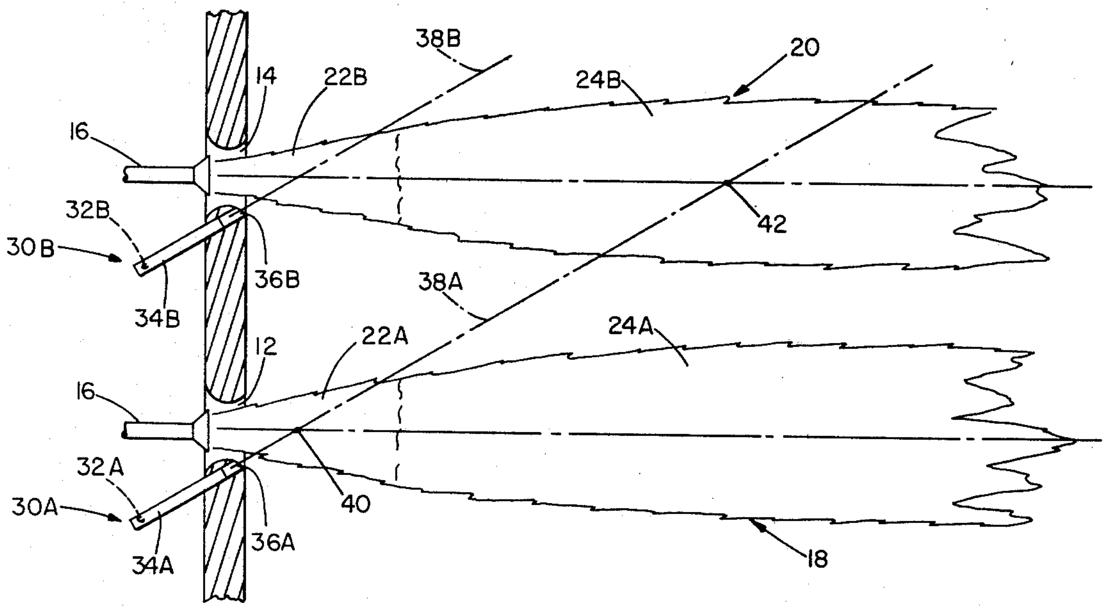
*Primary Examiner*—David C. Nelms


[57] **ABSTRACT**

A flame monitoring system includes a flame sensor for producing a flame signal as a function of flame conditions in a monitored environment and flame signal enhancing circuitry coupled to the flame sensor. The flame signal enhancing circuitry has a first response as a function of a first characteristic of the flame signal and a second response different from the first response as a function of a second characteristic of the flame signal and is arranged to combine the first and second responses to provide an enhanced flame signal representative of the monitored flame.


**24 Claims, 4 Drawing Figures**



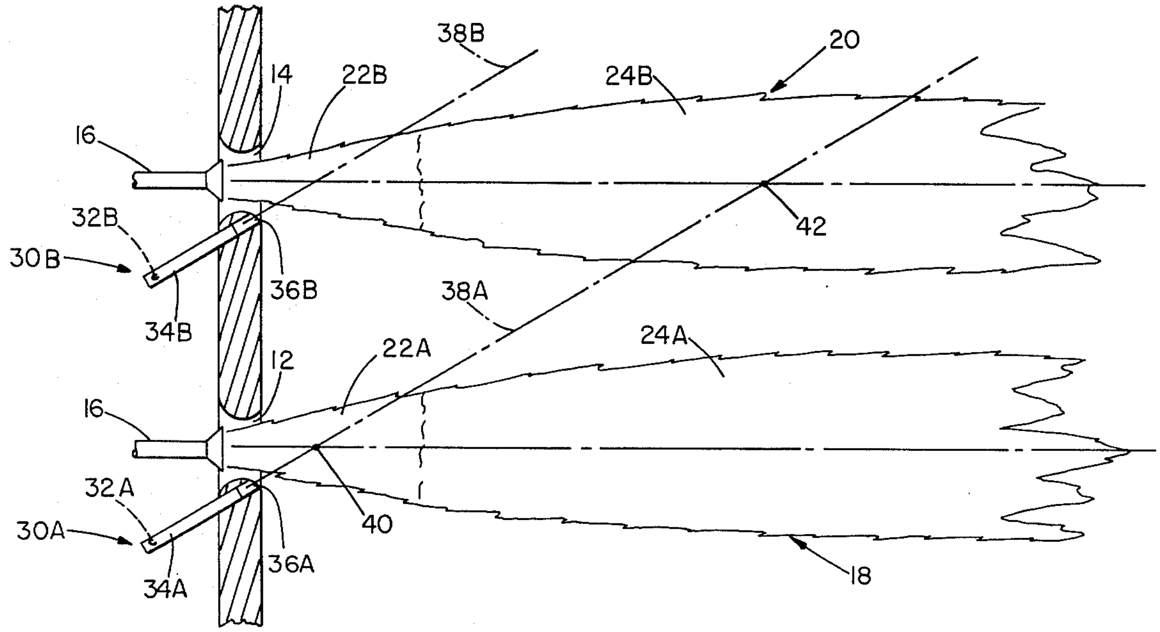



FIG 1

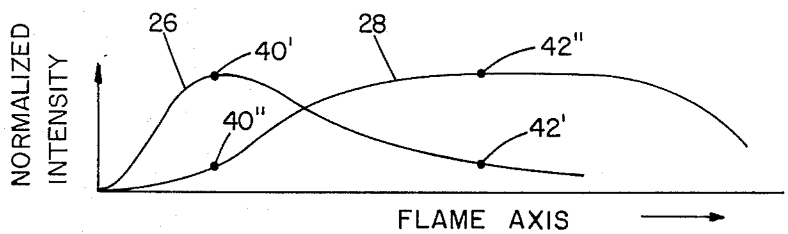



FIG 2

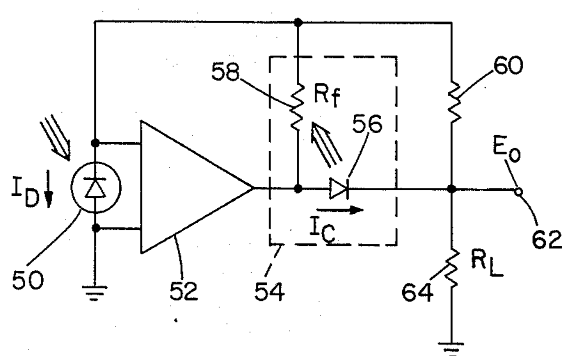



FIG 3

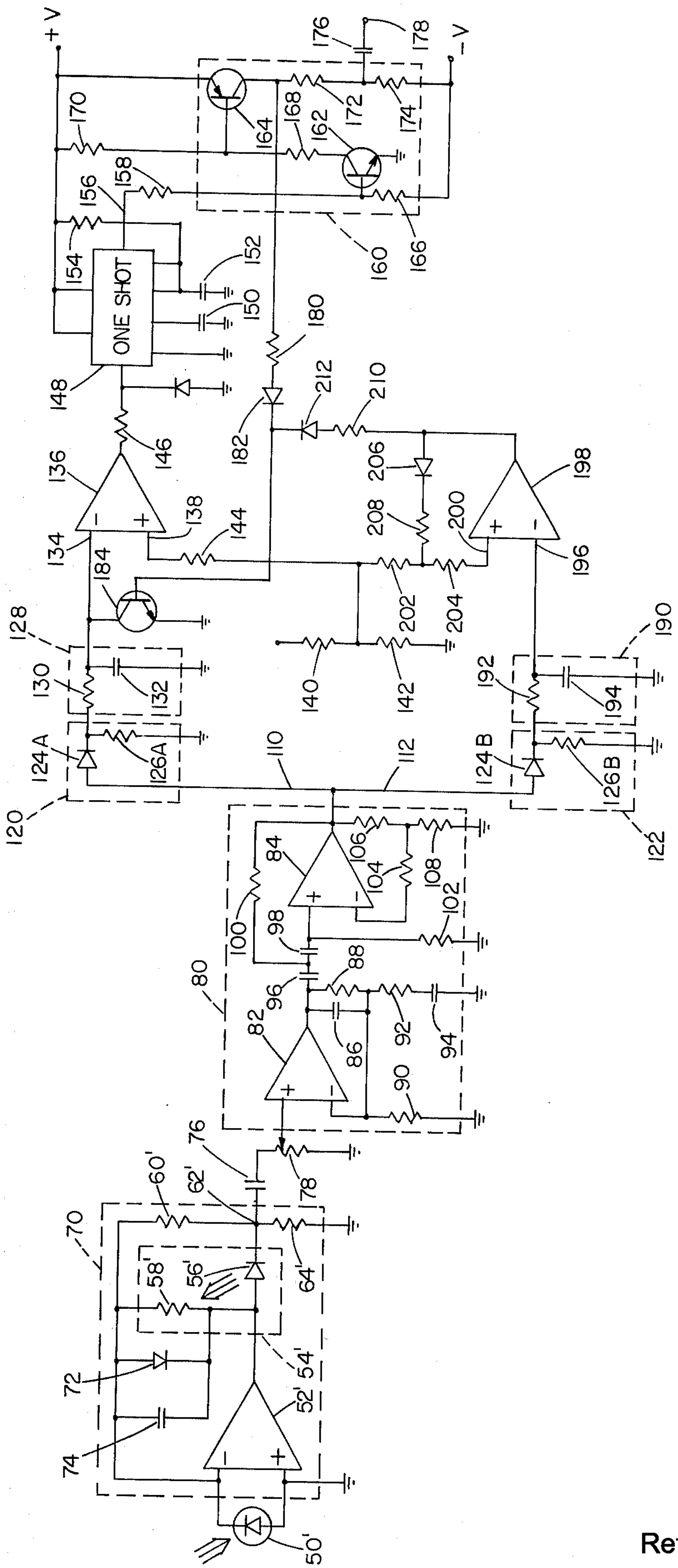



FIG 4

## FLAME MONITORING SYSTEM

### SUMMARY OF INVENTION

This invention relates to flame monitoring systems and more particularly to systems adapted for monitoring flames in multi-burner furnaces, such as boilers for large electrical power generating stations.

There is demand in modern steam generating stations, process systems and similar apparatus for the individual monitoring of burner flames so that immediate warning of flame failure can be given. The desirability of automatically monitoring flames in a furnace has long been recognized. When fuel continues to be supplied to a burner after the flame has been extinguished, the fuel may reignite explosively. While many flame detection systems responsive to flame radiation have been devised, such systems may give false indications that flame is present when they receive radiation from another source of comparable brightness, such as the furnace wall or an adjacent flame. In an effort to overcome such limitations, detector systems have been proposed which position plural detectors to view different areas of the same burner flame or which cross-correlate the signals from plural detectors positioned to view the same area of the burner flame. Certain flame detection systems utilize a flame responsive electrical output signal that has an alternating component, in some cases the utilized alternating component being in the order of 1–10 Hertz, while in other cases the utilized alternating component being of somewhat higher frequency, for example in the order of 100 Hertz.

The burner is frequently required to be monitored accurately at both low firing rates where the flame sensor must provide a useful signal when sensing radiation of low intensity, and at maximum firing rates where high radiation intensity on the flame sensor tends to mask components of higher frequency.

The source of alternating components of sensed flame radiation is not entirely clear but has been at times attributed to turbulence in the flame and/or to fluctuations in fuel supply. At the root or base of the flame, turbulence appears to distort the flame front, which distortions, it has been suggested, give rise to large variations in speed and direction of propagation of the combustion process and this may be the source of higher frequency alternating components. Lower frequency components exist in the flame region more remote from the base of the flame. With large turbulence, some unburned fuel may be carried periodically into the hotter regions of the flame where it suddenly ignites, propagating a region of hotter gas along the length of the flame. In practice, the magnitude of the higher frequency alternating component is low relative to the magnitude of the lower frequency or steady state component.

In accordance with an aspect of the invention, there is provided flame monitoring equipment for indicating the state of a burner flame by coordinating response of a single flame sensor or scanner to radiation components of different (e.g. higher and lower) frequencies that are sensed along a line of sight which passes through the root portion of the flame being monitored. The term "lower frequency components" is used herein to denominate steady and slowly varying components (up to a maximum of about 100 Hertz) while the term "higher frequency components" is used herein to denominate components that have a frequency above about 100 Hertz and up to 1000 Hertz and above.

Flame signal enhancing circuitry coupled to the flame sensor has a first response as a function of a first characteristic of the flame signal and a second response different from the first response as a function of a second characteristic of the flame signal and is arranged to combine the first and second responses to provide an enhanced flame signal representative of the monitored flame as an output signal. In preferred embodiments selective attenuation circuitry is coupled to the flame signal enhancing circuitry and has a low frequency cutoff that excludes all signals in the range of the second characteristic, a typical low frequency cutoff being about 200 Hertz. Gain adjustment means is provided for varying the magnitude of the enhanced flame signal.

The flame scanner conveniently comprises a photosensor mounted in tubular structure which serves to collimate the scanner path. The photosensor in practice may be mounted in a long tube which extends into the refractory wall of the combustion chamber; such a tube may be, for example, several feet in length to give protection for the sensor. The scanner path intersects the axis of its burner system at a selected point forward of the throat tile, a normal flame at selected point having a higher frequency component of significant intensity and the appropriate location of such point typically depending to some extent on conditions such as the nature of the fuel being fired. The root portion of a normal flame has a substantial higher frequency component while in portions of such flames more remote from the burner nozzle the magnitude of higher frequency components relative to lower frequency components is reduced. Background radiation conditions also have lower frequency characteristics. In a multi-burner system the scanner path may extend into more remote areas of the other flames (that is, areas of flames further spaced from the refractory wall than the monitored area of its flame). The ratio of lower to higher frequency components in such more remote areas is significantly greater than the lower/higher frequency component ratio in the monitored root portion of the supervised flame. Where the invention is utilized in such systems, it is not necessary that care be taken to direct the scanner away from the adjacent burners and towards a dark surface.

In preferred embodiments the signal processing circuitry produces an output that bears a direct relation to the higher frequency component and an inverse relation to the lower frequency component. While such direct and inverse relations may be obtained in various manner as, for example the higher frequency components being additively related and the lower frequency components subtractively related to the output signal, in particular embodiments the output signal is a ratio of the sensed higher and lower frequency components.

In a particular embodiment the photosensor is a silicon photodiode that has a high frequency response characteristic and a signal processing network coupled to the photodiode includes a radiation source that also has a high frequency response characteristic. A feedback circuit that includes a radiation responsive impedance element is optically coupled to the radiation source. The impedance of that impedance element changes as a function of radiation incident thereon at a rate that is much slower than the speed of response of the photodiode and of the radiation source. The feedback circuit moderates the output signal in proportion to the reciprocal of a fractional power of the low frequency component of the sensed radiation. It will be apparent that discrimination between the higher and lower frequency components of the sensed flame may be obtained in other manners, for example through use of a radiation source that has a damped output response or by separately extracting higher and lower frequency component signals and applying the extracted signals to a multiplier circuit. The alternating output signal of the signal processing network is applied to a band pass amplifier that has a pass band of about 400 Hertz and a low frequency cutoff at about 200 Hertz. The invention provides a simplified and more versatile monitoring system that is capable of providing enhanced discrimination between flames and also between flame and non-flame radiation sources in a combustion chamber. The system is useful in monitoring the quality as well as the presence of the supervised flame.

Other objects, features and advantages of the invention will be seen as the following description of a particular embodiment progresses, in conjunction with the drawings, in which:

FIG. **1** is a diagrammatic view of a flame monitoring arrangement for a multi-burner furnace;

FIG. **2** is a graph indicating the normalized relation of higher frequency and lower frequency components in a flame along the length of the flame;

FIG. **3** is a schematic diagram of a flame sensor circuit in accordance with features of the invention; and

FIG. **4** is a circuit diagram illustrating a flame monitoring system in accordance with the invention.

## DESCRIPTION OF PARTICULAR EMBODIMENT

There is shown in FIG. **1** a furnace structure having a refractory wall **10** with a plurality of burner throat apertures, two of which (**12, 14**) are shown. Conventional fuel supply and igniter structure **16** is associated with each burner system for establishing flames **18, 20.** Each flame has a primary combustion zone **22** adjacent to its burner throat aperture which contains a large proportion of unburned fuel. The brightness of this region is relatively low and high velocity air introduced through the burner throat creates turbulence in this primary combustion zone. As the flame extends further into the combustion chamber, combustion becomes complete with increased brightness in this secondary combustion zone **24,** and the high frequency modulation decreases in this region. Thus the primary zone **22** has a lower brightness and a significant proportion of higher frequency components, while the secondary zone **24** is brighter and has a lesser proportion of the higher frequency components.

The graph in FIG. **2** is an indication of the proportion of the higher and lower frequency components along the flame axis, the curves **26** and **28** being normalized as a typical average magnitude of the higher frequency component (represented by curve **26**) is in the order of 3–5 percent of the magnitude of the lower frequency component (represented by curve **28**).

A scanner system **30** is associated with each burner and includes a sensor **32** mounted in an elongated tube **34** that extends to a port **36** in the refractory wall **10** and that defines a line of sight **38.** Sensor **30A** is arranged to sense flame **18,** while sensor **30B** is arranged to sense flame **20.** Line of sight **38A** passes through the primary combustion zone **22A** of flame **18** (e.g. at point **40**) and the secondary combustion zone **24B** of flame **20** (e.g. at point **42**). The relative intensities of the higher and lower frequency components at points **40** and **42** along line of sight **38A** are indicated at **40'** and **40"**, and **42'** and **42"** respectively in FIG. **2.**

In particular embodiments a silicon photosensor is employed, its output response to sensed radiation components varying over the range of 1 to 500 microamperes. A circuit that accommodates the large dynamic range of sensed flame conditions and also produces an output that is directly related to the sensed higher frequency components and inversely related to the sensed lower frequency (including DC) components is shown in FIG. **3.** That circuit employs a silicon photodiode **50** which senses radiation energy of the flame in the rear infrared and visible red portions of the spectrum and has a speed of response that follows the second higher frequency components of the flame. The output of diode **50** is applied to operational amplifier **52** that is connected for current to voltage conversion and that has an optical coupler unit **54** connected to its output. That optical coupler includes a light emitting diode **56** optically coupled to a photoresistor **58** (e.g. cadmium sulfide) of slower response such that its response corresponds to the average current signal through diode **56.** Resistor **60** connected in parallel with photoresistor **58** in the feedback path of operational amplifier **52** limit the maximum gain of the circuit.

The transfer function for this circuit is of the form:

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $n$ has been found to be in the range of 0.6–0.8.

Thus, the AC output signal ($E_0$(AC)) is directly proportional to the AC component of the current ($I_D$) flowing through photodiode **50** and inversely proportional to a fractional power of the DC component of the current flowing through diode **50.** As $I_C$ (the output current) increases, the illumination of $R_f$ increases and causes its resistance value to decrease. The effect is to decrease the gain of the circuit. The frequency response of photosensor **58** in the optical coupler is less than 100 Hertz, lower than the response of photosensor **50** and so slow that it does not affect the high frequency component of the signal of interest.

This detection system senses the presence of flame of the particular burner it is supervising by sensing the presence of the higher frequency component of the signal, which signal presence is moderated by the effect of the second lower frequency component. Thus if there is either a significant decrease of the higher frequency signal or the lower frequency signal increases significantly more than the higher frequency signal, the output voltage will be reduced providing a flame out indication. The relationship between the higher and lower frequency components of a sensed flame is also useful in monitoring the quality of that flame.

The relationship between higher and lower frequency components of the radiation conditions along the sensed path in the combustion chamber may be usefully provided in various forms, for example a ratio of the higher to the lower frequency components or a diference between normalized values of the higher and lower frequency components, and by circuit arrangements other than that shown in FIG. **3.**

A schematic diagram of a particular embodiment is shown in FIG. **4.** That circuit includes a flame sensor **50'** connected across the input terminals of operational amplifier **52'**. Sensor **50'** is a silicon diode that is connected to operate in a photoconductive mode as a current source so that the sensed radiation intensity modifies the diode current flow as a function of the radiation incident on the diode. Connected to the output of amplifier **52'** is a photocoupler **54'** that includes a silicon light emitting diode **56'** optically coupled to a cadmium sulfide photoresistor **58'**. Supplemental resistor **60'** is connected in the feedback path and diode **72** and capacitor **74** are connected across photoresistor **58'**. This input stage **70** produces an output signal that is a direct function of the higher and an inverse function of the lower frequency components of the sensed radiation condition.

That output signal is coupled by capacitor **76** to a gain control potentiometer **78.** Potentiometer **78** provides gain adjustment for band pass filter **80** that includes operational amplifiers **82** and **84.** The band pass filter components are selected to provide a center frequency of about 400 Hertz and a pass band of 400 Hertz. The resulting output signal is applied on lines **110** and **112** to detector networks **120, 122,** each of which includes a diode **124** and a resistor **126.**

The signal from detector **120** is applied to high speed filter **128** that includes resistor **130** and capacitor **132** and has a time constant of about 50 milliseconds. The output of the filter **128** is applied to terminal **134** of operational amplifier **136** which is connected to function as a comparator. The voltage at reference terminal **138** of comparator **136** is supplied from a divider network includes resistors **140** and **142** and is about 0.15 volt. When capacitor **132** is sufficiently charged so that the voltage at terminal **134** exceeds the voltage at terminal **138,** amplifier **136** triggers one shot circuit **148** which generates an output pulse of forty microsecond duration on output line **156.** That output pulse is applied through resistor **158** to driver amplifier **160** that includes transistors **162** and **164** and the amplified output pulse is coupled by capacitor **176** to output terminal **178** as a flame present pulse. The amplified pulse is also coupled through resistor **180** and diode **182** to switch clamp transistor **184** into conduction, thus discharging capacitor **132** and resetting the filter **128.**

A slow filter **190** includes resistor **192** and capacitor **194** and has a time constant of about 1½ seconds. The output of filter **190** is applied to input terminal **196** of comparator **198** whose reference terminal **200** which is connected to the voltage divider network of resistors **140, 142** via resistors **202** and **204.** A second connection to reference terminal **200** is from the feedback network from the output of comparator **198** via diode **206** and resistor **208.** The comparator output is also applied via resistor **210** and diode **212** to switch clamp transistor **184** into conduction. Should the output of filter **190** fall below 0.15 volt (the reference voltage at terminal **200**), the output of comparator switches positive and applies a voltage through diode **206** to increase the reference voltage at terminal **200** to about 0.5 volt (thus raising the comparator threshold about 2½ times) and at the same time clamps capacitor **132** in discharged condition (via transistor **184**) thus preventing the production of flame present pulse signals at terminal **178.**

Thus, when the flame signal from the band pass amplifier **80** drops, in response to a low flame or no flame condition, comparator **198** switches its output signal, terminating the generation of output pulses at terminal **178** and also increasing the threshold of comparator **198.** A larger flame signal (0.5 volt) is required to switch comparator **198** to remove the clamp from the flame pulse producing channel so that flame pulses will be again produced at output terminal **178** and when such flame signal is produced by filter **190,** comparator **198** is switched back to the lower threshold value.

In operation, the burner **16A** in proper operation provides a flame condition with fluctuating components in zone **22A.** The sensor circuit **70** senses that fluctuating component and steady state components in zone **24** of flame **20** as well as in background radiation and produces an AC signal which coupled by capacitor **76** to the band pass amplifier **80** which amplifies that AC signal. As long as that AC signal above a minimum threshold is present, filter **128** periodically causes comparator **136** to trigger one shot **148** to produce a forty microsecond pulse at output terminal **178.** Those output pulses are compatible with operating circuitry designed to respond to an ultraviolet flame sensor, for example. Should the magnitude of the output signal from the band pass amplifier fall sufficiently to switch comparator **198,** however, the pulse generating circuit is clamped off and the threshold level is shifted by the feedback loop of comparator **198** to require a substantially greater magnitude of flame signal at terminal **62'** to reinitiate the generation of output pulses at terminal **178** than was required to maintain application of those pulses at that terminal.

Values and types of components employed in the embodiment shown in FIG. **4** are set out in the following table:

| Reference No. | Component Value or Type |
|---|---|
| 52' | N5556T |
| 54' | CLM8500 |
| 60' | 1M |
| 64' | 3.2K |
| 74 | 100pf |
| 76 | 0.01uf |
| 78 | 100K |
| 82 | N5558T |
| 84 | N5558T |
| 86 | 220pf |
| 88 | 1M |
| 90 | 1M |
| 92 | 3.3K |
| 94 | 0.47uf |
| 96 | 0.022uf |
| 98 | 0.022uf |
| 100 | 39K |
| 102 | 39K |
| 104 | 33K |
| 106 | 10K |
| 108 | 10K |
| 124A | 1N4448 |
| 124B | 1N4448 |
| 126A | 3.3K |
| 126B | 3.3K |
| 130 | 33K |
| 132 | 1.8uf |
| 136 | N5558T |
| 140 | 10K |
| 142 | 100 |
| 144 | 33K |
| 146 | 4.7K |
| 148 | NE555T |
| 150 | 0.01uf |
| 152 | 0.001uf |
| 154 | 33K |
| 158 | 10K |
| 162 | 2N2222 |
| 164 | 2N3073 |
| 166 | 100K |
| 168 | 1K |
| 170 | 10K |
| 172 | 100 |
| 174 | 220 |
| 176 | 0.47uf |
| 180 | 1K |
| 182 | 1N4448 |
| 184 | 2N2222 |
| 192 | 33K |
| 194 | 56uf |

-continued

| Reference No. | Component Value or Type |
|---|---|
| 198 | N5558T |
| 202 | 3.3K |
| 204 | 33K |
| 206 | 1N4448 |
| 208 | 100K |
| 210 | 10K |

While a particular embodiment of the invention has been shown and described, various modifications thereof will be apparent to those skilled in the art and therefore it is not intended that the invention be limited to the disclosed embodiment or to details thereof and departures may be made therefrom within the spirit and scope of the invention as defined in the claims.

What is claimed is:

**1.** A flame monitoring system comprising

a flame sensor producing an electrical output signal having both higher frequency and lower frequency components derived from a monitored flame environment,

and signal processing circuitry connected to said flame sensor and responsive to both said higher frequency and said lower frequency components of said output signal, said signal processing circuitry including an amplifier and a feedback network with a variable impedance and being arranged so that said higher frequency components are amplified and the amplifier gain is decreased in response to an increase in said lower frequency components such that the resulting output of said signal processing circuitry provides discrimination between the flame monitored by said sensor and other conditions in the supervised environment.

**2.** The system as claimed in claim **1** wherein said flame sensor is a photosensor that has a high speed response characteristic.

**3.** The system as claimed in claim **1** wherein said signal processing circuit has a transfer function of the form

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $E_{O(AC)}$ is the output signal of said signal processing circuitry, $I_{D(AC)}$ is a higher frequency component of said flame signals, $I_{D(DC)}$ is a lower frequency component of said flame signal, and $n$ is in the range of 0.6–0.8.

**4.** The system as claimed in claim **2** wherein said signal processing circuitry further includes a radiation source connected to the output of said amplifier, and said feedback network includes a radiation responsive impedance element that is optically coupled to said radiation source and that has a response speed that is much slower than the response speed of said photosensor.

**5.** The system as claimed in claim **4** and further including selective attenuation circuitry coupled to said signal processing circuitry for attenuating components of said signal processing circuitry output.

**6.** The system as claimed in claim **5** wherein said selective attenuation circuitry includes band pass amplifier circuitry that has a band corresponding to the frequency range of said higher frequency components.

**7.** A flame monitoring system comprising:



a flame sensor for producing a flame signal as a function of flame conditions in a monitored environment,

flame signal enhancing circuitry coupled to said flame sensor, said flame signal enhancing circuitry having an amplifier and a feedback network with a variable impedance and being arranged so that a first characteristic of said flame signal is amplified and the amplifier gain is decreased in response to an increase in a second characteristic of said flame signal to provide an enhanced flame signal representative of the monitored flame as an output signal.

**8.** The system as claimed in claim **7** wherein said first characteristic is a higher frequency component of said flame signal and said second characteristic is a lower frequency component of said flame signal.

**9.** The system as claimed in claim **8** wherein said flame signal enhancing circuitry has a transfer function of the form

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $E_{O(AC)}$ is said enhanced flame signal, $I_{D(AC)}$ is said first characteristic of said flame signal, $I_{D(DC)}$ is said second characteristic of said flame signal, and $n$ is in the range of 0.6–0.8.

**10.** The system as claimed in claim **7** and further including selective attenuation circuitry coupled to said flame signal enhancing circuitry for attenuating components of said output signal corresponding to the frequency range of said second characteristic of said flame signal.

**11.** The system as claimed in claim **10** wherein said selective attenuation circuitry has a low frequency cutoff that excludes all signals in the range of said second characteristic.

**12.** The system as claimed in claim **11** wherein said low frequency cutoff is about 200 Hertz.

**13.** The system as claimed in claim **12** wherein said selective attenuation circuitry includes a band pass amplifier that has a center frequency of about 400 Hertz and a pass band of about 400 Hertz.

**14.** The system as claimed in claim **12** and further including gain adjustment means for varying the magnitude of said enhanced flame signal.

**15.** The system as claimed in claim **7** wherein said flame sensor is a photosensor.

**16.** The system as claimed in claim **15** wherein said photosensor is a solid state device that has a photosensitive junction region.

**17.** The system as claimed in claim **16** wherein said solid state device is a silicon photodiode device.

**18.** The system as claimed in claim **7** wherein said flame signal enhancing circuitry has a transfer function of the form

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $E_{O(AC)}$ is said enhanced flame signal, $I_{D(AC)}$ is said first characterstic of said flame signal, $I_{D(DC)}$ is said second characteristic of said flame signal, and $n$ is in the range of 0.6–0.8.

**19.** The system as claimed in claim **18** wherein said feedback network includes an impedance element that has a damped response to said flame signal.

20. The system as claimed in claim 19 and further including a radiation source coupled to be energized by the output of said amplifier and a slow speed photoresistor connected in said feedback network and optically coupled to said radiation source.

21. The system as claimed in claim 20 and further including gain adjustment means for varying the magnitude of said enhanced flame signal.

22. The system as claimed in claim 21 and further including selective attenuation circuitry coupled to said flame signal enhancing circuitry for attenuating components of said enhanced flame signal corresponding to the frequency range of said second characteristic of said flame signal.

23. The system as claimed in claim 22 wherein said sensor is a solid state silicon device that has a photosensitive junction region.

24. The system as claimed in claim 23 wherein said first characteristic is a higher frequency component of said flame signal and said second characteristic is a lower frequency component of said flame signal and said selective attenuation circuitry has a low frequency cutoff of about 200 Hertz.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 4,039,844

DATED : August 2, 1977

INVENTOR(S) : Malcolm F. MacDonald

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 36, delete "the";

Column 4, line 6, after "1", insert --microampere--;

Column 4, line 13, change "rear" to --near--;

Column 4, line 15, change "second" to --sensed--;

Column 7, line 49, change "signals" to --signal--;

Column 7, line 66, after "a", insert --pass--.

**Signed and Sealed this**

*Twenty-eighth* Day of *March 1978*

[SEAL]

*Attest:*

RUTH C. MASON
*Attesting Officer*

LUTRELLE F. PARKER
*Acting Commissioner of Patents and Trademarks*

# Reference 4

Reference 4

# United States Patent [19]

**Kompelien**

[11] **Patent Number: 5,073,769**

[45] **Date of Patent: Dec. 17, 1991**


[54] **FLAME DETECTOR USING A DISCRETE FOURIER TRANSFORM TO PROCESS AMPLITUDE SAMPLES FROM A FLAME SIGNAL**


[75] Inventor: **Arlon D. Kompelien**, Crosslake, Minn.

[73] Assignee: **Honeywell Inc.**, Minneapolis, Minn.



[21] Appl. No.: **608,054**

[22] Filed: **Oct. 31, 1990**

[51] **Int. Cl.**[5] ........................................ **G08B 17/12**

[52] **U.S. Cl.** ........................................ **340/578**; 250/554; 364/576

[58] **Field of Search** ........................ 340/578; 250/554; 364/576, 550



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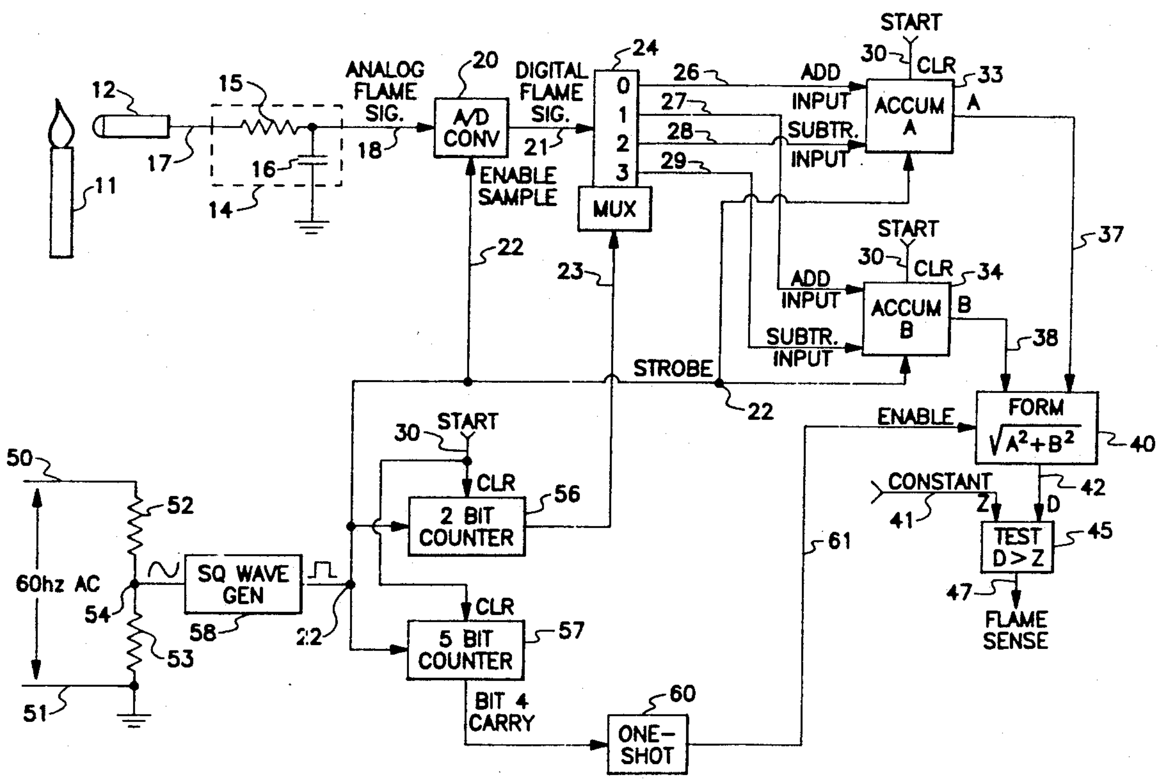
*Primary Examiner*—Jin F. Ng
*Assistant Examiner*—C. Oda
*Attorney, Agent, or Firm*—Edward Schwarz



[57] **ABSTRACT**

A circuit for detecting presence of a flame receives a flame signal from a standard photocell positioned to receive radiation from the flame and digitally processes the amplitude variations in the photocell's output to sense for the presence of frequencies near a frequency which is characteristic of a flame. The frequencies substantially higher than the characteristic frequency are filtered from the signal, and the remaining signal is sampled at a frequency which is preferably four times the characteristic frequency. The samples are converted to digital values and processed using a discrete Fourier transform. If the value resulting from the transform operation exceeds a preselected value, presence of a flame is essentially certain. Such digital processing allows use of a dedicated microcircuit or a microprocessor for the flame sensing function and avoids the need for many large discrete components.


**7 Claims, 4 Drawing Sheets**



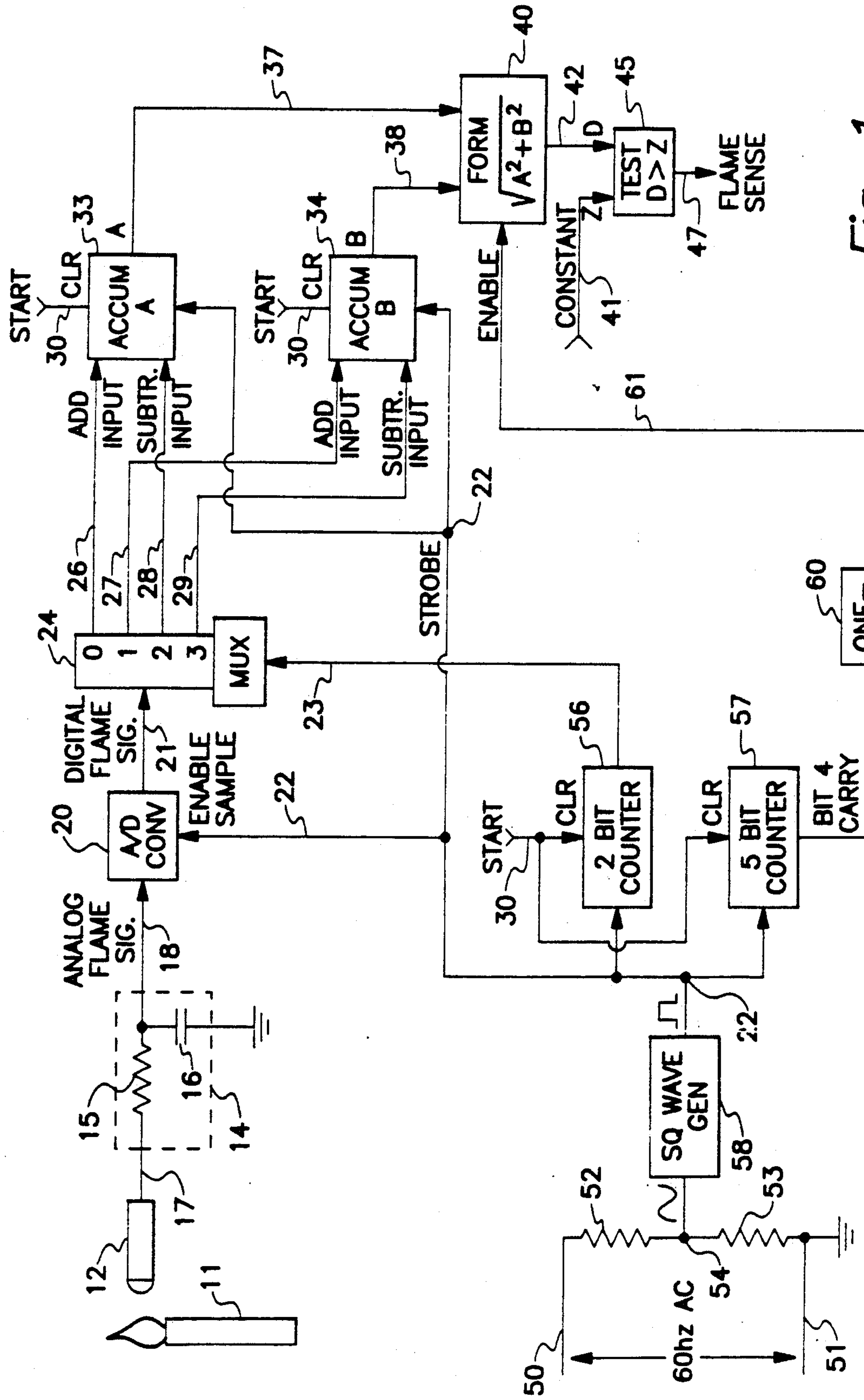

ANALOG FLAME SIG.
A/D CONV
ENABLE SAMPLE
DIGITAL FLAME SIG.
MUX
STROBE
START
CLR
ACCUM A
ACCUM B
ADD INPUT
SUBTR. INPUT
FORM $\sqrt{A^2+B^2}$
TEST D>Z
FLAME SENSE
CONSTANT
ENABLE
ONE-SHOT
2 BIT COUNTER
5 BIT COUNTER
BIT 4 CARRY
SQ WAVE GEN
60hz AC

Fig. 1

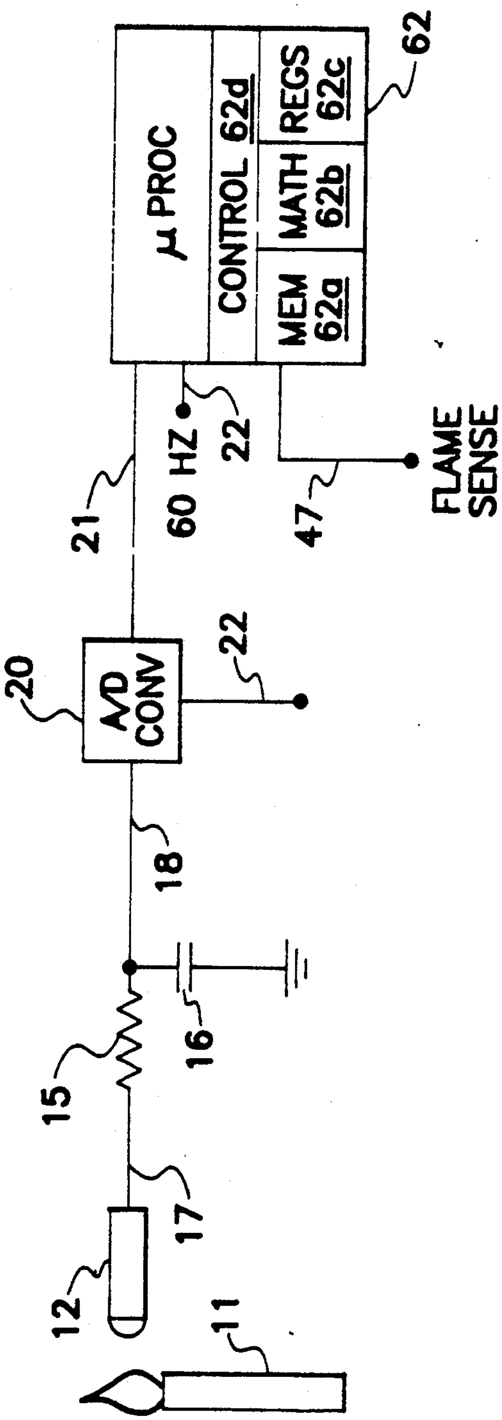

μ PROC
CONTROL 62d
MEM 62a
MATH 62b
REGS 62c
62
60 HZ
22
21
47
FLAME SENSE
A/D CONV
20
22
18
16
15
17
12
11

Fig. 2

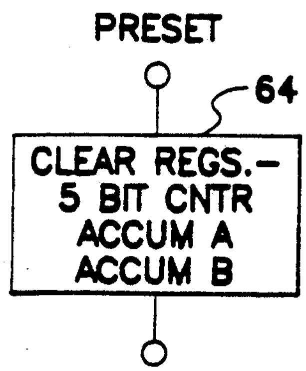
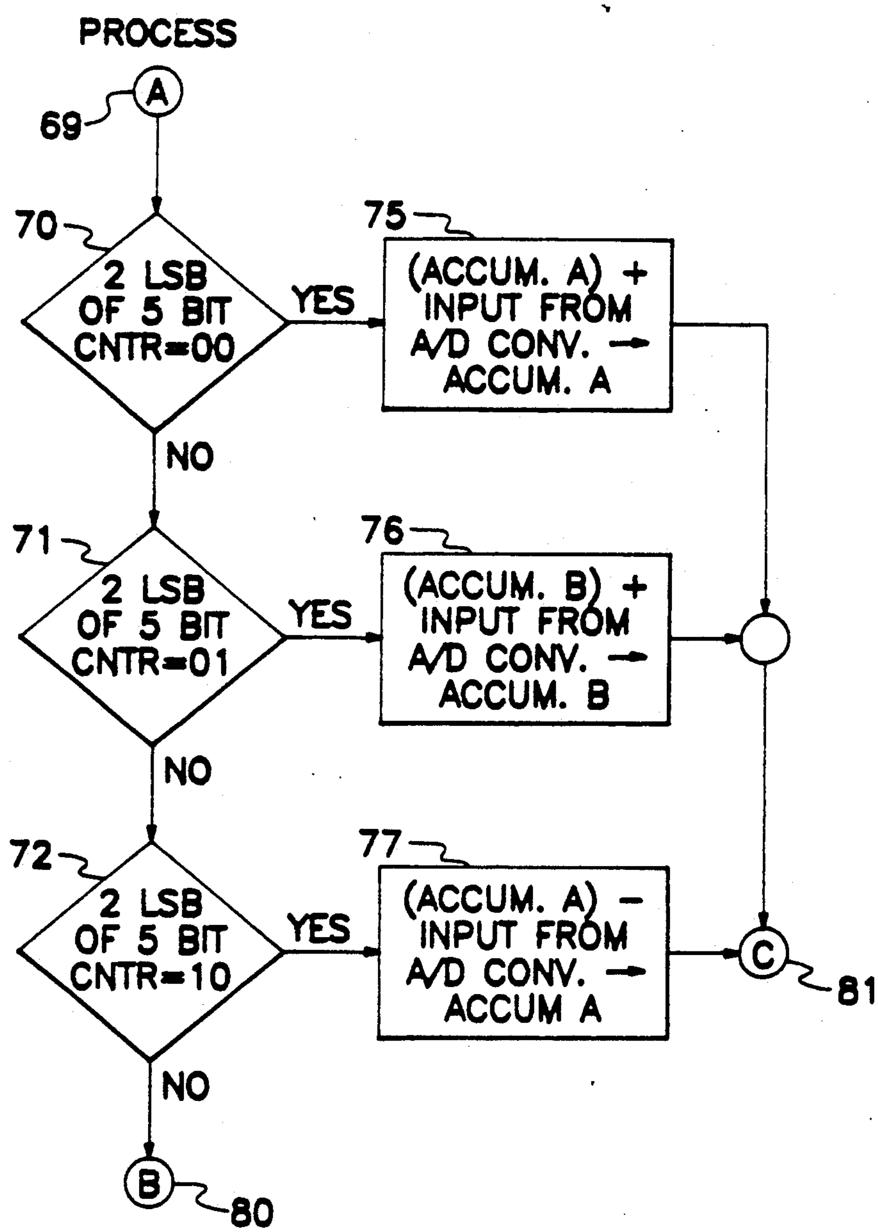

PRESET
64
CLEAR REGS.–
5 BIT CNTR
ACCUM A
ACCUM B

Fig. 3A


PROCESS
A
69
70
2 LSB
OF 5 BIT
CNTR=00
YES
NO
75
(ACCUM. A) +
INPUT FROM
A/D CONV. →
ACCUM. A
71
2 LSB
OF 5 BIT
CNTR=01
YES
NO
76
(ACCUM. B) +
INPUT FROM
A/D CONV. →
ACCUM. B
72
2 LSB
OF 5 BIT
CNTR=10
YES
NO
77
(ACCUM. A) –
INPUT FROM
A/D CONV. →
ACCUM A
C
81
B
80

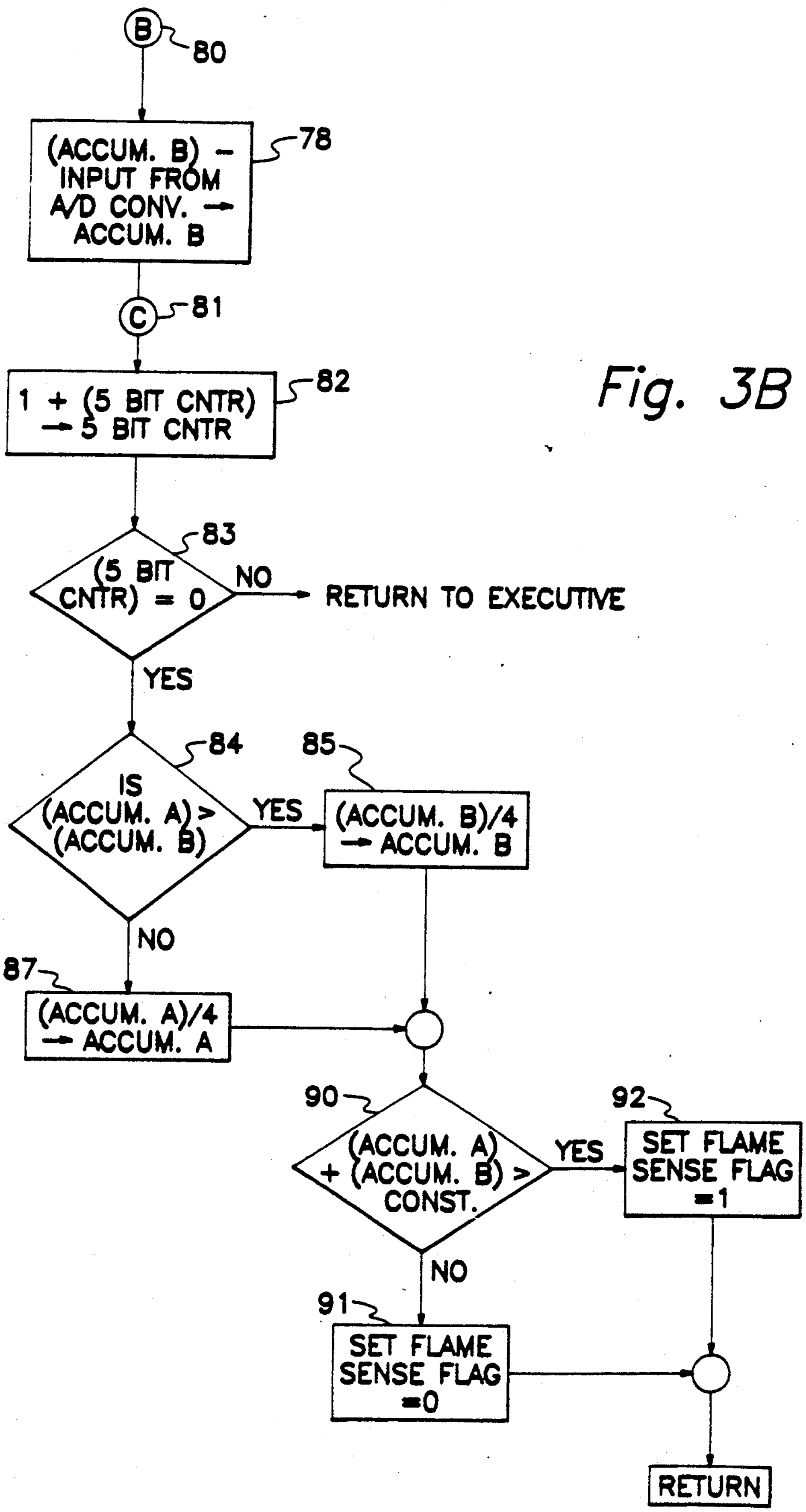

80
(ACCUM. B) − INPUT FROM A/D CONV. → ACCUM. B
78
81
1 + (5 BIT CNTR) → 5 BIT CNTR
82
83
(5 BIT CNTR) = 0
NO
RETURN TO EXECUTIVE
YES
84
IS (ACCUM. A) > (ACCUM. B)
YES
85
(ACCUM. B)/4 → ACCUM. B
NO
87
(ACCUM. A)/4 → ACCUM. A
90
(ACCUM. A) + (ACCUM. B) > CONST.
YES
92
SET FLAME SENSE FLAG =1
NO
91
SET FLAME SENSE FLAG =0
RETURN

Fig. 3B

# FLAME DETECTOR USING A DISCRETE FOURIER TRANSFORM TO PROCESS AMPLITUDE SAMPLES FROM A FLAME SIGNAL

## BACKGROUND OF THE INVENTION

In fuel burners such as furnaces where the main burner is lit by a pilot burner, it is necessary for obvious reasons to assure that the pilot burner is lit before the main burner fuel valve is opened. This is true whether a standing pilot or intermittent pilot is involved. While there are many different types of sensing operations which can reliably detect presence of a pilot flame, one which is preferred senses the flicker frequency of typical pilot flames. This flicker is a periodic variation of the intensity or amplitude of the infrared, visible, or ultraviolet radiation produced by the burning of the fuel sustaining the pilot flame. The flicker frequency of this radiation in most cases has a component in the range of 13-17 hz. This characteristic is fairly independent of the fuel and the size of the pilot flame.

In the past an analog circuit has been used to sense for presence of this flicker in the intensity of the radiation emanating from the location of the pilot flame. However, the relatively large size of components for an analog-based flame sensing system for the low frequencies involved here, cannot be easily included on a single circuit board with the smaller digital and logic-based circuits which are now more and more often being used to implement other functions of typical fuel burners. This necessitates a separate flame sensor board or a larger single board with a larger power supply, resulting in turn in undesirable expense and inconvenience.

## BRIEF DESCRIPTION OF THE INVENTION

The so-called fast Fourier transform (FFT) is a mathematical algorithm which has been used for signal frequency analysis for some time. When one desires to sense the presence of frequencies in a neighborhood of a particular single frequency, one can use a variation of the FFT called the discrete Fourier transform (DFT). A circuit for detecting presence of a radiation source such as a pilot flame having a significant flicker in its energy within a predetermined frequency range may use a particular variation of the DFT for the purpose of pilot flame detection. Such a circuit receives from a photocell a flame signal instantaneously representative of the intensity of the energy emanating from the flame. A simple analog low pass filter receives the flame signal and providing a filtered flame signal from which a substantial percentage of the amplitude of frequencies above the predetermined frequency range has been removed. This prevents the higher frequencies from simulating the flicker frequency of interest, a condition known as "aliasing", which is possible when using a DFT.

A clock circuit provides a clock signal having individual pulses at four times the frequency of the midpoint of the predetermined frequency range. For a common flicker frequency of 15 hz., it is convenient to use the normal 60 hz. power as the source of the clock signal. An analog to digital converter receives the filtered flame signal and the clock signal, samples the filtered flame signal responsive to each clock signal pulse, and provides a digital flame signal having a plurality of successive discrete, ordinally designated, digital values each encoding the amplitude of the filtered flame signal at successive sampling instants over a predetermined sampling interval. A first accumulator register receives the digital flame signal and forms from the plurality of digital values comprising the flame signal, the sum of the difference of successive pairs of even numbered ordinal digital values and provides at the end of each sampling interval a first intermediate digital transform signal encoding the current contents of the first accumulator register. A second accumulator register receives the digital flame signal and forms the sum of the difference of successive pairs of odd numbered ordinal digital values for the predetermined sampling interval, and provides at the end of each sampling interval a second intermediate digital transform signal encoding the current contents of the second accumulator register.

A calculator means receives the first and second intermediate digital transform signals from their respective accumulator registers and provides a transform signal digitally encoding a value at least approximately equal to the square root of the sum of the square of the digital values encoded in each of the first and second intermediate digital transform signals. That is, the actual computed value encoded in the transform signal to be used in the next phase of the operation of this apparatus should have at least the accuracy of an approximation of the precise value. A comparator means receives the transform signal from the calculator means and compares the value encoded in the transform signal with a predetermined transform constant value, and if greater than the transform constant value, issues a flame sense signal signifying presence of flame.

All of these elements except for the photocell analog low pass filter, and clock means can be formed by the proper programming of a microprocessor, and in fact this is the preferred embodiment for the invention.

Accordingly, one purpose of the invention is to reduce the size and power requirements of the flame sensing system in a burner control system.

A second purpose of the invention is to allow the flame sensing system to be included in the micro electronics package containing the control circuitry for the burner.

Yet another purpose of the invention is to allow changes in the sensitivity and response of the flame detector by software means only.

A further purpose is to increase the accuracy and reliability in detecting presence of a flame in a burner.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of electrical circuit employing discrete components to implement the invention.

FIG. 2 is a block diagram of a system implementing the invention using a microprocessor to perform the functions of the digital and logical blocks of FIG. 1.

FIGS. 3A and 3B flow diagram of instructions which may be loaded into the microprocessor of FIG. 2 to implement the invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention is for detecting a flame which has in its energy output intensity a flicker whose frequency is within a predetermined frequency range. The detection process used involves the so-called discrete Fourier transform (DFT) calculation to sense the presence of a component of the flicker frequency in the flame. In FIG. 1, a conventional burner **11**, which may be a pilot burner such as is used in a conventional furnace or heater, produces a flame sensed by a photocell **12**. The photocell **12** provides a flame signal on path **17** which is instantaneously representative of the intensity of the energy emanating from the flame. For the typical pilot flame, there a frequency component in this flame signal within the 13–17 hz. range whose presence is a sufficient condition for the presence of a pilot flame, even though there are invariably many other frequencies present in the composite signal as well. This frequency component arises from the flow velocity, pressure, and combustion characteristics of the gaseous fuel supplying the typical pilot burner **11**, and is independent of the size or design of the pilot burner itself. However, the overall signal energy of this frequency component is substantially less than the signal energy of other frequencies present These other frequencies typically are radiated by the hot surfaces of the furnace interior after the pilot flame goes out, and thus of course provide no indication of the presence of any pilot flame. Accordingly, it is necessary to carefully tune a detector intended to sense presence of this frequency component, to detect frequencies within this 13–17 hz. range.

The flame signal on path **17** is filtered by a low pass filter **14** which comprises a series resistor **15** and a shunt capacitor **16** as shown. Preferably filter **14** has a cutoff frequency of approximately 20 hz., so that the amplitude of frequencies above 20 hz. is substantially attenuated. The output of filter **14** is a filtered flame signal on path **18** which is supplied to an analog to digital (A/D) converter **20**. In response to an enable sample signal on path **22**, A/D converter **20** provides a digital flame signal on path **21** which digitally encodes the digital value of the amplitude of the filtered flame signal at the instant that the enable sample signal on path **22** occurred. The range of converter **20** must be great enough to assure that there is no clipping of the input voltage level of the filtered flame signal reflected in the digital output. The enable sample signal is provided at fixed intervals by other circuitry of FIG. **1**, and it is strongly preferred that the enable sample signal occur at four times the rat of the flame signal frequency to be detected. Other sampling rates are possible, but any other rate involves substantially more complicated calculations to determine the DFT value of interest. When the invention is implemented within a simple and low powered microprocessor, complicated calculations are not easy to make, and such an implementation is the most likely. For the remainder of this description, the sampling rate of four times the DFT frequency will be assumed.

One can consider the output of A/D converter **20** as comprising a series of successive discrete, ordinally designated, digital values each encoding the magnitude of the filtered flame signal on path **18** at successive sampling instants occurring at the fixed enable sample rate. If a specific digital value is chosen as the first for a detection calculation, then it and the succeeding values may also be ordinally designated as well, as $x_0$, $x_1$, etc., with the subscripts forming the successive ordinal designations of the digital sample values.

The elements of FIG. **1** which will now be discussed will typically form parts of a microprocessor which is programmed to at the appropriate instants of time, perform the functions which the elements involved provide. In fact, many such microprocessors also include an A/D converter **20** as part of the package containing the microprocessor.

The digital flame signal on path **21** is supplied to the input of an output multiplexer **24**. Such a multiplexer has a number of output paths **26–29**, each of which has a unique address. The multiplexer **24** provides the binary digits encoded on its digital data input path **21** to the one of the output paths **26–29** whose address is specified by the address encoded in the signal on an address path **23**. All of the output paths **26–29** except for the one designated by the two bit address path **23** carry a digital value of zero. That is, the digital data on the input path **21** is carried by the output path **26**, **27**, **28** or **29** of multiplexer **24** accordingly as the input on the two bit address path **23** encodes a zero, one, two, or three. Output paths **26–29** which are not designated by the two bit address on path **23** encode a digital value of zero.

To understand the processing which is performed using the digital flame signal provided on path **21** it is useful to examine the mathematical expression of the discrete Fourier transform (DFT) which is employed here. A flicker signal generated when flame is present will almost always have a detectable frequency component at 15 hz. using the system being described, and will essentially never have such a component when no flame is present. As mentioned earlier, one can consider the A/D converter **20** as providing a plurality of successive discrete, ordinally designated, digital values each encoding the magnitude of the filtered flame signal on path **18** at successive sampling instants. The general theory for calculating a DFT for a waveform can be considerably simplified when the values of the waveform are sampled at a rate four times that of the DFT target frequency. In this simplified case, calculating the DFT involves forming two related summations to be explained shortly. For the purpose of reliably detecting presence of a pilot flame, it has been found to be sufficient to continue the summation over eight successive cycles of the 15 hz. frequency component. In the first summation, the sum of the difference of successive pairs o digital values having even ordinal designations must be formed. For the second summation, the sum of the difference of successive pairs of digital values having odd ordinal designations must be formed. If the first series value is designated A, and the ordinal designation of the successive digital values is represented by a subscript of from 0 to 31, then $A=x_0-x_2+x_4-x_6+\ldots+x_{28}-x_{30}$. (Equation 1) Similarly, the equation for the second series summation of the digital values can be written as $B=x_1-x_3+x_5-x_7+\ldots+x_{29}-x_{31}$. (Equation 2) The DFT for this wave form as sampled by converter **22** at these precise intervals is then given by $D=(A^2+B^2)^{\frac{1}{2}}$. (equation 3) It is possible to use other than precisely **32** samples for a single calculation, but I have found **32** to be adequate for accurate and reliable flame detection without excessive calculations or time required. At any rate, with this detection algorithm, the number of samples involved in a single evaluation should be a multiple of four.

To allow sampling to occur at exactly four times the rate of the target frequency of 15 hz., the enable sample signal must occur at 60 times per second. It is extremely convenient to use the standard 60 hz. power wave form as the clock which generates the enable sample signal on path **22** which controls the sampling of the filtered flame signal on path **18**. Accordingly, a 60 hz. AC signal on paths **50** and **51** is placed across a voltage divider comprising resistors **52** and **53**. The common point **54** of these resistors provides a low voltage 60 hz. sine wave input to a square wave generator **58** which produces a 60 hz. square wave output on path **22**. As mentioned earlier of course, the individual square wave pulses on path **22** enable successive samples of the filtered flame signal on path **18**. The square wave signal on path **22** is also provided to a two bit counter **56** and a five bit counter **57** to increment the contents of each of these counters by one each time a pulse is provided to the input on path **22**. It can be seen that two bit counter **56** counts from 0 to 3 decimal (0 to 11 binary) and then returns to 0 and continues cycling in that manner. Similarly, five bit counter **57** advances by one in response to each pulse on path **22** and after reaching **31** (11111 binary) returns to 0 and continues to advance with each additional pulse. It may well be more convenient to use the two least significant bits of five bit counter **57** as two bit counter **56**, and this is completely acceptable.

For sequencing purposes, it is necessary to employ a start signal provided by some external controller on path **30**. With respect to counters **56** and **57**, this signal is applied to clear (CLR) inputs which cause the counter **56** or **57** to be reset to 0. In addition, counter **57** provides a carry from its high order bit, bit 4 (the low order bit being bit 0), to indicate that 32 pulses have been applied to it since the counter **57** was last cleared. This bit 4 carry signal is applied to a one shot **60** which provides an output pulse whose duration is set by the internal characteristics of one shot **60**.

Multiplexer **24** along with an A accumulator **33** and a B accumulator **34** are the circuit elements directly involved with forming the two series summations of equations 1 and 2. While these two accumulators are shown here as discrete hardware elements, it is very likely that in a preferred embodiment using a microprocessor, these accumulators will be individual registers within the microprocessor memory. In such a case, the arithmetic unit of the microprocessor alternately cooperating with each of the registers to function as a part of one or the other of the accumulators. Each accumulator **33** or **34** has an add input and a subtract input, as the labeling indicates. Data on add input path **26** or **28** is added to the value stored in an accumulator **33** or **34** respectively responsive to a strobe signal on path **22**. Similarly, the data on subtract path **27** or **29** is subtracted from the value in the respective accumulator **33** or **34** responsive to a strobe signal on path **22**. It can thus be seen that individual digital values comprising the digital flame signal on path **21** are gated to one of the four output paths **26–29** of multiplexer **24** according to the value contained in two bit counter **56**, and each is then added to or subtracted from the respective accumulator contents. The start signal on path **30** clears the accumulators **33** and **34** prior to forming these two series. It can be seen that as two bit counter **56** continuously increments from 0 through 3, resets back to 0 and counts up again through **3**, each digital value from A/D converter **20** which is presented on path **21** when the two bit counter **56** is 0 is provided on path **26** to accumulator A **33** to be added to its contents. When the contents of two bit counter **56** equals 1 the digital value on path **21** is provided to accumulator B **34** to be added to its contents. When the contents of two bit counter **56** equals 2 then the digital value on path **21** is provided on path **28** to be subtracted from the contents of accumulator A **33**. And lastly when the contents of two bit counter **56** eequals 3 then the digital value on path **21** is gated to path **29** or subtraction from the contents of accumulator B **34**.

This sequence of cycling incrementally through two bit counter **56** occurs precisely eight times at which time five bit counter **57** crosses from a decimal value of 31 to 0 and a carry is provided on the bit four carry output of counter **57**. In this way exactly 32 sequential digital values are made available to compute the A and B summation series. The bit four carry signal is used to set one shot **60** which provides an enable signal on path **61** to a first arithmetic element **40** which receives the series summations in the A accumulator **33** and the B accumulator **34** on path A **37** and path B **38** respectively. Arithmetic module **40** computes the value $(A^2+B^2)^{\frac{1}{2}}$ and provides a digital representation D of this value encoded in a signal on path **42**. It is possible to employ an approximation for computing the value of D, and one possible formula for an acceptable approximation is explained in connection with the software implementation of FIGS. 3A and 3B. Thus, it may be said that if D is calculated by such an approximation, it is at least approximately equal to the precise value of D, and such precision is typically acceptable.

The value D is the actual DFT value for the flame signal on path **17** at 15 hz. To determine whether the 15 hz. frequency amplitude component in the flame signal on path **17** is sufficiently strong to indicate the presence of a flame, the value D is tested to be greater than a constant value Z provided on path **41**, and this test is performed by a digital comparator shown as test element **45**. As with the accumulators **33** and **34**, this test element will usually comprise circuitry within a microprocessor. If the inequality is true then a flame sense signal is provided on path **47**. This flame sense signal may be used for example as a precondition for opening the main valve of a burner, since this inequality assures that a pilot flame is present. The value Z should normally be equal to approximately four to five times the peak voltage of the filtered flame signal applied to the input of the A/D converter **20**, taking into account any scale factor which the A/D converter uses in determining the individual digital values indicative of the instantaneous flame signal voltage.

While FIG. **1** is a block diagram of a dedicated discrete component system for performing the operations of this invention, FIG. **2** shows a system having identical functions but implemented with a microprocessor **62** which performs all of the functions shown in FIG. **1** except for the square wave generation and initial signal acquisition and filtering. Such a microprocessor is currently available on the market with input channels such as shown connected to input paths **21** and **22** and a memory **62*a*** in Which instructions for accomplishing the computations of a DFT may be stored. Such a microprocessor **62** also includes computational and arithmetic capabilities in circuitry **62*b***, data storage in registers **62*c*** which typically comprise a random access memory, and overall control and decision making capabilities in the circuitry shown generally as **62*d***. In particular, the instructions stored in memory **62*a*** are selected so as to cause microprocessor **62** to function as the individual elements shown in FIG. **1** as directed by the instructions in memory **62*a***.

FIGS. 3A and 3B together form a flow chart of instructions which will direct microprocessor **62** to function as the individual elements shown in FIG. **1**. In FIGS. 3A and 3B, rectangular boxes are activity elements which denote instructions performing arithmetic and data transfer operations. Diamond-shaped boxes denote decision making elements. Within individual activity elements, a horizontal arrow denotes transfer of data identified o the left side of the arrow to the location specified on the right side of the arrow. Parentheses conventionally indicate the numeric or logical contents or value of whatever register or element is contained within the parentheses. It should be understood that microprocessor **62** will typically have many other functions to perform besides those related to this invention. In particular, there will typically be a control or executive software module which directs individual operating modules of the software to execute their functions as appropriate. Typically, some signal will be provided within microprocessor **62** which will eventually culminate in what is shown in FIG. **1** as the start signal encoded in the signal on path **30**.

It is desirable to test for flame at many times during a complete burner operating sequence, and each of these individual test times will typically be selected by microprocessor **6** operations. Each time that such a test time occurs, a short preset routine comprising instructions forming activity element **64** are executed. These presetting instructions clear five bit counter which may be a register forming one of the registers **62***c*, and also clear the A and B accumulators which will typically comprise two other registers of the registers **62***c*. The internal signals of microprocessor **62** which initiate this presetting operation correspond to the start signal carried on path **30** of the circuit of FIG. **1**.

The 60 hz. square wave signal is applied to an input **22** of microprocessor **62** which causes an internal interrupt within microprocessor **62** transferring execution of instructions to the A connector element **69** shown in FIG. **3**A, meaning that instructions commencing with decision element **70** and those following will be executed. The execution of instructions by microprocessor **62** is so fast compared with the 60 hz. sampling rate of A/D converter **20** that in every case the entire calculation plus whatever other functions which it may be necessary for microprocessor **62** to perform, have occurred before the next interrupt to connector element **69** occurs. The internal interrupt signal is simply one form of the enable sample signal on path **22** of FIG. **1**. As shown in FIGS. **1** and **2**, the signal on path **22** is also provided to an A/D converter **20** which provides a digital flame signal on path **21** to an input channel of microprocessor **62**.

The flow chart elements starting with connector **69** perform the actual update on a digital value to a digital value basis for computing the A and B summation series discussed earlier. After the last of the **32** values for a single DFT computation has been received and processed, the actual DFT value D is computed and compared with the constant shown on path **41** in FIG. **1**, to determine presence of a flame. In this embodiment, it is likely that this constant is internally stored by microprocessor **62**. Decision elements **70**–**72** and activity elements **75**–**78** compute the actual values of the A and B summation series. It is convenient to use the two least significant bits (LSB) of the five bit counter which counts the total number of digital data values provided by the A/D converter **20** to determine the position in the ordinal designation of each digital value and hence what series and what sign is required when the value is summed with the accumulator A or B value.

As indicated by decision element **70**, if the two least significant bits (LSB) of the five bit counter equal 00 (binary) then execution passes to the instructions represented by activity element **75**. These instructions read up the input from A/D converter **20** currently available on the associated input channel and read up the contents of the register functioning as accumulator A, add these two values together and store the value back into the register functioning as accumulator A.

If the two least significant bits of the five bit counter equal 01 binary, then the instructions of decision element **71** cause the instructions of activity element **76** to be executed. These instructions represented by element **76** take the input from the A/D converter **20**, add that digital value to the contents of the register functioning as accumulator B, and stores this sum back into accumulator B.

If the two least significant bits of the five bit counter are unequal to 01, then execution of instructions instead passe to the instructions represented by decision element **72**. If the instructions of decision element **72** find the two least significant bits of the five bit digital value counter to be equal to 10 (binary), then execution passes to the instructions represented by activity element **77**. Instructions of this element **77** cause the contents of the register serving as accumulator A to be read up, and then the input from the A/D converter **20** to be read up and subtracted from the contents of accumulator A. This difference is then stored back into accumulator A.

If the two least significant bits of the five bit counter are unequal to 00, 01, and 10 as sensed by the instructions of decision elements **70**–**72**, then control is transferred to the instructions comprising activity element **78** as symbolized by the B connector **80**. The instructions of element **78** cause the contents of the register functioning as accumulator B to be read up and from this value the input from the A/D converter **20** is subtracted. This difference value is then stored back into the register serving as accumulator B. It can be seen that the instructions symbolized by the activity and decision elements discussed above for computing the values in accumulators A and B in essence cause the microprocessor **62** to momentarily comprise multiplexer **24** and the A and B accumulators **33** and **34** of FIG. **1**.

After one of the instruction groups for elements **75**, **76**, **77**, or **78** have been executed during a pass through the program and the digital flame signal value has been added to or subtracted from the appropriate accumulator, control then passes to C element connector **81** and the instructions symbolized by activity element **82**. The instructions of this element **82** simply increment the contents of the five bit counter by **1** and store that value back into the five bit counter. Then the contents of the five bit counter are tested, and if equal to 0 this implies that the contents of the counter has advanced to 32 (decimal) on the previous pass through this sequence of instructions because this last increment by the instructions of element **82** changed the value from 31 to 0. If the counter value is unequal to 0 then control is returned to the executive portion of the software module for further processing of other functions of the burner control system. If however, the five bit counter is equal to 0 then the A and B summation series of equations 1 and 2 has been computed, and the value $D=(A^2+B^2)^{\frac{1}{2}}$ can be computed.

Because the small microprocessors likely to be used in these applications typically perform multiplications and extract square roots very slowly, it is frequently preferable to use an approximation so as to save instruction execution time for other functions. An appropriate approximation here is given by $(A^2+B^w)^{\frac{1}{2}} \sim A + B/4$, where A>B. The division by 4 can be accomplished easily with a right shift of the value of B two binary places. This approximation is accurate to within 5% for the values which will typically occur for A and B, and 5% is more than adequate accuracy. Of course, the reader understands that where B>A, that B +A/4 must be calculated.

To implement this approximation algorithm, the instructions represented by decision element **84** compares the magnitude A of the contents of accumulator A with the magnitude B of the contents of the register containing accumulator B, and if A>B, then the instructions represented by activity element **85** are executed. These instructions cause the contents of accumulator B to be right shifted two places, which is the same as a divide by **4** without rounding, and then store this right shifted value back into the register functioning as accumulator B. If B>A, then the result of activity element **87** is that value A is divided by 4 by a right shift of two and this result stored back into the register functioning a accumulator A. Then regardless of whether the instructions of activity elements **85** or **87** were executed, instruction execution proceeds with those represented by decision element **90**. The sum of the contents of the registers functioning as accumulators A and B are compared with a constant value and if the sum is greater than the constant value then the instructions represented by activity element **92** are executed. These instructions set a flame sense flag equal to 1, which symbolizes that flame has been detected. The flame sense flag value may be made available externally on path **47** if desired, or may be used as the criteria for further operations in a burner operation sequence If the sum of the contents of the registers functioning as accumulators A and B is equal to or less than the constant value, then the flame sense flag is cleared by the instructions which activity element **91** represents. In either case, then operation returns to the executive portion of the program for further operation in the burner control sequence.

The preceding describes my invention.

What I wish to claim by letters patent is:

**1.** A flame sensing system for providing a flame sense signal responsive to receiving a flame signal from a photocell receiving radiative energy from a flame having in its energy output intensity a flicker whose frequency is within a predetermined frequency range, said flame signal instantaneously representative of the intensity of the energy emanating from the flame, the system comprising

a) a low pass filter receiving the flame signal and providing a filtered flame signal from which a substantial percentage of the amplitude of frequencies above the predetermined frequency range has been removed;

b) a clock circuit providing a clock signal having individual pulses at four times the frequency of the midpoint of the predetermined frequency range;

c) an analog to digital converter receiving the filtered flame signal and the clock signal, sampling he filtered flame signal responsive to each clock signal pulse, and providing a digital flame signal having a plurality of successive discrete, ordinary designated, digital values each encoding the amplitude of the filtered flame signal at successive sampling instants;

d) a fist accumulator register receiving the digital flame signal and forming from the plurality of digital values in the flame signal, the sum of the difference of successive pairs of digital values having even oridinal designations, and providing after a sampling instant a first intermediate digital transform signal ascending he current contents o the fist accumulator register;

e) a second accumulator register receiving the digital flame signal and forming from the plurality of digital values in the flame signal, the sum of he difference of successive pairs of digital values having odd ordinal designations, and providing after a sampling instant a second intermediate digital transform signal encoding the current contents of the second accumulator register;

f) a calculator means receiving the first ad second intermediate digital transform signals, and providing a transform signal at lest approximately equal o the square root of the sum of the squares of the digital value encoded in each of the fist and second intermediate digital transform signals; and

g) a comparator means receiving he transom signal for comparing the digital value encoded in the transform signal with a predetermined transform constant value, and if generator than the transform constant value, issuing a flame sense signal signifying presence of flame.

**2.** The sensing system of claim **1** adapted for detecting a flame having a flicker frequency range of approximately 13 to 17 hz., where the clock circuit has a pluse rate of 60 hz. and wherein the low pass filter has a cutoff frequency of approximately 20 hz.

**3.** The sensing system of claim **1** wherein the clock circuit comprises a signal generator receiving a 60 hz. AC signal input and providing a 60 hz. square wave logic level signal whose frequency is that of the AC signal input.

**4.** The sensor of claim **1** wherein the calculator means comprises means for comparing the digital value encoded in the first intermediate digital transform signal with that encoded in the second intermediate digital transform signal, selecting the larger of the two intermediate digital transform signals, and forming the sum of the larger of the digital values encoded in the intermediate digital transform signals and one fourth of the smaller of the digital values encoded in the intermediate digital transform signals, and encoding this value in the transform signal.

**5.** A flame sensing system for providing a flame sense signal responsive to receiving a flame signal from a photocell receiving radiative energy from a flame having a flicker in its energy intensity whose frequency is within a predetermined frequency range, said flame signal instantaneously representative of the intensity of the energy emanating from the flame, the system comprising

a) a low pass filter receiving the flame signal and providing a filtered flame signal from which a substantial percentage of the amplitude of frequencies above the predetermined frequency range has been removed;

b) a clock circuit providing a clock signal having individual pulses at four times the frequency of the midpoint of the predetermined frequency range;

c) an analog to digital converter receiving the filtered flame signal and the clock signal, sampling the filtered flame signal responsive to each clock signal pulse, and providing a digital flame signal having a plurality of successive discrete, ordinally designated, digital values each encoding the amplitude of the filtered flame signal at successive sampling instants; and

d) a microprocessor for executing instructions and including data registers, an instruction memory containing a plurality of instructions, and a digital input channel, said microprocessor instruction memory including instructions for causing the microprocessor to function as:

i) a first accumulator register receiving through the input channel the digital flame signal from the analog to digital converter and forming from the plurality of digital values in the flame signal, the sum of the difference of successive pairs o f digital values having even ordinal designations, and providing at the end of each sampling interval a first intermediate digital transform signal encoding the current contents of the first accumulator register;

ii) a second accumulator register receiving through the input channel the digital flame signal from the analog to digital converter and forming from the plurality of digital values in the flame signal, the sum of the difference of successive pairs of digital values having odd ordinal designations, and providing at the end of each sampling interval a second intermediate digital transform signal encoding the current contents of the second accumulator register;

iii) a calculator means receiving the first and second intermediate digital transform signals and providing a transform signal approximating the square root of sum of the squares of the digital values encoded in each of the first and second intermediate digital transform signals; and

iv) a comparator means receiving the transform signal for comparing the digital value encoded in the transform signal with a predetermined transform constant value, and if greater than the transform constant value, issuing a flame sense signal signifying presence of flame.

**6**. The flame sensing system of claim **5** adapted for detecting a flame having a flicker frequency range of approximately 13 to 17 hz., where the clock circuit has a pulse rate of 60 hz. and wherein the low pass filter has a cutoff frequency of approximately 20 hz.

**7**. The sensor of claim **5** wherein the calculator means comprises means for comparing the digital value encoded in the first intermediate digital transform signal with that encoded in the second intermediate digital transform signal, selecting the larger of the two intermediate digital transform signals, and forming the sum of the larger of the digital values encoded in the intermediate digital transform signals and one fourth of the smaller of the digital values encoded in the intermediate digital transform signals, and encoding this value in the transform signal.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 5,073,769

DATED : December 17, 1991

INVENTOR(S) : Arlon D. Kompelien

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 9, line 59, cancel "he" and substitute --the--.
Column 9, line 62, cancel "ordinary" and substitute --ordinally--.
Column 10, line 2, cancel "oridinal" and substitute --ordinal--.
Column 10, line 4, cancel "ascending he" and substitute --encoding the--
Column 10, line 8, cancel "he" and substitute --the--.
Column 10, line 14, cancel "ad" and substitute --and--.
Column 10, line 16, cancel "o" and substitute --to--.
Column 10, line 18, cancel "fist" and substitute --first--.
Column 10, line 20, cancel "he transom" and substitute --the transform--.
Column 10, line 23, cancel "generator" and substitute --greater--.

**Signed and Sealed this**

**Thirtieth Day of March, 1993**

*Attest:*

STEPHEN G. KUNIN

*Attesting Officer*

*Acting Commissioner of Patents and Trademarks*

# Reference 5

Reference 5

**IEEE Std 315-1975 (Reaffirmed 1993)**
**ANSI Y32.2-1975 (Reaffirmed 1989)**
**CSA Z99-1975**
(Revision of IEEE Std 315-1971
ANSI Y32.1-1972
CSA Z99-1972)

## IEEE Standard
## American National Standard
## Canadian Standard

# Graphic Symbols for Electrical and Electronics Diagrams

## (Including Reference Designation Letters)

Sponsor
**IEEE Standards Coordinating Committee 11, Graphic Symbols**

Secretariat for American National Standards Committee Y32

**American Society of Mechanical Engineers**
**Institute of Electrical and Electronics Engineers**

Approved September 4, 1975
Reaffirmed October 20, 1988
Reaffirmed December 2, 1993
**IEEE Standards Board**

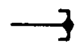
Approved October 31, 1975
Reaffirmed January 16, 1989
**American National Standards Institute**

Approved October 9, 1975
**Canadian Standards Association**

Approved Adopted for Mandatory Use October 31, 1975
**Department of Defense, United States of America**

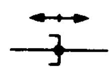
**3.8.2** Short circuit (short). Not a fault.

NOTE — 3.8.2A: Use of the dot is optional.

IEC 

See Note 3.8.2A

**3.8.3** Application: movable short circuit



See Note 3.8.2A

## 3.9 Circuit Return

**3.9.1** Ground, general symbol

NOTE — 3.9.1A: Supplementary information may be added to define the status or purpose of the earth if this is not readily apparent.

1) A direct conducting connection to the earth or body of water that is a part thereof.
2) A conducting connection to a structure that serves a function similar to that of an earth ground (that is, a structure such as a frame of an air, space, or land vehicle that is not conductively connected to earth).

IEC 

**3.9.1.1** Low-noise ground (IEC) noiseless, clean earth)

IEC 

**3.9.1.2** Safety or protective ground

NOTE — 3.9.1.2A: This symbol may be used in place of symbol 3.9.1 to indicate a ground connection having a specified protective function (e.g., for protection against electrical shock in case of a fault).

IEC 

**3.9.2** Chassis or frame connection; equivalent chassis connection (of printed-wiring boards)

A conducting connection to a chassis or frame, or equivalent chassis connection of a printed-wiring board. The chassis or frame (or equivalent chassis connection of a printed-wiring board) may be at substantial potential with respect to the earth or structure in which this chassis or frame (or printed-wiring board) is mounted.

# Reference 6

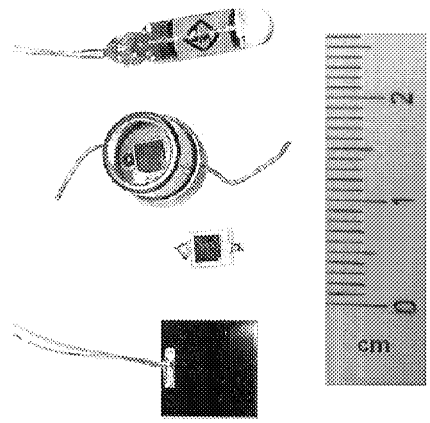
Reference 6

# Photodiode

From Wikipedia, the free encyclopedia

A **photodiode** is a semiconductor device that converts light into current. The current is generated when photons are absorbed in the photodiode. A small amount of current is also produced when no light is present. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. Photodiodes usually have a slower response time as their surface area increases. The common, traditional solar cell used to generate electric solar power is a large area photodiode.

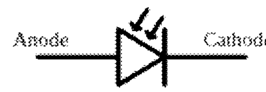
**Photodiode**




Three Si and one Ge (top) photodiodes.

| | |
|---|---|
| **Type** | Passive |
| **Working principle** | Converts light into current |
| **Pin configuration** | anode and cathode |

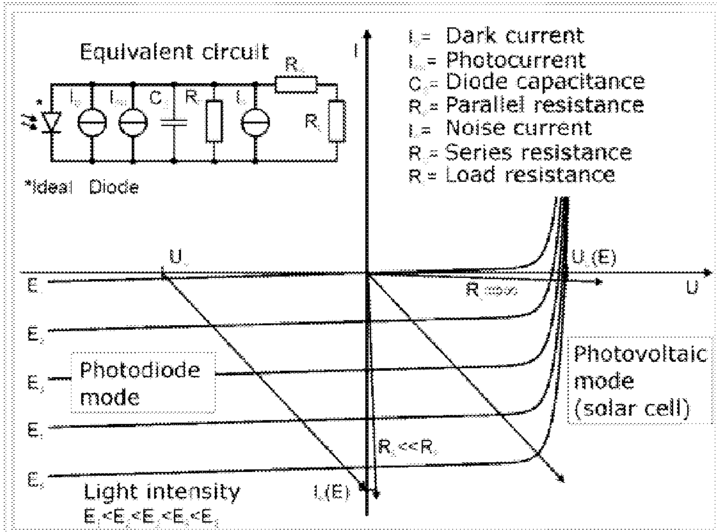
**Electronic symbol**




Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p–n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.[1]

## Contents






I-V characteristic of a photodiode. The linear load lines represent the response of the external circuit: I=(Applied bias voltage-Diode voltage)/Total resistance. The points of intersection with the curves represent the actual current and voltage for a given bias, resistance and illumination.

## Principle of operation

A photodiode is a p–n junction or PIN structure. When a photon of sufficient energy strikes the diode, it creates an electron-hole pair. This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device.[2]

### Photovoltaic mode

When used in zero bias or ***photovoltaic mode***, the flow of photocurrent out of the device is restricted and a voltage builds up. This mode exploits the photovoltaic effect, which is the basis for solar cells – a traditional solar cell is just a large area photodiode.

### Photoconductive mode

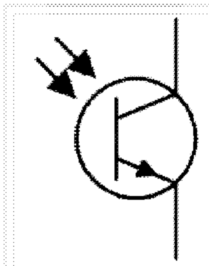
In this mode the diode is often reverse biased (with the cathode driven positive with respect to the anode). This reduces the response time because the additional reverse bias increases the width of the depletion layer, which decreases the junction's capacitance. The reverse bias also increases the dark current without much change in the photocurrent. For a given spectral distribution, the photocurrent is linearly proportional to the illuminance (and to the irradiance).[3]

Although this mode is faster, the photoconductive mode tends to exhibit more electronic noise.[4] The leakage current of a good PIN diode is so low (<1 nA) that the Johnson–Nyquist noise of the load resistance in a typical circuit often dominates.

### Other modes of operation

**Avalanche photodiodes** are photodiodes with structure optimized for operating with high reverse bias, approaching the reverse breakdown voltage. This allows each *photo-generated* carrier to be multiplied by avalanche breakdown, resulting in internal gain within the photodiode, which increases the effective *responsivity* of the device.

A **phototransistor** is a light-sensitive transistor. A common type of phototransistor, called a photobipolar transistor, is in essence a bipolar transistor encased in a transparent case so that light can reach the *base–collector junction*. It was invented by Dr. John N. Shive (more famous for his wave machine) at Bell Labs in 1948,[5]:205 but it was not announced until 1950.[6] The electrons that are generated by photons in the base–collector junction are injected into the base, and this photodiode current is amplified by the transistor's current gain $\beta$ (or $h_{fc}$). If the base and collector leads are used and the emitter is left unconnected, the phototransistor becomes a photodiode. While phototransistors have a higher responsivity for light they are not able to detect low levels of light any better than photodiodes. Phototransistors also have significantly longer response times. Field-effect phototransistors, also known as photoFETs, are light-sensitive field-effect transistors. Unlike photobipolar transistors, photoFETs control drain-source current by creating a gate voltage.


Electronic symbol for a phototransistor

## Materials

The material used to make a photodiode is critical to defining its properties, because only photons with sufficient energy to excite electrons across the material's bandgap will produce significant photocurrents.

Materials commonly used to produce photodiodes include:[7]

| Material | Electromagnetic spectrum wavelength range (nm) |
|---|---|
| Silicon | 190–1100 |
| Germanium | 400–1700 |
| Indium gallium arsenide | 800–2600 |
| Lead(II) sulfide | <1000–3500 |
| Mercury cadmium telluride | 400–14000 |

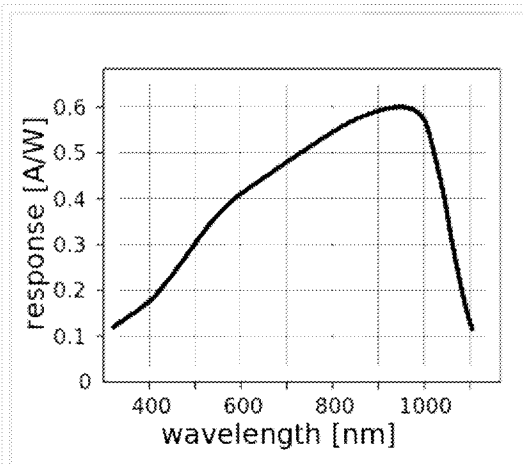
Because of their greater bandgap, silicon-based photodiodes generate less noise than germanium-based photodiodes.

### Unwanted photodiode effects

Any p–n junction, if illuminated, is potentially a photodiode. Semiconductor devices such as transistors and ICs contain p–n junctions, and will not function correctly if they are illuminated by unwanted electromagnetic radiation (light) of wavelength suitable to produce a photocurrent;[8][9] this is avoided by encapsulating devices in opaque housings. If these housings are not completely opaque to high-energy radiation (ultraviolet, X-rays, gamma rays), transistors and ICs can malfunction[10] due to induced photo-currents. Background radiation from the packaging is also significant.[11] Radiation hardening mitigates these effects.

# Features

Critical performance parameters of a photodiode include:



Response of a silicon photo diode vs wavelength of the incident light

**Responsivity**
: The Spectral responsivity is a ratio of the generated photocurrent to incident light power, expressed in A/W when used in photoconductive mode. The wavelength-dependence may also be expressed as a *Quantum efficiency*, or the ratio of the number of photogenerated carriers to incident photons, a unitless quantity.

**Dark current**
: The current through the photodiode in the absence of light, when it is operated in photoconductive mode. The dark current includes photocurrent generated by background radiation and the saturation current of the semiconductor junction. Dark current must be accounted for by calibration if a photodiode is used to make an accurate optical power measurement, and it is also a source of noise when a photodiode is used in an optical communication system.

**Response time**
: A photon absorbed by the semiconducting material will generate an electron-hole pair which will in turn

start moving in the material under the effect of the electric field and thus generate a current. The finite duration of this current is known as the transit-time spread and can be evaluated by using Ramo's theorem. One can also show with this theorem that the total charge generated in the external circuit is well e and not 2e as might seem by the presence of the two carriers. Indeed, the integral of the current due to both electron and hole over time must be equal to e. The resistance and capacitance of the photodiode and the external circuitry give rise to another response time known as RC time constant $\tau = RC$. This combination of R and C integrates the photoresponse over time and thus lengthens the impulse response of the photodiode. When used in an optical communication system, the response time determines the bandwidth available for signal modulation and thus data transmission.

**Noise-equivalent power**

(NEP) The minimum input optical power to generate photocurrent, equal to the rms noise current in a 1 hertz bandwidth. NEP is essentially the minimum detectable power. The related characteristic detectivity ($D$) is the inverse of NEP, 1/NEP. There is also the specific detectivity ($D^\star$) which is the detectivity multiplied by the square root of the area ($A$) of the photodetector, ($D^\star = D\sqrt{A}$) for a 1 Hz bandwidth. The specific detectivity allows different systems to be compared independent of sensor area and system bandwidth; a higher detectivity value indicates a low-noise device or system.[12] Although it is traditional to give ($D^\star$) in many catalogues as a measure of the diode's quality, in practice, it is hardly ever the key parameter.

When a photodiode is used in an optical communication system, all these parameters contribute to the *sensitivity* of the optical receiver, which is the minimum input power required for the receiver to achieve a specified *bit error rate*.

# Applications

P–n photodiodes are used in similar applications to other photodetectors, such as photoconductors, charge-coupled devices, and photomultiplier tubes. They may be used to generate an output which is dependent upon the illumination (analog; for measurement and the like), or to change the state of circuitry (digital; either for control and switching, or digital signal processing).

Photodiodes are used in consumer electronics devices such as compact disc players, smoke detectors, and the receivers for infrared remote control devices used to control equipment from televisions to air conditioners. For many applications either photodiodes or photoconductors may be used. Either type of photosensor may be used for light measurement, as in camera light meters, or to respond to light levels, as in switching on street lighting after dark.

Photosensors of all types may be used to respond to incident light, or to a source of light which is part of the same circuit or system. A photodiode is often combined into a single component with an emitter of light, usually a light-emitting diode (LED), either to detect the presence of a mechanical obstruction to the beam (slotted optical switch), or to couple two digital or analog circuits while maintaining extremely high electrical isolation between them, often for safety (optocoupler). The combination of LED and photodiode is also used in many sensor systems to characterize different types of products based on their optical absorbance.

Photodiodes are often used for accurate measurement of light intensity in science and industry. They generally have a more linear response than photoconductors.

They are also widely used in various medical applications, such as detectors for computed tomography (coupled with scintillators), instruments to analyze samples (immunoassay), and pulse oximeters.

PIN diodes are much faster and more sensitive than p–n junction diodes, and hence are often used for optical communications and in lighting regulation.

P–n photodiodes are not used to measure extremely low light intensities. Instead, if high sensitivity is needed, avalanche photodiodes, intensified charge-coupled devices or photomultiplier tubes are used for applications such as astronomy, spectroscopy, night vision equipment and laser rangefinding.

Pinned photodiode is not a PIN photodiode, it has p+/n/p regions in it. It has a shallow P+ implant in N type diffusion layer over a P-type epitaxial substrate layer. It is used in CMOS Active pixel sensor.[13]

### Comparison with photomultipliers

Advantages compared to photomultipliers:[14]

1. Excellent linearity of output current as a function of incident light
2. Spectral response from 190 nm to 1100 nm (silicon), longer wavelengths with other semiconductor materials
3. Low noise
4. Ruggedized to mechanical stress
5. Low cost
6. Compact and light weight
7. Long lifetime
8. High quantum efficiency, typically 60–80% [15]
9. No high voltage required

Disadvantages compared to photomultipliers:

1. Small area
2. No internal gain (except avalanche photodiodes, but their gain is typically $10^2$–$10^3$ compared to $10^5$-$10^8$ for the photomultiplier)
3. Much lower overall sensitivity
4. Photon counting only possible with specially designed, usually cooled photodiodes, with special electronic circuits
5. Response time for many designs is slower
6. latent effect

## Photodiode array

A one-dimensional array of hundreds or thousands of photodiodes can be used as a position sensor, for example as part of an angle sensor.[16] One advantage of photodiode arrays (PDAs) is that they allow for high speed parallel read out since the driving electronics may not be built in like a traditional CMOS or CCD sensor.

## See also

- Electronics
- Band gap
- Infrared
- Optoelectronics
- Optical interconnect
- Light Peak
- Interconnect bottleneck
- Optical fiber cable
- Optical communication
- Parallel optical interface
- Opto-isolator
- Semiconductor device
- Solar cell
- Avalanche photodiode
- Transducer

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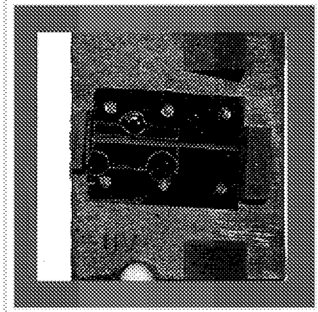
- LEDs as Photodiode Light Sensors
- Light meter
- Image sensor
- Transimpedance amplifier


A 2 x 2 cm photodiode array chip with more than 200 diodes

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This article incorporates public domain material from the General Services Administration document "Federal Standard 1037C" (http://www.its.bldrdoc.gov/fs-1037/fs-1037c.htm).


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2. Tavernier, Filip and Steyaert, Michiel (2011) *High-Speed Optical Receivers with Integrated Photodiode in Nanoscale CMOS*. Springer. ISBN 1-4419-9924-8. Chapter 3 *From Light to Electric Current – The Photodiode*
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14. Photodiode Technical Guide (http://sales.hamamatsu.com/assets/html/ssd/si-photodiode/index.htm) on Hamamatsu website
15. Knoll, F.G. (2010). *Radiation detection and measurement*, 4th ed. Wiley, Hoboken, NJ. p. 298. ISBN 978-0-470-13148-0
16. Gao, Wei (2010). *Precision Nanometrology: Sensors and Measuring Systems for Nanomanufacturing*. Springer. pp. 15–16. ISBN 978-1-84996-253-7.


# External links

- Hamamatsu Application Note (http://www.hamamatsu.com/resources/pdf/ssd/e02_handbook_si_photodiode.pdf)
- Using the Photodiode to convert the PC to a Light Intensity Logger (http://www.emant.com/324003.page)
- Design Fundamentals for Phototransistor Circuits (http://www.fairchildsemi.com/an/AN/AN-3005.pdf)
- Working principles of photodiodes (http://ece-www.colorado.edu/~bart/book/book/chapter4/ch4_7.htm)

Wikimedia Commons has media related to ***Photodiodes***.

- Excelitas Application Notes on Pacer Website (http://www.pacer.co.uk/Assets/Pacer/User/Photodiodes.pdf)

# Reference 7

Reference 7

# Phase-locked loop

From Wikipedia, the free encyclopedia

A **phase-locked loop** or **phase lock loop (PLL)** is a control system that generates an output signal whose phase is related to the phase of an input signal. While there are several differing types, it is easy to initially visualize as an electronic circuit consisting of a variable frequency oscillator and a phase detector. The oscillator generates a periodic signal, and the phase detector compares the phase of that signal with the phase of the input periodic signal, adjusting the oscillator to keep the phases matched. Bringing the output signal back toward the input signal for comparison is called a feedback loop since the output is "fed back" toward the input forming a loop.

Keeping the input and output phase in lock step also implies keeping the input and output frequencies the same. Consequently, in addition to synchronizing signals, a phase-locked loop can track an input frequency, or it can generate a frequency that is a multiple of the input frequency. These properties are used for computer clock synchronization, demodulation, and frequency synthesis.

Phase-locked loops are widely employed in radio, telecommunications, computers and other electronic applications. They can be used to demodulate a signal, recover a signal from a noisy communication channel, generate a stable frequency at multiples of an input frequency (frequency synthesis), or distribute precisely timed clock pulses in digital logic circuits such as microprocessors. Since a single integrated circuit can provide a complete phase-locked-loop building block, the technique is widely used in modern electronic devices, with output frequencies from a fraction of a hertz up to many gigahertz.

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# Practical analogies

## Automobile race analogy

For a practical idea of what is going on, consider an auto race. There are many cars, and the driver of each of them wants to go around the track as fast as possible. Each lap corresponds to a complete cycle, and each car will complete dozens of laps per hour. The number of laps per hour (a speed) corresponds to an angular velocity (i.e. a frequency), but the number of laps (a distance) corresponds to a phase (and the conversion factor is the distance around the track loop).

During most of the race, each car is on its own and the driver of the car is trying to beat the driver of every other car on the course, and the phase of each car varies freely.

However, if there is an accident, a pace car comes out to set a safe speed. None of the race cars are permitted to pass the pace car (or the race cars in front of them), but each of the race cars wants to stay as close to the pace car as it can. While it is on the track, the pace car is a reference, and the race cars become phase-locked loops. Each driver will measure the phase difference (a distance in laps) between him and the pace car. If the driver is far away, he will increase his engine speed to close the gap. If he's too close to the pace car, he will slow down. The result is all the race cars lock on to the phase of the pace car. The cars travel around the track in a tight group that is a small fraction of a lap.

## Clock analogy

Phase can be proportional to time,[1] so a phase difference can be a time difference. Clocks are, with varying degrees of accuracy, phase-locked (time-locked) to a master clock.

Left on its own, each clock will mark time at slightly different rates. A wall clock, for example, might be fast by a few seconds per hour compared to the reference clock at NIST. Over time, that time difference would become substantial.

To keep the wall clock in sync with the reference clock, each week the owner compares the time on his wall clock to a more accurate clock (a phase comparison), and he resets his clock. Left alone, the wall clock will continue to diverge from the reference clock at the same few seconds per hour rate.

Some clocks have a timing adjustment (a fast-slow control). When the owner compared his wall clock's time to the reference time, he noticed that his clock was too fast. Consequently, he could turn the timing adjust a small amount to make the clock run a little slower (frequency). If things work out right, his clock will be more accurate than before. Over a series of weekly adjustments, the wall clock's notion of a second would agree with the reference time (locked both in frequency and phase within the wall clock's stability).

An early electromechanical version of a phase-locked loop was used in 1921 in the Shortt-Synchronome clock.

# History

Spontaneous synchronization of weakly coupled pendulum clocks was noted by the Dutch physicist Christiaan Huygens as early as 1673.[2] Around the turn of the 19th century, Lord Rayleigh observed synchronization of weakly coupled organ pipes and tuning forks.[3] In 1919, W. H. Eccles and J. H. Vincent found that two electronic oscillators that had been tuned to oscillate at slightly different frequencies but that were coupled to a resonant circuit would soon oscillate at the same frequency.[4] Automatic synchronization of electronic oscillators was described in 1923 by Edward Victor Appleton.[5]

Earliest research towards what was later named the phase-locked loop goes back to 1932, when British researchers developed an alternative to Edwin Armstrong's superheterodyne receiver, the Homodyne or direct-conversion receiver. In the homodyne or synchrodyne system, a local oscillator was tuned to the desired input frequency and multiplied with the input signal. The resulting output signal included the original modulation information. The intent was to develop an alternative receiver circuit that required fewer tuned circuits than the superheterodyne receiver. Since the local oscillator would rapidly drift in frequency, an automatic correction signal was applied to the oscillator, maintaining it in the same phase and frequency of the desired signal. The technique was described in 1932, in a paper by Henri de Bellescize, in the French journal *L'Onde Électrique*.[6][7][8]

In analog television receivers since at least the late 1930s, phase-locked-loop horizontal and vertical sweep circuits are locked to synchronization pulses in the broadcast signal.[9]

When Signetics introduced a line of monolithic integrated circuits like the NE565 that were complete phase-locked loop systems on a chip in 1969,[10] applications for the technique multiplied. A few years later RCA introduced the "CD4046" CMOS Micropower Phase-Locked Loop, which became a popular integrated circuit.

# Structure and function

Phase-locked loop mechanisms may be implemented as either analog or digital circuits. Both implementations use the same basic structure. Both analog and digital PLL circuits include four basic elements:

- Phase detector,
- Low-pass filter,
- Variable-frequency oscillator, and
- feedback path (which may include a frequency divider).

## Variations

There are several variations of PLLs. Some terms that are used are analog phase-locked loop (APLL) also referred to as a linear phase-locked loop (LPLL), digital phase-locked loop (DPLL), all digital phase-locked loop (ADPLL), and software phase-locked loop (SPLL).[11]

**Analog or linear PLL (APLL)**

Phase detector is an analog multiplier. Loop filter is active or passive. Uses a Voltage-controlled oscillator (VCO).

**Digital PLL (DPLL)**

An analog PLL with a digital phase detector (such as XOR, edge-trigger JK, phase frequency detector).

May have digital divider in the loop.

**All digital PLL (ADPLL)**
: Phase detector, filter and oscillator are digital. Uses a numerically controlled oscillator (NCO).

**Software PLL (SPLL)**
: Functional blocks are implemented by software rather than specialized hardware.

**Neuronal PLL (NPLL)**
: Phase detector, filter and oscillator are neurons or small neuronal pools. Uses a rate controlled oscillator (RCO). Used for tracking and decoding low frequency modulations (< 1 kHz), such as those occurring during mammalian-like active sensing.

### Performance parameters

- Type and order
- Hold-in range
- Pull-in range (capture range, acquisition range)
- Lock-in range
- Loop bandwidth: Defining the speed of the control loop.
- Transient response: Like overshoot and settling time to a certain accuracy (like 50ppm).
- Steady-state errors: Like remaining phase or timing error.
- Output spectrum purity: Like sidebands generated from a certain VCO tuning voltage ripple.
- Phase-noise: Defined by noise energy in a certain frequency band (like 10 kHz offset from carrier). Highly dependent on VCO phase-noise, PLL bandwidth, etc.
- General parameters: Such as power consumption, supply voltage range, output amplitude, etc.

# Applications

Phase-locked loops are widely used for synchronization purposes; in space communications for coherent demodulation and threshold extension, bit synchronization, and symbol synchronization. Phase-locked loops can also be used to demodulate frequency-modulated signals. In radio transmitters, a PLL is used to synthesize new frequencies which are a multiple of a reference frequency, with the same stability as the reference frequency.

Other applications include:

- Demodulation of both FM and AM signals
- Recovery of small signals that otherwise would be lost in noise (lock-in amplifier to track the reference frequency)
- Recovery of clock timing information from a data stream such as from a disk drive
- Clock multipliers in microprocessors that allow internal processor elements to run faster than external connections, while maintaining precise timing relationships
- DTMF decoders, modems, and other tone decoders, for remote control and telecommunications
- DSP of video signals; Phase-locked loops are also used to synchronize phase and frequency to the input analog video signal so it can be sampled and digitally processed
- Atomic force microscopy in tapping mode, to detect changes of the cantilever resonance frequency due to tip–surface interactions
- DC motor drive

### Clock recovery

Some data streams, especially high-speed serial data streams (such as the raw stream of data from the magnetic head of a disk drive), are sent without an accompanying clock. The receiver generates a clock from an approximate frequency reference, and then phase-aligns to the transitions in the data stream with a PLL. This process is referred to as clock recovery. In order for this scheme to work, the data stream must have a transition frequently enough to correct any drift in the PLL's oscillator. Typically, some sort of line code, such as 8b/10b encoding, is used to put a hard upper bound on the maximum time between transitions.

## Deskewing

If a clock is sent in parallel with data, that clock can be used to sample the data. Because the clock must be received and amplified before it can drive the flip-flops which sample the data, there will be a finite, and process-, temperature-, and voltage-dependent delay between the detected clock edge and the received data window. This delay limits the frequency at which data can be sent. One way of eliminating this delay is to include a deskew PLL on the receive side, so that the clock at each data flip-flop is phase-matched to the received clock. In that type of application, a special form of a PLL called a delay-locked loop (DLL) is frequently used.[12]

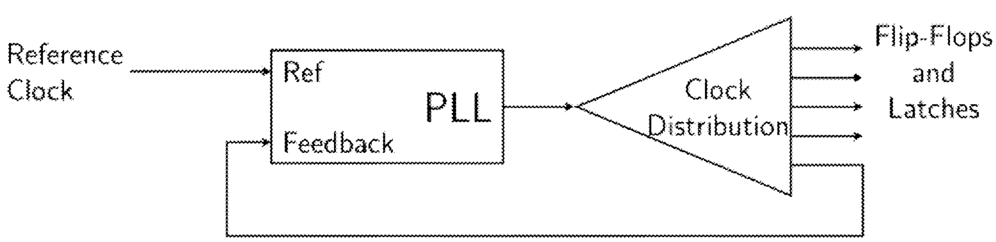
## Clock generation

Many electronic systems include processors of various sorts that operate at hundreds of megahertz. Typically, the clocks supplied to these processors come from clock generator PLLs, which multiply a lower-frequency reference clock (usually 50 or 100 MHz) up to the operating frequency of the processor. The multiplication factor can be quite large in cases where the operating frequency is multiple gigahertz and the reference crystal is just tens or hundreds of megahertz.

## Spread spectrum

All electronic systems emit some unwanted radio frequency energy. Various regulatory agencies (such as the FCC in the United States) put limits on the emitted energy and any interference caused by it. The emitted noise generally appears at sharp spectral peaks (usually at the operating frequency of the device, and a few harmonics). A system designer can use a spread-spectrum PLL to reduce interference with high-Q receivers by spreading the energy over a larger portion of the spectrum. For example, by changing the operating frequency up and down by a small amount (about 1%), a device running at hundreds of megahertz can spread its interference evenly over a few megahertz of spectrum, which drastically reduces the amount of noise seen on broadcast FM radio channels, which have a bandwidth of several tens of kilohertz.

## Clock distribution




Typically, the reference clock enters the chip and drives a phase locked loop (**PLL**), which then drives the system's clock distribution. The clock distribution is usually balanced so that the clock arrives at every endpoint simultaneously. One of those endpoints is the PLL's feedback input. The function of the PLL is to compare the distributed clock to the incoming reference clock, and vary the phase and frequency of its output until the reference and feedback clocks are phase and frequency matched.

**References - 53**

PLLs are ubiquitous—they tune clocks in systems several feet across, as well as clocks in small portions of individual chips. Sometimes the reference clock may not actually be a pure clock at all, but rather a data stream with enough transitions that the PLL is able to recover a regular clock from that stream. Sometimes the reference clock is the same frequency as the clock driven through the clock distribution, other times the distributed clock may be some rational multiple of the reference.

### Jitter and noise reduction

One desirable property of all PLLs is that the reference and feedback clock edges be brought into very close alignment. The average difference in time between the phases of the two signals when the PLL has achieved lock is called the **static phase offset** (also called the **steady-state phase error**). The variance between these phases is called **tracking jitter**. Ideally, the static phase offset should be zero, and the tracking jitter should be as low as possible.

Phase noise is another type of jitter observed in PLLs, and is caused by the oscillator itself and by elements used in the oscillator's frequency control circuit. Some technologies are known to perform better than others in this regard. The best digital PLLs are constructed with emitter-coupled logic (ECL) elements, at the expense of high power consumption. To keep phase noise low in PLL circuits, it is best to avoid saturating logic families such as transistor-transistor logic (TTL) or CMOS.

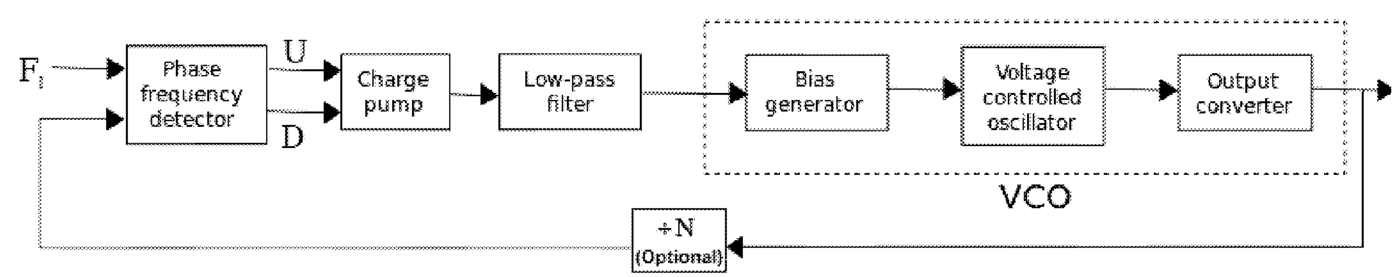
Another desirable property of all PLLs is that the phase and frequency of the generated clock be unaffected by rapid changes in the voltages of the power and ground supply lines, as well as the voltage of the substrate on which the PLL circuits are fabricated. This is called substrate and supply noise rejection. The higher the noise rejection, the better.

To further improve the phase noise of the output, an injection locked oscillator can be employed following the VCO in the PLL.

### Frequency synthesis

In digital wireless communication systems (GSM, CDMA etc.), PLLs are used to provide the local oscillator up-conversion during transmission and down-conversion during reception. In most cellular handsets this function has been largely integrated into a single integrated circuit to reduce the cost and size of the handset. However, due to the high performance required of base station terminals, the transmission and reception circuits are built with discrete components to achieve the levels of performance required. GSM local oscillator modules are typically built with a frequency synthesizer integrated circuit and discrete resonator VCOs.

## Block diagram




Block diagram of a phase-locked loop

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A phase detector compares two input signals and produces an error signal which is proportional to their phase difference. The error signal is then low-pass filtered and used to drive a VCO which creates an output phase. The output is fed through an optional divider back to the input of the system, producing a negative feedback loop. If the output phase drifts, the error signal will increase, driving the VCO phase in the opposite direction so as to reduce the error. Thus the output phase is locked to the phase at the other input. This input is called the reference.

Analog phase locked loops are generally built with an analog phase detector, low pass filter and VCO placed in a negative feedback configuration. A digital phase locked loop uses a digital phase detector; it may also have a divider in the feedback path or in the reference path, or both, in order to make the PLL's output signal frequency a rational multiple of the reference frequency. A non-integer multiple of the reference frequency can also be created by replacing the simple divide-by-*N* counter in the feedback path with a programmable pulse swallowing counter. This technique is usually referred to as a fractional-N synthesizer or fractional-N PLL.

The oscillator generates a periodic output signal. Assume that initially the oscillator is at nearly the same frequency as the reference signal. If the phase from the oscillator falls behind that of the reference, the phase detector changes the control voltage of the oscillator so that it speeds up. Likewise, if the phase creeps ahead of the reference, the phase detector changes the control voltage to slow down the oscillator. Since initially the oscillator may be far from the reference frequency, practical phase detectors may also respond to frequency differences, so as to increase the lock-in range of allowable inputs.

Depending on the application, either the output of the controlled oscillator, or the control signal to the oscillator, provides the useful output of the PLL system.

# Elements

## Phase detector

A phase detector (PD) generates a voltage, which represents the phase difference between two signals. In a PLL, the two inputs of the phase detector are the reference input and the feedback from the VCO. The PD output voltage is used to control the VCO such that the phase difference between the two inputs is held constant, making it a negative feedback system. There are several types of phase detectors in the two main categories of analog and digital.

Different types of phase detectors have different performance characteristics.

For instance, the frequency mixer produces harmonics that adds complexity in applications where spectral purity of the VCO signal is important. The resulting unwanted (spurious) sidebands, also called "reference spurs" can dominate the filter requirements and reduce the capture range well below and/or increase the lock time beyond the requirements. In these applications the more complex digital phase detectors are used which do not have as severe a reference spur component on their output. Also, when in lock, the steady-state phase difference at the inputs using this type of phase detector is near 90 degrees. The actual difference is determined by the DC loop gain.

A **bang-bang** charge pump phase detector must always have a **dead band** where the phases of inputs are close enough that the detector detects no phase error. For this reason, bang-bang phase detectors are associated with significant minimum peak-to-peak jitter, because of drift within the dead band. However these types, having outputs consisting of very narrow pulses at lock, are very useful for applications requiring very low VCO spurious outputs. The narrow pulses contain very little energy and are easy to filter out of the VCO control voltage. This results in low VCO control line ripple and therefore low FM sidebands on the VCO.

In PLL applications it is frequently required to know when the loop is out of lock. The more complex digital phase-frequency detectors usually have an output that allows a reliable indication of an out of lock condition.

## Filter

The block commonly called the PLL loop filter (usually a low pass filter) generally has two distinct functions.

The primary function is to determine loop dynamics, also called stability. This is how the loop responds to disturbances, such as changes in the reference frequency, changes of the feedback divider, or at startup. Common considerations are the range over which the loop can achieve lock (pull-in range, lock range or capture range), how fast the loop achieves lock (lock time, lock-up time or settling time) and damping behavior. Depending on the application, this may require one or more of the following: a simple proportion (gain or attenuation), an integral (low pass filter) and/or derivative (high pass filter). Loop parameters commonly examined for this are the loop's gain margin and phase margin. Common concepts in control theory including the PID controller are used to design this function.

The second common consideration is limiting the amount of reference frequency energy (ripple) appearing at the phase detector output that is then applied to the VCO control input. This frequency modulates the VCO and produces FM sidebands commonly called "reference spurs". The low pass characteristic of this block can be used to attenuate this energy, but at times a band reject "notch" may also be useful.

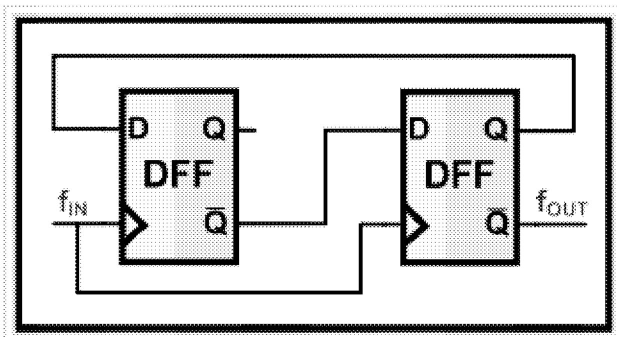
The design of this block can be dominated by either of these considerations, or can be a complex process juggling the interactions of the two. Typical trade-offs are: increasing the bandwidth usually degrades the stability or too much damping for better stability will reduce the speed and increase settling time. Often also the phase-noise is affected.

## Oscillator

All phase-locked loops employ an oscillator element with variable frequency capability. This can be an analog VCO either driven by analog circuitry in the case of an APLL or driven digitally through the use of a digital-to-analog converter as is the case for some DPLL designs. Pure digital oscillators such as a numerically controlled oscillator are used in ADPLLs.

## Feedback path and optional divider

PLLs may include a divider between the oscillator and the feedback input to the phase detector to produce a frequency synthesizer. A programmable divider is particularly useful in radio transmitter applications, since a large number of transmit frequencies can be produced from a single stable, accurate, but expensive, quartz crystal–controlled reference oscillator.




An example digital divider (by 4) for use in the feedback path of a multiplying PLL

Some PLLs also include a divider between the reference clock and the reference input to the phase detector. If the divider in the feedback path divides by $N$ and the reference input divider divides by $M$, it allows the PLL to multiply the reference frequency by $N/M$. It might seem simpler to just feed the PLL a lower frequency, but in some cases the reference frequency may be constrained by other issues, and then the reference divider is useful.

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Frequency multiplication can also be attained by locking the VCO output to the *N*th harmonic of the reference signal. Instead of a simple phase detector, the design uses a harmonic mixer (sampling mixer). The harmonic mixer turns the reference signal into an impulse train that is rich in harmonics.[13] The VCO output is coarse tuned to be close to one of those harmonics. Consequently, the desired harmonic mixer output (representing the difference between the *N* harmonic and the VCO output) falls within the loop filter passband.

It should also be noted that the feedback is not limited to a frequency divider. This element can be other elements such as a frequency multiplier, or a mixer. The multiplier will make the VCO output a sub-multiple (rather than a multiple) of the reference frequency. A mixer can translate the VCO frequency by a fixed offset. It may also be a combination of these. An example being a divider following a mixer; this allows the divider to operate at a much lower frequency than the VCO without a loss in loop gain.

# Modeling

## Time domain model

The equations governing a phase-locked loop with an analog multiplier as the phase detector and linear filter may be derived as follows. Let the input to the phase detector be $f_1(\theta_1(t))$ and the output of the VCO is $f_2(\theta_2(t))$ with phases $\theta_1(t)$ and $\theta_2(t)$. The functions $f_1(\theta)$ and $f_2(\theta)$ describe waveforms of signals. Then the output of the phase detector $\phi(t)$ is given by

$$\phi(t) = f_1(\theta_1(t)) f_2(\theta_2(t))$$

The VCO frequency is usually taken as a function of the VCO input $g(t)$ as

$$\dot{\theta}_2(t) = \omega_2(t) = \omega_{free} + g_v g(t)$$

where $g_v$ is the *sensitivity* of the VCO and is expressed in Hz / V; $\omega_{free}$ is a free-running frequency of VCO.

The loop filter can be described by a system of linear differential equations

$$\begin{array}{rcl} \dot{x} & = & Ax + b\phi(t), \\ g(t) & = & c^* x, \end{array} \quad x(0) = x_0,$$

where $\phi(t)$ is an input of the filter, $g(t)$ is an output of the filter, $A$ is $n$-by-$n$ matrix, $x \in \mathbb{C}^n, \quad b \in \mathbb{R}^n, \quad c \in \mathbb{C}^n, \quad . x_0 \in \mathbb{C}^n$ represents an initial state of the filter. The star symbol is a conjugate transpose.

Hence the following system describes PLL

$$\begin{array}{rcl} \dot{x} & = & Ax + b f_1(\theta_1(t)) f_2(\theta_2(t)), \\ \dot{\theta}_2 & = & \omega_{free} + g_v(c^* x) \end{array} \quad x(0) = x_0, \quad \theta_2(0) = \theta_0.$$

where $\theta_0$ is an initial phase shift.

## Phase domain model

Consider the input of PLL $f_1(\theta_1(t))$ and VCO output $f_2(\theta_2(t))$ are high frequency signals. Then for any

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piecewise differentiable $2\pi$-periodic functions $f_1(\theta)$ and $f_2(\theta)$ there is a function $\varphi(\theta)$ such that the output $G(t)$ of Filter

$$\begin{array}{rcl}\dot{x} & = & Ax + b\varphi(\theta_1(t) - \theta_2(t)), \\ G(t) & = & c^* x,\end{array} \quad x(0) = x_0,$$

in phase domain is asymptotically equal ( the difference $G(t) - g(t)$ is small with respect to the frequencies) to the output of the Filter in time domain model. [14] [15] Here function $\varphi(\theta)$ is a phase detector characteristic.

Denote by $\theta_\Delta(t)$ the phase difference

$$\theta_\Delta = \theta_1(t) - \theta_2(t).$$

Then the following dynamical system describes PLL behavior

$$\begin{array}{rcl}\dot{x} & = & Ax + b\varphi(\theta_\Delta), \\ \dot{\theta}_\Delta & = & \omega_\Delta - g_v(c^* x).\end{array} \quad x(0) = x_0, \quad \theta_\Delta(0) = \theta_1(0) - \theta_2(0).$$

Here $\omega_\Delta = \omega_1 - \omega_{free}$; $\omega_1$ is the frequency of a reference oscillator (we assume that $\omega_{free}$ is constant).

**Example**

Consider sinusoidal signals

$$f_1(\theta_1(t)) = A_1 \sin(\theta_1(t)), \quad f_2(\theta_2(t)) = A_2 \cos(\theta_2(t))$$

and a simple one-pole RC circuit as a filter. The time-domain model takes the form

$$\dot{x} = -\frac{1}{RC}x + \frac{1}{RC}A_1 A_2 \sin(\theta_1(t))\cos(\theta_2(t)),$$

$$\dot{\theta}_2 = \omega_{free} + g_v(c^* x)$$

PD characteristics for this signals is equal[16] to

$$\varphi(\theta_1 - \theta_2) = \frac{A_1 A_2}{2}\sin(\theta_1 - \theta_2)$$

Hence the phase domain model takes the form

$$\dot{x} = -\frac{1}{RC}x + \frac{1}{RC}\frac{A_1 A_2}{2}\sin(\theta_\Delta),$$

$$\dot{\theta}_\Delta = \omega_\Delta - g_v(c^* x).$$

This system of equations is equivalent to the equation of mathematical pendulum

$$x = \frac{\dot{\theta}_2 - \omega_2}{g_v c^*} = \frac{\omega_1 - \dot{\theta}_\Delta - \omega_2}{g_v c^*},$$

$$\dot{x} = \frac{\ddot{\theta}_2}{g_v c^*},$$

$$\theta_1 = \omega_1 t + \Psi,$$

$$\theta_\Delta = \theta_1 - \theta_2,$$

$$\dot{\theta}_\Delta = \dot{\theta}_1 - \dot{\theta}_2 = \omega_1 - \dot{\theta}_2,$$

$$\frac{1}{g_v c^*}\ddot{\theta}_\Delta - \frac{1}{g_v c^* RC}\dot{\theta}_\Delta - \frac{A_1 A_2}{2RC}\sin\theta_\Delta = \frac{\omega_2 - \omega_1}{g_v c^* RC}.$$

## Linearized phase domain model

Phase locked loops can also be analyzed as control systems by applying the Laplace transform. The loop response can be written as:

$$\frac{\theta_o}{\theta_i} = \frac{K_p K_v F(s)}{s + K_p K_v F(s)}$$

Where

- $\theta_o$ is the output phase in radians
- $\theta_i$ is the input phase in radians
- $K_p$ is the phase detector gain in volts per radian
- $K_v$ is the VCO gain in radians per volt-second
- $F(s)$ is the loop filter transfer function (dimensionless)

The loop characteristics can be controlled by inserting different types of loop filters. The simplest filter is a one-pole RC circuit. The loop transfer function in this case is:

$$F(s) = \frac{1}{1 + sRC}$$

The loop response becomes:

$$\frac{\theta_o}{\theta_i} = \frac{\frac{K_p K_v}{RC}}{s^2 + \frac{s}{RC} + \frac{K_p K_v}{RC}}$$

This is the form of a classic harmonic oscillator. The denominator can be related to that of a second order system:

$$s^2 + 2s\zeta\omega_n + \omega_n^2$$

Where

- $\zeta$ is the damping factor
- $\omega_n$ is the natural frequency of the loop

For the one-pole RC filter,

$$\omega_n = \sqrt{\frac{K_p K_v}{RC}}$$
$$\zeta = \frac{1}{2\sqrt{K_p K_v RC}}$$

The loop natural frequency is a measure of the response time of the loop, and the damping factor is a measure of the overshoot and ringing. Ideally, the natural frequency should be high and the damping factor should be near 0.707 (critical damping). With a single pole filter, it is not possible to control the loop frequency and damping factor independently. For the case of critical damping,

$$RC = \frac{1}{2K_p K_v}$$
$$\omega_c = K_p K_v \sqrt{2}$$

A slightly more effective filter, the lag-lead filter includes one pole and one zero. This can be realized with two resistors and one capacitor. The transfer function for this filter is

$$F(s) = \frac{1 + sCR_2}{1 + sC(R_1 + R_2)}$$

This filter has two time constants

$$\tau_1 = C(R_1 + R_2)$$
$$\tau_2 = CR_2$$

Substituting above yields the following natural frequency and damping factor

$$\omega_n = \sqrt{\frac{K_p K_v}{\tau_1}}$$
$$\zeta = \frac{1}{2\omega_n \tau_1} + \frac{\omega_n \tau_2}{2}$$

The loop filter components can be calculated independently for a given natural frequency and damping factor

$$\tau_1 = \frac{K_p K_v}{\omega_n^2}$$
$$\tau_2 = \frac{2\zeta}{\omega_n} - \frac{1}{K_p K_v}$$

Real world loop filter design can be much more complex e.g. using higher order filters to reduce various types or source of phase noise. (See the D Banerjee ref below)

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## Implementing a digital phase-locked loop in software

Digital phase locked loops can be implemented in hardware, using integrated circuits such as a CMOS 4046. However, with microcontrollers becoming faster, it may make sense to implement a phase locked loop in software for applications that do not require locking onto signals in the MHz range or faster, such as precisely controlling motor speeds. Software implementation has several advantages including easy customization of the feedback loop including changing the multiplication or division ratio between the signal being tracked and the output oscillator. Furthermore, a software implementation is useful to understand and experiment with. As an example of a phase-locked loop implemented using a phase frequency detector is presented in MATLAB, as this type of phase detector is robust and easy to implement. This example uses integer arithmetic rather than floating point, as such an example is likely more useful in practice.

```
% This example is written in MatLab

% Initialize variables
vcofreq = zeros(1, numiterations);
ervec = zeros(1, numiterations);
% keep track of last states of reference, signal, and error signal
qsig = 0; qref = 0; lref = 0; lsig = 0; lersig = 0;
phs = 0;
freq = 0;

% Loop filter constants (proportional and derivative)
% Currently powers of two to facilitate multiplication by shifts
prop = 1/128;
deriv = 64;

for it=1:numiterations
    % Simulate a local oscillator using a 16 bit counter
    phs = mod(phs + floor(freq/2^16), 2^16);
    ref = phs < 32768;
    % Get the next digital value (0 or 1) of the signal to track
    sig = tracksig(it);
    % Implement the phase-frequency detector
    rst = ~(qsig & qref);  % Reset the "flip flop" of the phase frequency
                           % detector when both signal and reference are high
    qsig = (qsig | (sig & ~lsig)) & rst;   % Trigger signal flip-flop and leading edge of signal
    qref = (qref | (ref & ~lref)) & rst;   % Trigger reference flip-flop on leading edge of reference
    lref = ref; lsig = sig; % Store these values for next iteration (for edge detection)
    ersig = qref   qsig;    % Compute the error signal (whether frequency should increase or decrease)
                            % Error signal is given by one or the other flip flop signal
    % Implement a pole-zero filter by proportional and derivative input to frequency
    filtered_ersig = ersig + (ersig - lersig) * deriv;
    % Keep error signal for proportional output
    lersig = ersig;
    % Integrate VCO frequency using the error signal
    freq = freq   2^16 * filtered_ersig * prop;
    % Frequency is tracked as a fixed-point binary fraction
    % Store the current VCO frequency
    vcofreq(1, it) = freq / 2^16;
    % Store the error signal to show whether signal or reference is higher frequency
    ervec(1, it) = ersig;
end
```

In this example, an array `tracksig` is assumed to contain a reference signal to be tracked. The oscillator is implemented by a counter, with the most significant bit of the counter indicating the on/off status of the oscillator. This code simulates the two D-type flip-flops that comprise a phase-frequency comparator. When either the reference or signal has a positive edge, the corresponding flip-flop switches high. Once both reference and signal is high, both flip-flops are reset. Which flip-flop is high determines at that instant whether the reference or signal leads the other. The error signal is the difference between these two flip-flop values. The pole-zero filter is implemented by adding the error signal and its derivative to the filtered error signal. This in turn is integrated to find the oscillator frequency.

**References - 61**

In practice, one would likely insert other operations into the feedback of this phase-locked loop. For example, if the phase locked loop were to implement a frequency multiplier, the oscillator signal could be divided in frequency before it is compared to the reference signal.

# See also

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- Costas loop
- Kalman filter
- Direct conversion receiver
- Circle map – a simple mathematical model of the phase-locked loop showing both mode-locking and chaotic behavior.
- Carrier recovery
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Categories: Oscillators | Communication circuits | Electronic design | Radio electronics

# Reference 8

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# *Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques*

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## ABSTRACT

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Statistical parameters of the phase-error behavior of a phase-locked loop tracking a constant frequency signal in the presence of additive, stationary, Gaussian noise are obtained by treating the problem as a continuous random walk with a sinusoidal restoring force. The Fokker-Planck or diffusion equation is obtained for a general loop. An exact expression for the steady-state phase-error distribution is available only for the first-order loop, but approximate and asymptotic expressions are derived for the second-order loop. Results are obtained also for the expected time to loss of lock and for the frequency of skipping cycles. Threshold criteria for the phase-locked loop are discussed, and thresholds of approximate models which have been widely accepted are obtained by comparison with the exact results available for the first-order loop.

# I. INTRODUCTION

The phase-locked loop is a communication receiver which operates as a coherent detector by continuously correcting its local oscillator frequency according to a measurement of the phase error. A block diagram of the device is shown in Fig. 1 with the pertinent input and output signals indicated. The output of the voltage-controlled oscillator (VCO) is a sinusoid whose frequency is controlled by the input voltage $e(t)$; that is,

$$\dot{\theta}_2(t) = \frac{d\theta_2}{dt} = K_2\, e(t) \qquad (1)$$

so that when $e(t) = 0$, the oscillator frequency is $\omega_0$. The received signal is a sinusoid of power $A^2$ w, of arbitrary

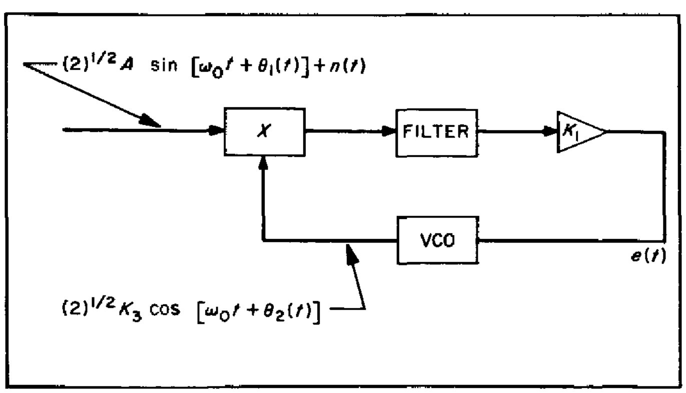


Fig. 1. Phase-locked loop

frequency $\omega$, and of phase $\theta$. Thus, it is represented by the expression

$$(2)^{1/2} A \sin[\omega t + \theta] = (2)^{1/2} A \sin[\omega_0 t + \theta_1(t)]$$

where

$$\theta_1(t) = (\omega - \omega_0)t + \theta \qquad (2)$$

The noise is assumed to be stationary, Gaussian, and white of one-sided spectral density $N_0$ w/cps. The noise process over an arbitrary period of duration $T$ can be expanded in a Fourier series whose coefficients become independent Gaussian variables in the limit as $T$ approaches infinity (Ref. 1). By collecting the sine and cosine terms of the series, we can represent the noise process of infinite duration by the expression

$$n(t) = (2)^{1/2} n_1(t) \sin(\omega t + \theta) + (2)^{1/2} n_2(t) \cos(\omega t + \theta)$$

where $n_1(t)$ and $n_2(t)$ are both stationary, white, Gaussian processes of one-sided spectral density $N_0$ w/cps and are statistically independent of one another.

Thus the product of input and reference signals is

$$\begin{aligned}
2\{&A \sin[\omega_0 t + \theta_1(t)] + n_1(t)\sin(\omega t + \theta) \\
&+ n_2(t)\cos(\omega t + \theta)\}\{K_3 \cos[\omega_0 t + \theta_2(t)]\} \\
&= AK_3 \sin[\theta_1(t) - \theta_2(t)] \\
&\quad + K_3 n_1(t) \sin[(\omega - \omega_0)t + \theta - \theta_2(t)] \\
&\quad + K_3 n_2(t) \cos[(\omega - \omega_0)t + \theta - \theta_2(t)] \\
&\quad + \text{double frequency terms} \\
&= AK_3 \sin[\theta_1(t) - \theta_2(t)] \\
&\quad + K_3 n_1(t) \sin[\theta_1(t) - \theta_2(t)] \\
&\quad + K_3 n_2(t) \cos[\theta_1(t) - \theta_2(t)] \\
&\quad + \text{double frequency terms}
\end{aligned}$$

where $\theta_1(t)$ is given by Eq. (2). The double frequency terms may be neglected since neither the filter nor the VCO will respond significantly to these for reasonably large $\omega_0$. Then from Fig. 1 we see that

$$\begin{aligned}
e(t) = K_1 F(s)\{&AK_3 \sin[\theta_1(t) - \theta_2(t)] \\
&+ K_3 n_1(t) \sin[\theta_1(t) - \theta_2(t)] \\
&+ K_3 n_2(t) \cos[\theta_1(t) - \theta_2(t)]\}
\end{aligned} \qquad (3)$$

where $F(s)$ is a rational function which represents in operational notation the effect of the linear filter in the loop. If we let $\phi(t) = \theta_1(t) - \theta_2(t)$ and $K = K_1 K_2 K_3$ and use Eq. (1), we obtain

$$\dot{\phi}(t) = \dot{\theta}_1(t) - K_2 e(t)$$

Then from Eq. (2) and (3) we have

$$\begin{aligned}
\dot{\phi}(t) = (\omega - \omega_0) - KF(s)\,[&A \sin\phi(t) \\
&+ n_1(t)\sin\phi(t) + n_2(t)\cos\phi(t)]
\end{aligned} \qquad (4)$$

The instantaneous phase error or difference between the received signal and the reference signal at the output of the VCO is $\phi(t)$. Equation (4) is the exact expression for the operation of the phase-locked loop in the presence of noise. Several authors beginning with Gruen (Ref. 2) have obtained solutions of this equation in the absence of noise for a number of filter transfer functions and also for the case of linearly time-varying input frequency. The most complete treatment of the noise-free performance is contained in Ref. 3. The general case in which additive noise is present has been treated by a variety of approximations. Jaffe and Rechtin (Ref. 4) assumed $\phi(t)$ to be at all times small enough that $\cos\phi \simeq 1$ and $\sin\phi \simeq \phi << 1$ so that the expression in brackets in Eq. (4) becomes $A\phi(t) + n_2(t)$. This produces a linear time-invariant model of the system. Recently Van Trees (Ref. 5) refined this analysis by linearizing about the equilibrium point $\phi_0$, making the assumption

$$\sin(\phi - \phi_0) \simeq \phi - \phi_0$$

and

$$\cos(\phi - \phi_0) \simeq 1$$

This generates a linear time-varying model. Develet (Ref. 6) applied Booton's quasi-linearization technique (Ref. 7), replacing the sinusoidal nonlinearity by its average gain. Both Van Trees' and Devlet's methods obtain estimates of the noise threshold of the device. Margolis (Ref. 8) obtained a series representation for the moments of the phase error, but the method was too involved to give useful results.

Unlike these analyses, continuous random walk or Fokker-Planck techniques yield exact expressions for the statistics of the random process $\phi(t)$. Unfortunately, expressions in closed form can be obtained only for the first-order loop (i.e., when the filter is omitted). For the general case, a partial differential equation in $\phi$ and its time derivatives is derived, but solutions cannot be obtained in general.

These techniques were first applied to this problem in the Soviet literature by Tikhonov (Ref. 9, 10), who obtained the steady-state probability distribution of $\phi$

for the first-order loop enclosed form and an approximate expression for the distribution when the loop contains a one-stage RC filter. Tikhonov's result on the steady-state distribution for the first-order loop is contained in Part III of this Report. The variance and cumulative distribution are also obtained. In Part IV, we derive the Fokker-Planck equation for the general loop filter which produces zero mean error. In Part V, this equation is specialized to the second-order loop, and the form of the solution for the steady-state probability distribution of $\phi$ is obtained. Part VI presents results on the mean time to loss of lock and the frequency of skipping cycles for the first-order loop, which is a random walk problem with absorbing boundaries. Finally, in Part VIII, the results are compared with those of the above mentioned approximate models in an attempt to determine validity thresholds for the models and a performance threshold for the device.

First of all, in the next Part, a simple mechanical analog of the phase-locked loop is presented which provides a qualitative description of the operation of the device and an understanding of the nature of the statistical parameters required for its quantitative description.

## II. THE FIRST-ORDER LOOP AND ITS MECHANICAL ANALOG

If the filter is omitted, we let $F(s) = 1$ in Eq. (4) and obtain the first-order differential equation

$$\dot{\phi}(t) = (\omega - \omega_0) - K[A \sin \phi(t) + n_1(t) \sin \phi(t) + n_2(t) \cos \phi(t)] \qquad (5)$$

Hence the term "first-order" loop. Since $n_1(t)$ and $n_2(t)$ are both white, the instantaneous change in $\phi$ represented by its derivative depends only on the present value of $\phi$ and the present value of the noise. Hence $\phi(t)$ is a continuous Markov process, permitting us to use random walk techniques to determine its probability distribution. A mechanical analog is useful in understanding the mechanism of this "random walk." Consider the pendulum of Fig. 2 consisting of a weightless ball attached by an infinitesimally thin, weightless rod to a fixed point, and let the apparatus be horizontal on a table top which is being randomly agitated. The pendulum is free to turn a full revolution about the point. Let the rod be initially at an angle $\phi$ with respect to the vertical axis. Let an external force (such as a constant wind) be exerted on the ball in the vertical direction. Let the surface of the table be rough so that it produces a frictional force opposing motion of magnitude $f\dot{\phi}$. In addition, let the ball be equipped with an internal engine which exerts a constant force $F$ along the axis of motion. The random agitation of the table produces a force on the ball which may be represented by the two stationary, white, Gaussian processes of zero means $n_1(t)$ in the vertical direction, and $n_2(t)$ in the horizontal direction. Then by equating forces along the instantaneous axis of motion, we obtain:

$$f\dot{\phi} + G \sin \phi = F - n_1(t) \sin \phi - n_2(t) \cos \phi \qquad (6)$$

If we divide by $f$ and identify $F/f$ with $(\omega - \omega_0)$, $G/f$ with $AK$, and $1/f$ with $K$, we see that Eq. (6) is the same as Eq. (5).

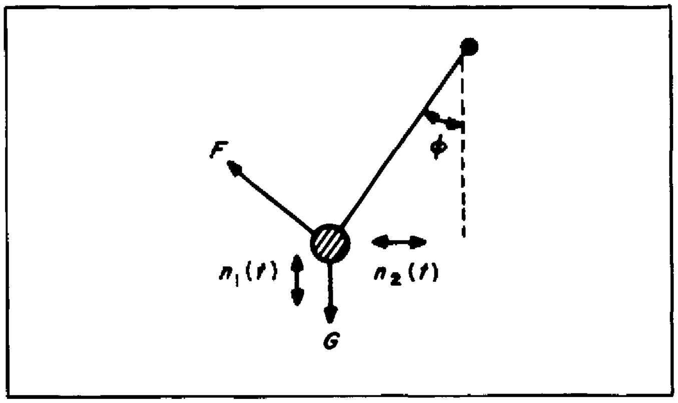


**Fig. 2. Mechanical analog of the first-order loop**

It is clear that in the absence of the random forces, the pendulum approaches the equilibrium position

$$\phi_0 = \sin^{-1}(F/G) = \sin^{-1}(\omega - \omega_0)/(AK) \qquad (7)$$

at which point the velocity is zero. Because this is a first-order system, there can be no overshoot. If $F > G$ or $(\omega - \omega_0) > AK$, there can be no equilibrium position, and the pendulum continues to revolve indefinitely which corresponds to a loop which can not achieve lock. When the random or noise forces are applied as well as the constant ones, the motion becomes a random walk, but when the noise variance is small, there is a strong tendency for the angle $\phi$ to approach and remain about this equilibrium position.

The complete statistical description of the random walk of the angle $\phi$ is given by its probability density as a function of time, $p(\phi, t)$. To understand qualitatively the behavior of this function, let us assume that the constant force $F = 0$ and that initially (at $t = 0$) the pendulum is at rest in the vertical position. Thus, $p(\phi, 0) = \delta(\phi)$. With the passage of time, the effect of the random forces will be felt in the movement of the pendulum from the equilibrium position. The qualitative behavior of the probability density function is sketched in Fig. 3. Of course, the condition

$$\int_{-\infty}^{\infty} p(\phi, t)\, d\phi = 1$$

must always be met. After a sufficient amount of time, the random forces will push the pendulum around by more than half a revolution so that it will tend to return to the equilibrium position after a full cycle of rotation in either direction. This corresponds to the reference signal of the phase-locked loop advancing or retreating one cycle relative to the received signal. The average time for this occurrence depends on the signal-to-noise ratio. Thus after a sufficiently long period, the probability density will appear as a multimodal function, each mode being centered about equilibrium positions spaced $2\pi$ rad apart, the central mode being the largest with each successive maximum progressively smaller. After an even longer period equal to several times the average time between revolutions, the central mode of the probability density will have diminished, the modes to either side will have become almost as large, and more modes of significant magnitude will have appeared. The central mode will remain the largest since the pendulum may have revolved in either direction with equal probability. Finally, in the steady state an arbitrary number of revolutions will have occurred. Then the probability density will be a periodic function (as will be proved in Part III). However, because the integral of the function must equal one at all times, the magnitude must be everywhere zero.

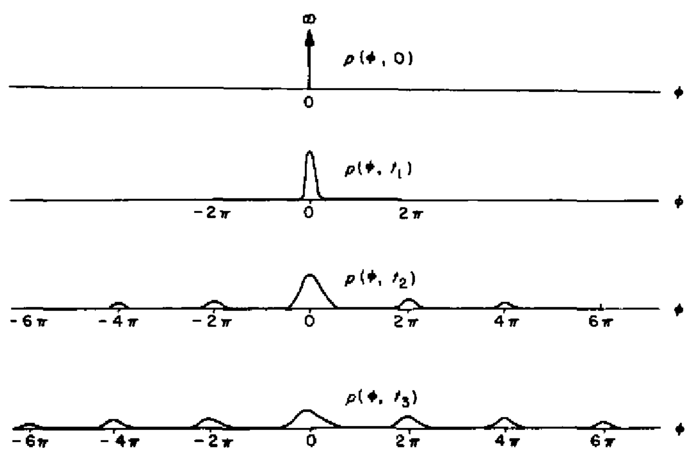


**Fig. 3. Qualitative behavior of the probability density function for the first-order loop, $\omega = \omega_0$**

In the case for which $F$ is not zero, or equivalently $\omega \neq \omega_0$, then clearly the pendulum will have a greater tendency to swing around in the sense corresponding to the direction of the force. Hence, the density function $p(\phi, t)$ will not be symmetrical. In either case, we are lead to realize that the significant parameter, at least in the steady state, is the angle (or phase error) $\phi$ modulo $2\pi$, since the number of revolutions of the pendulum which have occurred does not affect the present state of the system. In fact, although $p(\phi, t)$ yields a complete description of the statistical behavior, it would appear that a combination of the steady-state distribution of $\phi$ modulo $2\pi$ and the frequency or average time between revolutions would yield a simpler and equally valid representation. In the following Parts of this Report, these parameters will be obtained quantitatively.

## III. THE STEADY-STATE PHASE-ERROR PROBABILITY DENSITY FOR THE FIRST-ORDER LOOP

A continuous random walk which is a Markov process is described by the statistical parameters of the incremental change of position as a function of the present position. Thus from Eq. (5), in the infinitesimal increment of time $\Delta t$, the phase will change by an amount[1]

$$\Delta\dot{\phi} = \int_t^{t+\Delta t} \phi(t)\,dt = (\omega - \omega_0)\Delta t - (AK\sin\phi)\Delta t - K\left[\sin\phi\int_t^{t+\Delta t} n_1(u)\,du + \cos\phi\int_t^{t+\Delta t} n_2(u)\,du\right]$$

Thus, since $n_1(t)$ and $n_2(t)$ are white, Gaussian processes with

$$\overline{n_1(u)} = \overline{n_2(u)} = 0$$

and

$$\overline{n_1(u)\,n_1(v)} = \overline{n_2(u)\,n_2(v)} = (N_0/2)\,\delta(u - v)$$

it follows that for a given position $\phi$, $\Delta\phi$ is a Gaussian variable with mean

$$\overline{\Delta\phi} = [(\omega - \omega_0) - AK\sin\phi]\,\Delta t \tag{8}$$

and variance

$$\begin{aligned}\sigma^2_{\Delta\phi} &= (\overline{\Delta\phi})^2 - (\overline{\Delta\phi})^2 \\ &= K^2\left[\sin^2\phi\int_t^{t+\Delta t}\int_t^{t+\Delta t}\overline{n_1(u)\,n_1(v)}\,du\,dv + \cos^2\phi\int_t^{t+\Delta t}\int_t^{t+\Delta t}\overline{n_2(u)\,n_2(v)}\,du\,dv\right] \\ &= K^2(N_0/2)\,\Delta t\end{aligned} \tag{9}$$

It is worth noting in passing that for the determination of $p(\phi; t)$, Eq. (9) shows that the two noise terms could be replaced by a single noise $n'(t)$ of the same spectral density so that Eq. (5) could be rewritten

$$\dot{\phi}(t) = (\omega - \omega_0) - AK\sin\phi(t) - K\,n'(t) \tag{10}$$

which is conveniently represented by the block diagram of Fig. 4. The model can be shown trivially also to hold

[1]This assumes that $\phi(t)$ is a continuous process, which is justified by physical considerations.

for a higher order loop in which the filter is included after the amplifier. The VCO of Fig. 1 is replaced by an integrator and the multiplier by an adder and sinusoidal nonlinearity. This differs from the linearized model of Ref. 4 only in the inclusion of the sinusoidal nonlinearity.

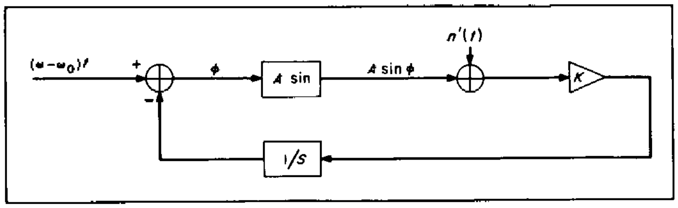


**Fig. 4. Model of first-order loop**

With the knowledge of the statistical parameters of the increment $\Delta\phi$, we may proceed to obtain $p(\phi,t)$. It was shown by Uhlenbeck and Ornstein (Ref. 11) and Wang and Uhlenbeck (Ref. 12) that for a continuous Markov process, the instantaneous probability density $p(\phi,t)$ must satisfy the partial differential equation

$$\frac{\partial p(\phi,t)}{\partial t} = -\frac{\partial}{\partial\phi}[A(\phi)\,p(\phi,t)] + \frac{1}{2}\frac{\partial^2}{\partial\phi^2}[B(\phi)\,p(\phi,t)] \tag{11}$$

with the initial condition

$$p(\phi,0) = \delta(\phi-\phi_0)$$

where $\phi_0$ is the initial value of $\phi$, and where $A(\phi)$ and $B(\phi)$ are normalized moments of the infinitesimal increment given by the following expressions:

$$A(\phi) = \lim_{\Delta t\to 0}(1/\Delta t)\overline{\Delta\phi}$$

$$B(\phi) = \lim_{\Delta t\to 0}(1/\Delta t)\,\sigma^2_{\Delta\phi}$$

Equation (11) is known as the Fokker-Planck equation or the diffusion equation because it is essentially the same as the equation for heat diffusion. From Eq. (8) and (9) we obtain

$$A(\phi) = (\omega-\omega_0) - AK\sin\phi$$

$$B(\phi) = K^2N_0/2$$

so that Eq. (11) becomes

$$\frac{\partial p}{\partial t} = \frac{\partial}{\partial\phi}[(AK\sin\phi + \omega_0 - \omega)\,p] + \frac{1}{4}K^2N_0\frac{\partial^2 p}{\partial\phi^2} \tag{12}$$

Although the equation is linear in $p$, the complete solution for $p(\phi,t)$ is somewhat complicated by the nonlinear behavior of the variable coefficients.

However, the result of greatest interest is the steady-state distribution

$$p(\phi) = \lim_{t\to\infty} p(\phi,t) \tag{13}$$

By definition, the steady-state distribution does not vary with time. Therefore,

$$\frac{\partial p(\phi)}{\partial t} = \lim_{t\to\infty}\frac{\partial p(\phi,t)}{\partial t} = 0 \tag{14}$$

Thus in the steady state, the partial differential Eq. (12) reduces to an ordinary differential equation in $p(\phi)$. Letting

$$\alpha = (4A)/(KN_0)$$

and

$$\beta = [4(\omega-\omega_0)]/(K^2N_0) \tag{15}$$

we obtain from Eq. (12)

$$0 = \frac{d}{d\phi}\left[(\alpha\sin\phi-\beta)\,p(\phi) + \frac{dp(\phi)}{d\phi}\right] \tag{16}$$

If we integrate once with respect to $\phi$, we obtain a first-order linear differential equation which is readily solved as[2]

$$p(\phi) = C\exp(\alpha\cos\phi + \beta\phi)\times\left[1 + D\int_{-\pi}^{\phi}\exp-(\alpha\cos x + \beta x)\,dx\right]\qquad -\pi\leq\phi\leq\pi \tag{17}$$

To evaluate the constants, we must utilize boundary conditions. First of all, as was pointed out in Part II, in the steady state we are interested in the distribution of $\phi$ modulo $2\pi$. Thus, one condition is:

$$p(\pi) = p(-\pi) \tag{18}$$

Secondly, since $\phi$ must lie between $-\pi$ and $\pi$ and $p(\phi)$ is a probability density, it follows that

[2]The results of Eq. (17) through (21) were first obtained by V. I. Tikhonov (Ref. 9). Actually, these are a special case of an expression derived by Andronov, Pontryagin and Witt (Ref. 13) for a random walk problem with arbitrary nonlinear restoring forces.

$$\int_{-\pi}^{\pi} p(\phi)\,d\phi = 1 \qquad (19)$$

Using Eq. (18), we obtain

$$D = \frac{\exp(-2\beta\pi) - 1}{\int_{-\pi}^{\pi} \exp - (\alpha\cos x + \beta x)\,dx} \qquad (20)$$

Then by means of Eq. (19), the constant $C$ can be evaluated.

In the special case $\beta = 0$ (which requires $\omega = \omega_0$; i.e., when the VCO quiescent frequency is exactly at the frequency of the incoming signal), from Eq. (20) we see that $D = 0$ and that when $\omega = \omega_0$, the probability density becomes

$$p(\phi) = \frac{\exp(\alpha\cos\phi)}{2\pi I_0(\alpha)} \qquad -\pi \leq \phi \leq \pi \qquad (21)$$

since

$$C = \frac{1}{\int_{-\pi}^{\pi} \exp(\alpha\cos\phi)\,d\phi} = \frac{1}{2\pi I_0(\alpha)}$$

The parameter $\alpha$ plays a very important role. From Eq. (15) we have

$$\alpha = \frac{(4A)}{(KN_0)} = \frac{(A^2)}{[N_0(AK/4)]} \qquad (22)$$

But $A^2$ is the received signal power, while $AK/4$ is an important parameter defined for the linearized model of the loop (Ref. 4). If we replace the sinusoidal nonlinearity in the model of Fig. 4 by its gain $A$ about $\phi = 0$, we obtain the linearized model. Then the variance of $\phi$ is obtained by using Parseval's theorem as:

$$\sigma_\phi^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{N_0}{2}\,\frac{K^2/\omega^2}{1 + (A^2K^2/\omega^2)}\,d\omega = N_0(AK/4)$$

The variance of $\phi$ is the same as the noise power at the output of an ideal low-pass filter of bandwidth $AK/4$ when the input is white noise of one-sided spectral density $N_0$. Hence, for the first-order filter, the loop bandwidth is defined as

$$B_L = AK/4 \qquad (23)$$

so that Eq. (22) becomes

$$\alpha = (A^2)/(N_0 B_L) \qquad (24)$$

which is the signal-to-noise ratio in the bandwidth of the loop.

Equation (21) is plotted in Fig. 5 for several values of $\alpha$. It resembles a Gaussian distribution for large signal-to-noise ratios, $\alpha$, and becomes flat as $\alpha$ approaches zero. The asymptotic behavior of Eq. (21) for large $\alpha$ is of interest. Since for large $\alpha$

$$I_0(\alpha) \sim (\exp\alpha)/(2\pi\alpha)^{1/2}$$

$$p(\phi) = \frac{[\exp(\alpha\cos\phi)]}{[2\pi I_0(\alpha)]} \sim \frac{\{\exp[\alpha(\cos\phi - 1)]\}}{(2\pi/\alpha)^{1/2}}$$

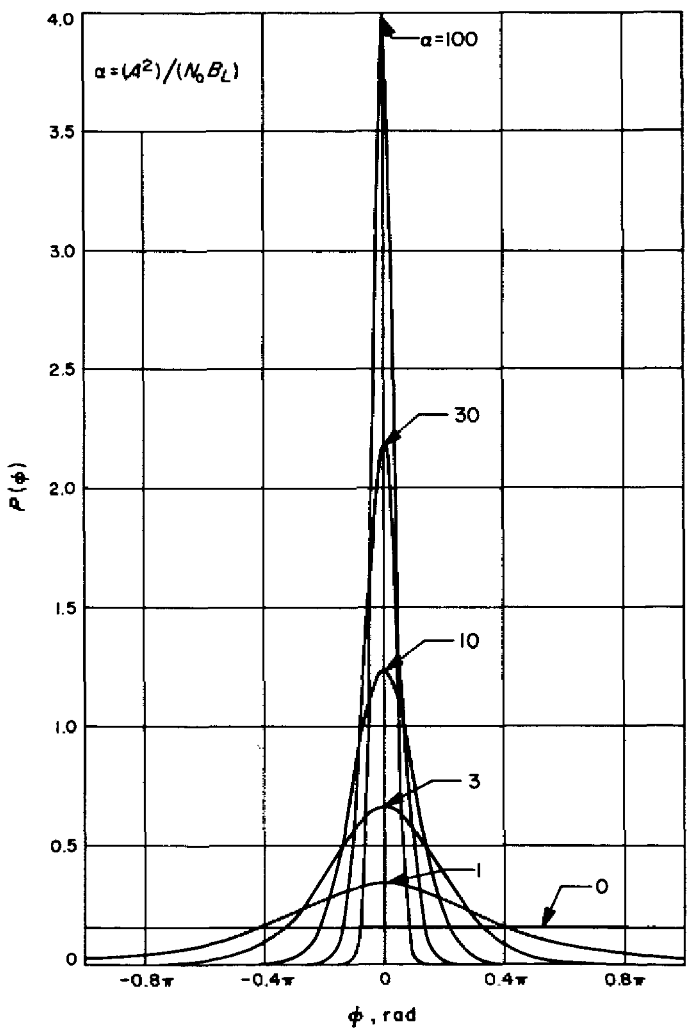


**Fig. 5. First-order loop, steady-state probability densities for $\omega = \omega_0$**

Expanding cos $\phi$ in a Taylor series, we obtain

$$p(\phi) \sim \frac{\exp\left[\frac{-\alpha\phi^2}{2}\left(1 - \frac{2\phi^4}{4!} + \frac{2\phi^6}{6!}\cdots\right)\right]}{(2\pi/\alpha)^{1/2}} \qquad (25)$$

$$-\pi \leqq \phi \leqq \pi$$

When $\alpha$ is large, $p(\phi)$ decays rapidly so that the function is very small for all but very small values of $\phi$. Thus the higher order terms of the series representation of cos $\phi$ have very little effect for moderate values of $p(\phi)$. Hence the graph of $p(\phi)$ will appear to be nearly Gaussian for large $\alpha$, and in this case, the results of the linear model are quite accurate.

The cumulative steady-state probability distribution

$$P(|\phi| < \phi_0) = \int_{-\phi_0}^{\phi_0} p(\phi)\, d\phi \qquad 0 < \phi_0 < \pi$$

is also of interest since it indicates the percentage of time during which the absolute value of the loop phase error $\phi$ is less than a given magnitude $\phi_0$. This may be calculated when $\omega = \omega_0$ in the following manner. Expanding $p(\phi)$ of Eq. (21) in a Fourier series, we have

$$p(\phi) = \frac{\exp(\alpha\cos\phi)}{2\pi I_0(\alpha)}$$

$$= \frac{1}{2\pi I_0(\alpha)}\left[I_0(\alpha) + 2\sum_{n=1}^{\infty} I_n(\alpha)\cos n\phi\right]$$

Then

$$P(|\phi| < \phi_0) = 2\int_0^{\phi_0} p(\phi)\, d(\phi)$$

$$= \frac{\phi_0}{\pi} + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{I_n(\alpha)\sin n\phi_0}{nI_0(\alpha)}$$

$$0 < \phi_0 < \pi \quad \text{for } \omega = \omega_0 \qquad (26)$$

This series converges rapidly so that Eq. (26) could be calculated for several values of $\alpha$ without the use of a large-scale digital computer. The results are shown in Fig. 6.

The variance of $\phi$ can be similarly obtained.

$$\sigma_\phi^2 = \int_{-\pi}^{\pi} \phi^2 \exp(\alpha\cos\phi)\, d\phi$$

$$= \frac{1}{2\pi I_0(\alpha)}\int_{-\pi}^{\pi}\phi^2\left[I_0(\alpha) + 2\sum_{n=1}^{\infty} I_n(\alpha)\cos n\phi\right]d\phi$$

$$= \frac{\pi^2}{3} + 4\sum_{n=1}^{\infty}\frac{(-1)^n I_n(\alpha)}{n^2 I_0(\alpha)} \qquad (27)$$

This series converges even more rapidly than that of Eq. (26). It was computed manually and is plotted in Fig. 7 as a function of $1/\alpha$. Note that as the SNR $\alpha$ approaches zero, the variance approaches $\pi^2/3$ which is the variance of a random variable that is uniformly distributed from $-\pi$ to $+\pi$.

For the general case ($\omega \neq \omega_0$), Eq. (17), (19), and (20) yield the entire distribution. However, analog or digital computation is required to evaluate the pertinent integrals. The case for which $(\beta/\alpha) = (\omega - \omega_0)/(AK) = \sin(\pi/4)$ is shown in Fig. 8. The constants as well as the distribution were obtained by means of the analog computer.

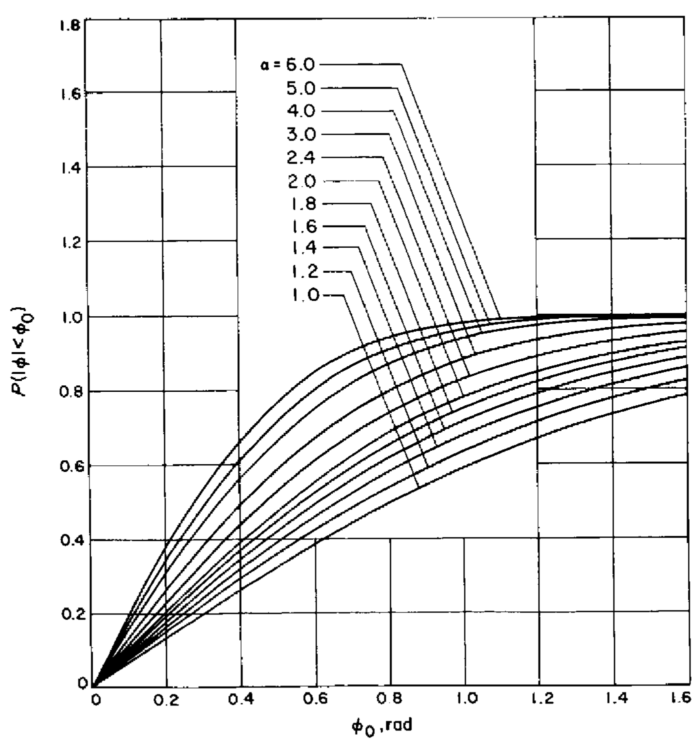


**Fig. 6. Steady-state, cumulative probability distribution of first-order loop for $\omega = \omega_0$**

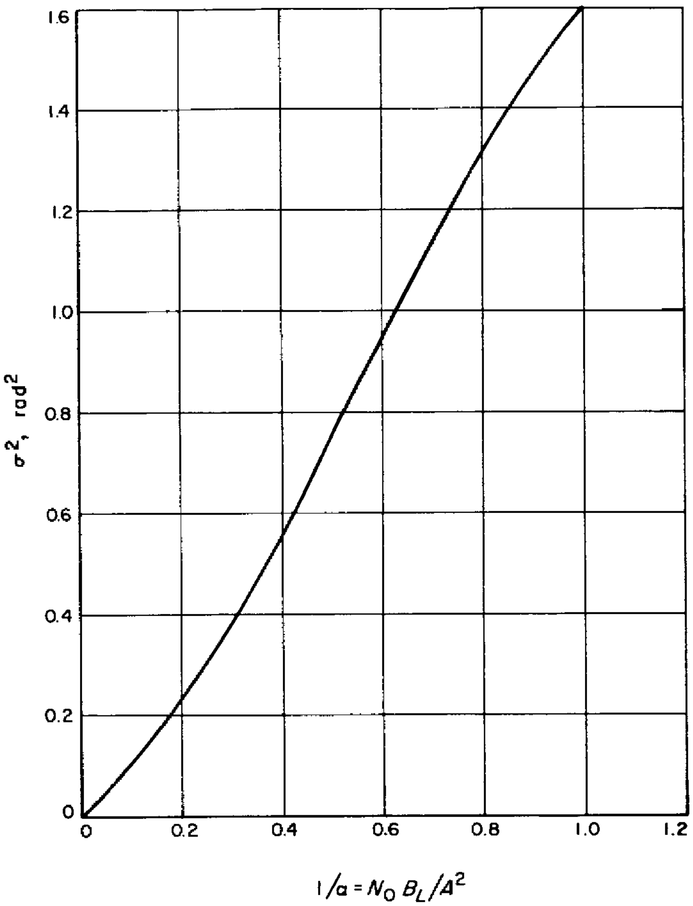


**Fig. 7. Variance of phase-error for first-order loop where $\omega = \omega_0$**

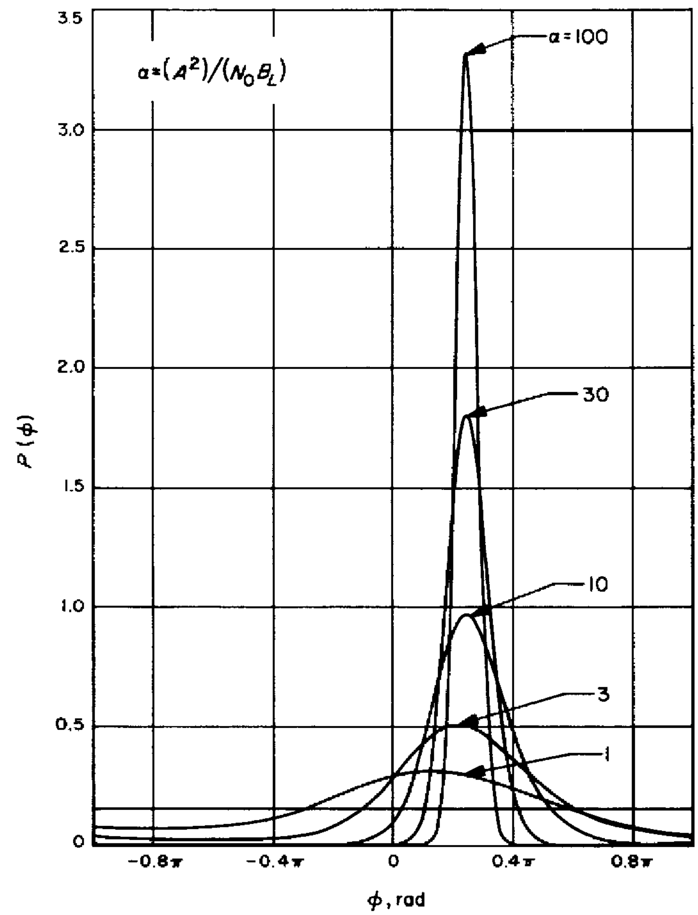


**Fig. 8. First-order loop, steady-state probability densities for $(\omega = \omega_0)/(A\,K) = \sin(\pi/4)$**

## IV. THE FOKKER-PLANCK EQUATION FOR HIGHER-ORDER LOOPS

Consider the phase-locked loop whose filter has the rational transfer function

$$F(s) = G(s)/H(s)$$

where $G(s)$ and $H(s)$ are polynomials such that $G(0) = 1$, $H(0) = 0$

$$\deg G(s) \leqq \deg H(s) = n - 1$$

then

$$G(s) = \sum_{k=0}^{n-1} a_k s^k \qquad a_0 \neq 0$$

$$H(s) = \sum_{k=1}^{n-1} b_k s^k \qquad b_{n-1} \neq 0 \tag{28}$$

This will be referred to as an $n$th-order loop. In this case, Eq. (4) which describes the operation of the loop becomes

$$sH(s)\,\phi = -KG(s)\,[(A + n_1)\sin\phi + n_2\cos\phi] \tag{29}$$

since

$$s^k(\omega - \omega_0) = \frac{dk}{dt}(\omega - \omega_0) = 0 \qquad \text{for } k \geqq 1$$

The reason for the pole at the origin of $F(s)$ is now clear. It eliminates the constant $(\omega - \omega_0)$ which causes the steady-state phase error in the first-order loop. Now let us define the random variable $\varepsilon$ by the relation[3]

$$\phi = G(s)\,\varepsilon \tag{30}$$

Inserting this in Eq. (29), we obtain

$$sH(s)\,\varepsilon = -K\{[A + n_1]\sin[G(s)\,\varepsilon] + n_2\cos[G(s)\,\varepsilon]\} \tag{31}$$

which is an $n$th-order differential equation. Now let us define the $n$ random variables $x_0, x_1, \cdots, x_{n-1}$ as

$$x_k = \frac{d^k\varepsilon}{dt^k} \qquad k = 0, 1, \cdots, n-1 \tag{32}$$

Inserting these for the derivatives of $\varepsilon$ in Eq. (31) and by using Eq. (28), we obtain

$$b_{n-1}\dot{x}_{n-1} + \sum_{k=1}^{n-2} b_k x_{k+1} = -K\left[(A + n_1)\sin\left(\sum_{k=0}^{n-1} a_k x_k\right) + n_2\cos\left(\sum_{k=0}^{n-1} a_k x_k\right)\right]$$

Also, we have

$$x_k = \frac{d}{dt}\frac{d^{k-1}\varepsilon}{dt^{k-1}} = \dot{x}_{k-1}$$

so that we may express the derivatives $\dot{x}_k$ in terms of the variables $x_k$ by the $n$ differential equations

$$\dot{x}_{n-1} = -\sum_{k=1}^{n-2}\frac{b_k}{b_{n-1}}x_{k+1} - \frac{K}{b_{n-1}} \times \left[(A + n_1)\sin\left(\sum_{k=0}^{n-1} a_k x_k\right) + n_2\cos\left(\sum_{k=0}^{n-1} a_k x_k\right)\right]$$

$$\dot{x}_{n-2} = x_{n-1}$$

$$\vdots$$

$$\dot{x}_0 = x_1 \tag{33}$$

It follows also from Eq. (28), (30), and (32) that

$$\phi = \sum_{k=0}^{n-1} a_k s^k \tag{34}$$

The random vector $(x_0, \cdots, x_{n-1})$ is a Markov vector since an incremental change depends only on the present state of the vector.

Wang and Uhlenbeck (Ref. 12) have shown that for a vector Markov process $\mathbf{x} = (x_0, x_1, \cdots, x_{n-1})$, the Fokker-Planck equation is

$$\frac{\partial P(\mathbf{x})}{\partial t} = -\sum_{k=0}^{n-1}\frac{\partial}{\partial x_k}[A_k(\mathbf{x})\,P(\mathbf{x})] + \frac{1}{2}\sum_{k=0}^{n-1}\sum_{l=0}^{n-1}\frac{\partial^2}{\partial x_k\,\partial x_l}[B_{kl}(\mathbf{x})\,P(\mathbf{x})]$$

where

$$A_k(\mathbf{x}) = \lim_{\Delta t \to 0}\frac{1}{\Delta t}\,(\overline{\Delta x_k})$$

and

$$B_{kl}(\mathbf{x}) = \lim_{\Delta t \to 0}\frac{1}{\Delta t}\,(\overline{(\Delta x_k)(\Delta x_l)}) \tag{35}$$

[3]This substitution which leads to the representation of $\phi$ as the sum of the components of a Markov vector (Eq. 33) was suggested by J. N. Franklin.

with the initial condition

$$P(\mathbf{x},0)=\prod_{k=0}^{n-1}\delta(x_k-x_{k,0})$$

$$A_k(\mathbf{x})=x_{k+1}\quad \text{for } k=0,1,\cdots,n-2$$

$$A_{n-1}(\mathbf{x})=-\sum_{k=1}^{n-2}\frac{b_k}{b_{n-1}}x_{k+1}-\frac{KA}{b_{n-1}}\sin\sum_{k=0}^{n-1}a_kx_k$$

$$B_{n-1,n-1}(\mathbf{x})=\lim_{\Delta t\to 0}\frac{1}{\Delta t}\frac{K^2}{b_{n-1}^2}\times\left[\sin^2\phi\int_t^{t+\Delta t}\int_t^{t+\Delta t}\overline{n_1(u)\,n_1(v)}\,du\,dv+\cos^2\phi\int_t^{t+\Delta t}\int_t^{t+\Delta t}\overline{n_2(u)\,n_2(v)}\,du\,dv\right]=\frac{K^2N_0/2}{b_{n-1}^2}$$

$$B_{k,l}(\mathbf{x})=0\quad\text{for all } k\neq n-1 \text{ and } l\neq n-1$$

Thus, the Fokker-Planck equation for the $n$th-order loop is

$$\frac{\partial P(x,t)}{\partial t}=-\sum_{k=0}^{n-2}x_{k+1}\frac{\partial P(x,t)}{\partial x_k}+\frac{1}{b_{n-1}}\frac{\partial}{\partial x_{n-1}}\times\left[\left(\sum_{k=0}^{n-2}b_kx_{k+1}+KA\sin\sum_{k=0}^{n-1}a_kx_k\right)P(x,t)\right]+\frac{K^2N_0}{4b_{n-1}^2}\frac{\partial^2P(x,t)}{\partial x_{n-1}^2}\tag{36}$$

where

$$\phi=\sum_{k=0}^{n-1}a_kx_k$$

Solution of this general case does not appear possible. However, in the next Section some results are obtained for the second-order loop.

## V. STEADY-STATE PROBABILITY DISTRIBUTION FOR THE SECOND-ORDER LOOP

The loop filter of greatest interest[4] is

$$F(s) = 1 + (a/s) = (s + a)/(s)$$

which requires a single integrator with gain $a$. In terms of the parameters of Eq. (28), $n = 2$, $a_0 = a$, $a_1 = 1$, $b_1 = 1$. Substituting these parameters in Eq. (33) and (36), we obtain the differential equations for the random variables

$$\dot{x}_1 = -K[(A + n_1)\sin(ax_0 + x_1)] - Kn_2\cos(ax_0 + x_1)$$
$$\dot{x}_0 = x_1 \tag{37}$$

and the Fokker-Planck equation

$$\frac{\partial P}{\partial t} = -x_1\frac{\partial p}{\partial x_0} + \frac{\partial}{\partial x_1}[(AK\sin(ax_0 + x_1)P] + \frac{K^2N_0}{4}\frac{\partial^2 P}{\partial x_1^2} \tag{38}$$

where

$$\phi = ax_0 + x_1$$

If we restrict our attention to the steady-state probability distribution

$$P(x_0, x_1) = \lim_{t\to\infty} P(x_0, x_1, t)$$

since

$$\lim_{t\to\infty}\frac{dP}{dt}(x_0, x_1, t) = 0$$

we obtain

$$x_1\frac{\partial P}{\partial x_0} = AK\frac{\partial}{\partial x_1}[\sin(ax_0 + x_1)P] + \frac{K^2N_0}{4}\frac{\partial^2 P}{\partial x_1^2} \tag{39}$$

With the substitutions

$$\phi = ax_0 + x_1$$
$$z = ax_0 \tag{40}$$

we obtain an equation in $P(\phi, z)$ (note that the Jacobian of the transformation is $a$)

$$a(\phi - z)\left(\frac{\partial P}{\partial \phi} + \frac{\partial P}{\partial z}\right) = AK\frac{\partial}{\partial \phi}(\sin\phi P) + \frac{K^2N_0}{4}\frac{\partial^2 P}{\partial \phi^2} \tag{41}$$

Even this partial differential equation cannot be solved directly. However, since we are interested only in the distribution of $\phi$

$$p(\phi) = \int_{-\infty}^{\infty} P(\phi, z)\,dz$$

we may integrate both sides of Eq. (41) with respect to $z$ over the infinite line and obtain an ordinary differential equation in $p(\phi)$

$$a\left\{\frac{d(\phi p)}{d\phi} - \frac{d}{d\phi}\left[\int_{-\infty}^{\infty} zP(\phi, z)\,dz\right]\right\} = AK\frac{d}{d\phi}(\sin\phi\, p) + \frac{K^2N_0}{4}\frac{d^2p}{d\phi^2} \tag{42}$$

But

$$\int_{-\infty}^{\infty} zP(\phi, z)dz = p(\phi)\int_{-\infty}^{\infty} zP(z|\phi)\,dz = p(\phi)E(z|\phi)$$

so that Eq. (42) becomes

$$0 = \frac{d}{d\phi}\left\{[AK\sin\phi - a\phi + aE(z|\phi)]p + \frac{K^2N_0}{4}\frac{dp}{d\phi}\right\} \tag{43}$$

Unfortunately, it is not possible to determine exactly $E(z|\phi)$, which is a function of $\phi$, without knowing $P(z, \phi)$, which would require solution of Eq. (41). However, its general form can be obtained as follows: from Eq. (40) we have $z = \phi - x_1$ so that

$$E[z(t)|\phi(t)] = E[\phi(t) - x_1(t)|\phi(t)] \tag{44}$$
$$= \phi(t) - E[x_1(t)|\phi(t)]$$

Integrating Eq. (37) using Eq. (40), we have

$$x_1(\infty) - x_1(t) = -AK\int_t^{\infty}\sin\phi(\xi)\,d\xi$$
$$- K\int_t^{\infty} n_1(\xi)\sin\phi(\xi)\,d\xi - K\int_t^{\infty} n_2(\xi)\cos\phi(\xi)\,d\xi$$

[4]Tikhonov (Ref. 10) considered the RC low-pass filter whose transfer function is $1/(s + b)$. Its value is questionable, however, since it does not reduce the mean phase error to zero, as the perfect integrator does.

Since the noise is white, $n_1(t)$ and $n_2(t)$ are independent of $\phi(t)$ for all $t$ so that, since $\overline{n_1(t)} = \overline{n_2(t)} = 0$, the expectations of the noise terms are zero. Also

$$E[x_1(\infty)|\phi(t)] = E[x_1(\infty)] = 0$$

since it is clear that the mean of the process is zero. Therefore,

$$E[x_1(t)|\phi(t)] = AK\int_t^\infty E[\sin\phi(\xi)|\phi(t)]\,d\xi \tag{45}$$

This is the integral of the expectation of sin $\phi$ over the entire past history of the process given the present value of $\phi$. Combining Eq. (43), (44), and (45), and letting $\xi = t + \tau$, we obtain

$$0 = \frac{d}{d\phi}\left\{\frac{4A}{KN_0}\left(\sin\phi - a\int_0^\infty E[\sin\phi(t+\tau)|\phi(t)]d\tau\right) \times p(\phi) + \frac{dp(\phi)}{d\phi}\right\} \tag{46}$$

The magnitude of the expectation is always less than one and becomes negligible for values of $\tau$ several times the inverse bandwidth of the spectrum of $\phi(t)$. This bandwidth is proportional to $AK$, as we found for the first-order loop. Therefore, the order of magnitude of the integral is inversely proportional to $AK$, and if $a << AK$, the second term in the coefficient of $p(\phi)$ is much smaller than the first. Neglecting this second term reduces Eq. 46 to the steady-state Fokker-Planck equation for the first-order loop (Eq. 16) with $\omega = \omega_0$, whose solution is Eq. (21). Thus when the second integrator gain $a << AK$,

$$p(\phi) \simeq \frac{\exp(\alpha\cos\phi)}{2\pi I_0(\alpha)} \qquad -\pi \leq \phi \leq \pi \tag{47}$$

On the other hand, for any value of $a$ when the SNR is large enough, $\phi(t)$ will be small for all time so that $\sin\phi(t) \simeq \phi(t)$ and both $\phi(t)$ and $\sin\phi(t)$ will be nearly Gaussian processes. In this case, the expectation can be approximated by

$$\int_0^\infty E[\sin\phi(t+\tau)|\phi(t)]\,d\tau \simeq \left[\int_0^\infty \rho_\phi(\tau)\,d\tau\right]\sin\phi \tag{48}$$

where $\rho_\phi(\tau)$ is the normalized autocorrelation function of the stationary process $\phi(t)$. The integral can be obtained by using Parseval's theorem:

$$\int_0^\infty \rho_\phi(\tau) = \frac{1}{2\sigma^2}\int_{-\infty}^\infty R_\phi(\tau)\,d\tau = \frac{S_\phi(0)}{2\sigma^2}$$

where $R_\phi(\tau)$ is the unnormalized autocorrelation function, $\sigma^2$ the variance of $\phi$, and $S_\phi(\omega)$ the spectral density. Since we have approximated sin $\phi$ by $\phi$, we may use the linearized version of Fig. 4 with the loop filter $F(s) = [1 + (a/s)]$ inserted. Then

$$S_\phi(\omega) = \frac{N_0K^2}{2}\left|\frac{s+a}{s^2+AKs+aAK}\right|^2$$

so that $S_\phi(0) = (N_0)/(2A^2)$.

$$\sigma^2 = \frac{1}{2\pi}\int_{-\infty}^\infty S_\phi(\omega)\,d\omega = \frac{N_0}{4A^2}(AK + a)$$

and

$$\int_0^\infty \rho_\phi(\tau)\,d\tau = 1/(AK + a)$$

Inserting this integral in Eq. (48) and substituting in Eq. (46), we obtain

$$0 = \frac{d}{d\phi}\left\{\frac{4A}{KN_0}\left[\sin\phi\left(\frac{AK}{AK+a}\right)\right]p(\phi) + \frac{dp(\phi)}{d\phi}\right\}$$

whose solution with the boundary conditions of Eq. (18) and (19) is

$$p(\phi) \simeq \frac{\exp(\alpha'\cos\phi)}{2\pi I_0(\alpha')} \qquad \text{for large } \alpha' \tag{49}$$

where the effective SNR, $\alpha'$, is given by

$$\alpha' = (A^2)/[N_0(AK + a)/(4)]$$

If we let $B_L = (AK + a)/4$, this is the same expression as that for the first-order loop with $\omega = \omega_0$. As would be expected, this expression for loop bandwidth for the second-order loop is that obtained from the linear model of the loop.

# VI. MEAN TIME TO LOSS OF LOCK AND FREQUENCY OF SKIPPING CYCLES

Since we have obtained only solutions for steady-state probabilities, a valuable statistic is the expected time required for the absolute value of the phase error to exceed some value $\phi_l$ when it is initially zero. When this occurs, the loop will be said to have lost lock. Of particular interest is the case for which $\phi_l = \pm 2\pi$, which represents a loss or gain of a complete cycle, or for the mechanical analog, a complete revolution of the pendulum.

We only treat the case of the first-order loop for which the received frequency $\omega$ equals the VCO quiescent frequency $\omega_0$ so that $\phi = 0$ is the equilibrium position. This is also a good approximation to the steady-state behavior of the second-order loop with any value of $\omega - \omega_0$ but with very small integrator gain $a$, as will be discussed later in this Part. For the first-order loop, when $\omega \neq \omega_0$, the same approach can be used measuring phase error from the equilibrium position rather than from zero, but the results are in the form of integrals which require numerical calculation.

Returning to the mechanical analog of the pendulum of Part II, we treat the motion of the ball by the operational equation

$$\dot{\phi} = -AK \sin\phi - Kn_1 \sin\phi - Kn_2 \cos\phi$$

as long as $|\phi| < \phi_l$. But when the pendulum angle $\phi$ reaches $\pm\phi_l$, we assume that it is grasped by a demon and removed from operation forever after. We seek the average time for this event to occur when the pendulum is initially at rest at $\phi = 0$. As long as $|\phi| < \phi_l$, the probability density of $\phi$ is described in the same manner as before by the Fokker-Planck equation

$$\frac{\partial p}{\partial t} = \frac{\partial}{\partial \phi}(AK \sin\phi\, p) + \frac{N_0 K^2}{4}\frac{\partial^2 p}{\partial \phi^2}$$

$$p(\phi, 0) = \delta(\phi) \quad \text{for } |\phi| < \phi_l \tag{50}$$

However, as soon as $|\phi|$ reaches $\phi_l$ for the first time, the pendulum is removed from action so that

$$p(\phi, t) = 0 \quad \text{for all } |\phi| \geqq \phi_l$$

Thus we have the boundary conditions[5]

$$p(\phi_l, t) = p(-\phi_l, t) = 0 \tag{51}$$

Solution of Eq. (50) over the interval $-\phi_l < \phi < \phi_l$ with the boundary conditions of Eq. (51) would yield the probability density $p(\phi, t)$. Its integral over the interval

$$\psi(t) = \int_{-\phi_l}^{\phi_l} p(\phi, t)\, d\phi \tag{52}$$

gives the probability that $\phi$ has not yet reached $\phi_l$ at time $t$. Then the probability density of the time when $|\phi|$ reaches $\phi_l$ is $-[\partial\psi(t)]/(\partial t)$. Thus the expected time to reach the out-of-lock position $\phi_l$ is

$$T = \int_0^\infty -t\frac{\partial\psi(t)}{\partial t} = -\Big[t\,\psi(t)\Big]_0^\infty + \int_0^\infty \psi(t)\, dt \tag{53}$$

Since with probability 1, $|\phi|$ must reach $\phi_l$ before $t = \infty$, then $\psi(\infty) = 0$ so that the combination of Eq. (52) and (53) yields the mean time to lose lock

$$T = \int_0^\infty \int_{-\phi_l}^{\phi_l} p(\phi, t)\, d\phi dt \tag{54}$$

Now if we integrate both sides of Eq. (50) with respect to $t$ over the infinite interval, we obtain

$$p(\phi, \infty) - p(\phi, 0) = \frac{\partial}{\partial\phi}(AK\sin\phi\, P) + \frac{N_0K^2}{4}\frac{\partial^2 P(\phi)}{\partial\phi^2} \tag{55}$$

where

$$P(\phi) = \int_0^\infty p(\phi, t)\, dt$$

As we noted previously, $p(\phi, \infty) = 0$, and since $\phi$ is assumed initially at zero, $p(\phi, 0) = \delta(\phi)$. Therefore, we have

$$-\delta(\phi) = \frac{\partial}{\partial\phi}[AK\sin\phi\, P(\phi)] + \frac{N_0K^2}{4}\frac{\partial^2 P(\phi)}{\partial\phi^2} \tag{56}$$

[5]The solution of the so-called first passage time problem by means of the Fokker-Planck equation with absorbing boundaries was first treated by Siegert (Ref. 14).

which may be solved using the boundary conditions

$$P(\phi_l) = \int_0^\infty p(\phi_l, t)\,dt = 0$$
$$P(-\phi_l) = \int_0^\infty p(-\phi_l, t)\,dt = 0 \tag{57}$$

The solution to Eq. (56) may then be integrated with respect to $\phi$ over the interval $-\phi_l, \phi_l$ to obtain $T$, the expected time to lose lock of Eq. (54). Taking the indefinite integral of both sides of Eq. (56), we obtain

$$C - u(\phi) = AK \sin\phi\, P(\phi) + \frac{N_0 K^2}{4} \frac{\partial P(\phi)}{\partial \phi} \tag{58}$$

where $C$ is a constant to be evaluated from the boundary conditions. The solution to the first-order differential equation is

$$P(\phi) = D \exp(\alpha \cos\phi) + \exp(\alpha\cos\phi) \int_{-\phi_l}^{\phi} \frac{\exp(-\alpha\cos x)}{\gamma} [C - u(x)]\,dx \tag{59}$$

where

$$\alpha = \frac{A^2}{N_0 (AK/4)}$$

and

$$\gamma = \frac{N_0 K^2}{4} = \frac{AK}{\alpha} = \frac{4B_L}{\alpha}$$

Applying the boundary conditions of Eq. (57) yields the values of the constants as $D = 0$ and $C = 1/2$.

Thus

$$P(\phi) = \frac{\exp(\alpha\cos\phi)}{\gamma} \int_{-\phi_l}^{\phi} \exp(-\alpha\cos x) \left[\frac{1}{2} - u(x)\right] dx \tag{60}$$

and integrating with respect to $\phi$ over the interval $[-\phi_l, \phi_l]$, we obtain an expression for the mean time to lose lock

$$T = \int_{\phi_l}^{\phi_l} P(\phi)\,d\phi = \frac{1}{\gamma}\int_{-\phi_l}^{\phi_l} d\phi \times \int_{-\phi_l}^{\phi} \exp\alpha(\cos\phi - \cos x)\left[\frac{1}{2} - u(x)\right] dx$$
$$= \frac{1}{\gamma}\int_0^{\phi_l}\int_{\phi}^{\phi_l} \exp\alpha(\cos\phi - \cos x)\,dx\,d\phi \tag{61}$$

The domain of integration is the right isosceles triangle shown in Fig. 9. We can obtain a series representation of this double integral by expanding the integrands in Fourier series

$$\exp(\alpha\cos\phi) = I_0(\alpha) + 2\sum_{m=1}^{\infty} I_m(\alpha)\cos m\phi$$
$$\exp(-\alpha\cos x) = I_0(\alpha) + 2\sum_{n=1}^{\infty} (-1)^n I_n(\alpha)\cos nx \tag{62}$$

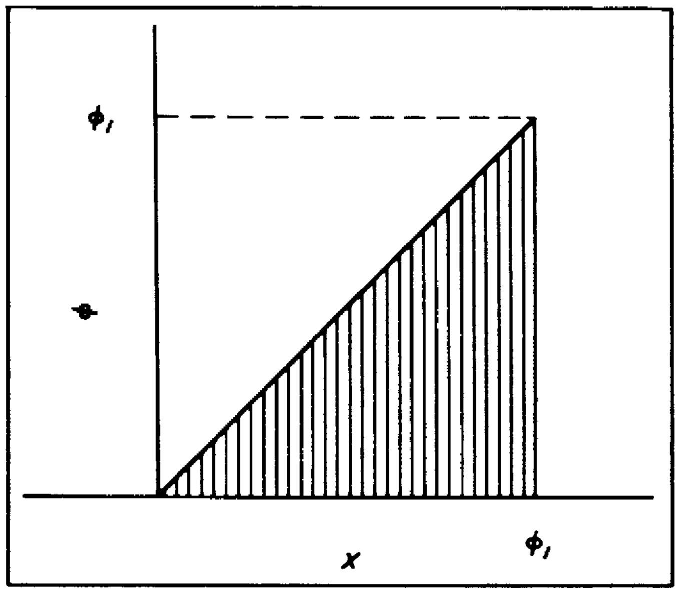


**Fig. 9. Domain of integral *T***

Then

$$T = \frac{1}{\gamma}\int_0^{\phi_l}\int_{\phi}^{\phi_l} \times \left[\begin{matrix} I_0^2(\alpha) + 4I_0(\alpha) \sum\limits_{n=2,4,6,\cdots}^{\infty} (-1)^n I_n(\alpha)\cos n\phi \\ + 4\sum\limits_{m=1}^{\infty}\sum\limits_{n=1}^{\infty} -(1)^n I_m(\alpha) I_n(\alpha)\cos m\phi\cos nx \end{matrix}\right] d\phi\,dx$$

$$= \frac{1}{\gamma}\Bigg[\frac{I_0^2(\alpha)\phi_l^2}{2} + 4I_0(\alpha)\sum_{n=1}^{\infty}\frac{I_{2n}(\alpha)}{2n}\sin 2n\phi_l + 4\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}(-1)^n I_m(\alpha) I_n(\alpha) \times \int_0^{\phi_l}\int_{\phi}^{\phi_l}\cos m\phi\cos nx\,dx\,d\phi\Bigg]$$

where

$$\int_0^{\phi_l}\int_{\phi}^{\phi_l}\cos m\phi\cos nx\,dx\,d\phi =$$

$$= \begin{cases} \cos(n-m)\phi_l\left[\dfrac{1}{nm}+\dfrac{1}{n(n-m)}\right] \\ -\dfrac{4\cos n\phi_l}{nm}-\dfrac{1}{(n-m)n} \end{cases} \text{when } n \neq m$$

$$= \left(\frac{1}{m^2}-\frac{\cos m\phi_l}{m^2}\right) \qquad \text{when } n = m \qquad (63)$$

This expression may be computed without the aid of a large-scale digital computer because the sequence $I_n(\alpha)$, and consequently the above series, converges quite rapidly.

However, the most important result which we seek can be obtained in closed form. This is the frequency of skipping cycles, or, in other words, the inverse of the expected time between skipping cycles, which is $T(\phi_l = 2\pi)$. It is clear from Eq. (63) that when $\phi_l = 2\pi$

$$T(2\pi) = \frac{2\pi^2}{\gamma} I_0^2(\alpha) = \frac{\pi^2\alpha I_0^2(\alpha)}{2B_L} \qquad (64)$$

where we have used

$$\gamma = \frac{N_0K^2}{4} = \frac{AK}{\alpha} = \frac{4B_L}{\alpha}$$

so that

$$\text{frequency of skipping cycles} = (2B_L)/[\pi^2\alpha I_0^2(\alpha)] \qquad (65)$$

This parameter normalized by $B_L$ is shown as a function of $\alpha$ in Fig. 10.

For large SNR, $\alpha$,

$$I_0(\alpha) \sim (e^{\alpha})/(2\pi\alpha)^{1/2}$$

so that

$$\text{frequency of skipping cycles} \simeq [(4B_L)/\pi]\,e^{-2\alpha} \qquad (66)$$

for large $\alpha$.

Another parameter which is equally significant is the frequency of dropping or advancing half cycles ($\phi_l = \pi$).

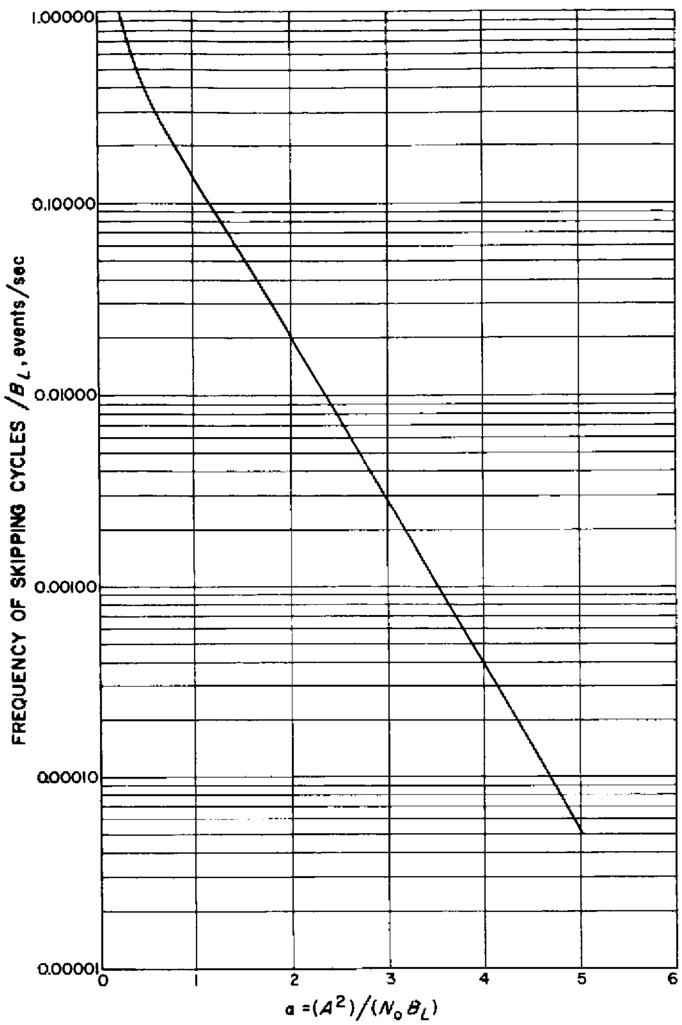


**Fig. 10. Frequency of skipping cycles normalized by loop bandwidth for first-order loop where $\omega = \omega_0$**

In the mechanical analog this corresponds to the pendulum arriving at the unstable equilibrium position and returning to the stable equilibrium position, either by the same route or by going around the full revolution. It is nearly intuitive that for a Markov process the frequency of this event is exactly double the frequency of skipping cycles. However, to show this rigorously, we note that the expected time for the pendulum to go from the equilibrium position $\phi = 0$ to $\phi = \pi$ and to return is $T(\pi) + T'(\pi)$, where $T(\pi)$ is the expected time to go from 0 to $\pm\pi$ and $T'(\pi)$ is the expected time to go from $\pi$ to either 0 or $2\pi$. $T(\pi)$ is given by Eq. (61) with $\phi_l = \pi$, while we can show that

$$T'(\pi) = \frac{1}{\gamma}\int_0^{\phi_l}\int_0^{\phi}\exp\alpha(\cos\phi - \cos x)\,dx\,d\phi$$

The integrand is the same as that for $T(\pi)$, but the domain of integration is its complement with respect to the square of side $\pi$ (Fig. 11). Therefore,

$$T(\pi) + T'(\pi) = \frac{1}{\gamma}\int_0^{\pi}\int_0^{\pi} \exp \alpha (\cos\phi - \cos x)\, dx\, d\phi$$

$$= (\pi^2/\gamma)\, I_0^2(\alpha) = [T(2\pi)/2] \qquad (67)$$

and

$$\text{frequency of skipping half-cycles} = (4B_L)/[\pi^2 \alpha I_0^2(\alpha)] \qquad (68)$$

We can show that these results are approximately correct also for the second-order loop when $\alpha$ is large or $a << 1$ by means of the arguments used in Part V to obtain Eq. (43) through (49).

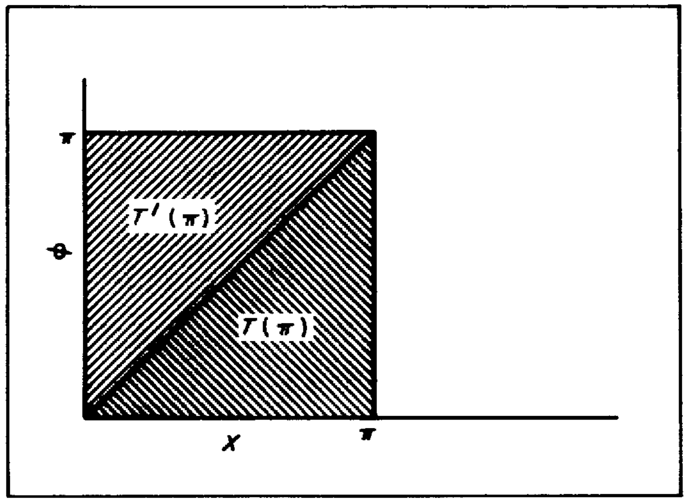


**Fig. 11. Domains of integration for $T(\pi)$ and $T'(\pi)$**

# VII. THRESHOLD CONSIDERATIONS AND CONCLUSIONS

By means of the approximate models discussed in Part I, Van Trees (Ref. 5) and Develet (Ref. 6) have attempted to determine the threshold of the phase-locked loop; the threshold, as they define it, is the value of SNR for which the variance of the phase error becomes unbounded. However, we have shown by an exact analysis that the variance of the steady-state error is always bounded by the variance of the rectangular distribution $p(\phi) = (1/2\pi)$ for $-\pi < \phi < \pi$, which equals $(\pi^2/3)$. This is due to the fact that phase is measured to the nearest cycle (i.e., modulo $2\pi$). On the other hand, if we count a change of a full cycle of phase as a phase error of $2\pi$, and consider the resulting distribution and its variance, we find that the variance is unbounded for all noise densities greater than zero, for with this premise, the steady-state probability density has been shown to be a periodic function, so that its variance is necessarily unbounded. In simple physical terms, for any nonzero noise power, if the noise has a Gaussian distribution with probability one the loop will gain or lose a cycle if enough time elapses. (For the first-order loop, the expected time was obtained exactly in Eq. 64). Therefore, in the steady state (i.e., after an infinite interval of time has elapsed), the number of cycles skipped has a flat probability distribution; hence the probability density function is periodic. Since the idea of infinite variance for all finite SNR is ridiculous, we have no alternative but to accept the concept that phase is meaningful only modulo $2\pi$, so that the variance is never unbounded. The mechanical analog of the simple pendulum discussed in Part II is useful in visualizing these conclusions.

If we redefine threshold to mean that value of SNR for which the linear model, or some other approximate model, becomes inadequate for the analysis, then our foregoing results can be utilized to determine the threshold of the model. It has been shown that, for a first-order loop with no frequency offset, the steady-state phase error has probability density

$$p(\phi) = \frac{\exp(\alpha \cos \phi)}{2\pi I_0(\alpha)} \qquad -\pi \leq \phi \leq \pi$$

where $\alpha = (A^2)/(N_0 B_L)$ and that this is approximately correct also for a second-order loop with small integrator gain. Also, we have shown that the variance of $\phi$ in this case is given by

$$\sigma_\phi^2 = \frac{\pi^2}{3} + 4 \sum_{n=1}^{\infty} \frac{(-1)^n I_n(\alpha)}{n^2 I_0(\alpha)} \tag{69}$$

This is shown in Fig. 12 as a function of $1/\alpha = N_0 B_L/A^2$, where it is compared with the variance obtained from the linear model which is simply

$$\sigma_\phi^2 = \frac{N_0 B_L}{A^2} = \frac{1}{\alpha} \qquad \text{(Linear)} \tag{70}$$

Also shown in Fig. 12 are the results using the approximate models of Van Trees and Develet. Van Trees (Ref. 5) shows that for the first-order loop with no frequency offset (in our terminology)

$$\sigma_\phi^2 = \frac{1}{\alpha - 1} \qquad \text{(Van Trees)} \tag{71}$$

so that the model yields an unbounded variance at $\alpha \leq 1$. Develet (Ref. 6) used the quasi-linearization technique of Booton (Ref. 7) which replaces the sinusoidal nonlinearity of Fig. 4 by its average gain, assuming that the input distribution is nearly Gaussian. The gain of a sinusoidal nonlinearity for an input of value $x$ is $A \cos x$. Therefore, the average gain when the input is Gaussian of mean zero and variance $\sigma^2$ is

$$\int_{-\infty}^{\infty} A \cos x \exp\left(\frac{x^2}{2\sigma^2}\right) dx = A \exp\left(-\frac{\sigma^2}{2}\right)$$

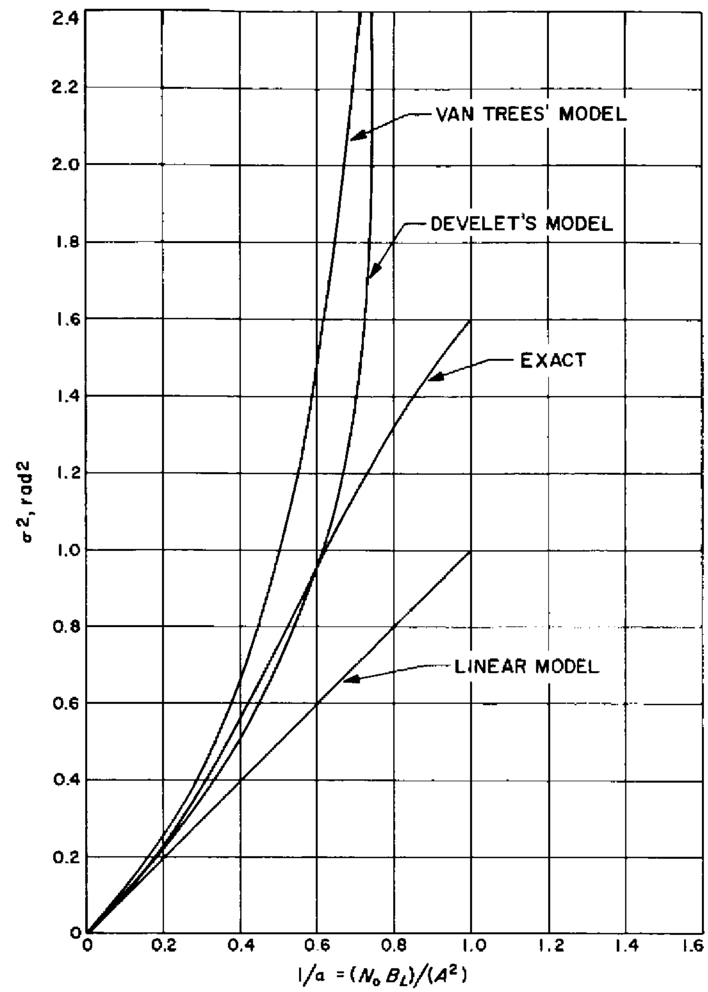


**Fig. 12. Comparison of variance for first-order loop with results of approximate models**

Replacing the nonlinear element of Fig. 4 by this gain, we obtain, by the usual linear analysis, the variance of the phase error for the first-order loop:

$$\sigma^2 = (1/\alpha) \exp(\sigma^2/2) \quad \text{(Develet)} \tag{72}$$

The solution of this transcendental equation yields the value of the variance which is also shown in Fig. 12. The maximum of $\sigma^2$ exp $-(\sigma^2/2)$ is $2/e$ so that there can be no solution for $\alpha < e/2$. This is the point of unbounded variance for Develet's model.

In Fig. 12 we see that for SNR $= \alpha > 1$, the linear model always yields an underestimate while Van Trees' result is always an overestimate of the variance of the phase error, as might be expected from the nature of the approximations. With the linear model the error in the approximation is less than 20% as long as $[(N_0 B_L)/A^2] < 1/4$, or $\alpha > 4$ which is a figure often quoted by experimenters as a threshold of the linear model. Develet's model yields by far the most accurate result. In fact, it differs from the exact result by less than 10% for $[(N_0 B_L)/A^2] < 0.65$, or $\alpha > 1.54$. Thus it would appear that if the exact solution cannot be obtained, as is the case for higher order loops, colored noise, or a modulated carrier, the Booton quasi-linearized model would yield quite accurate results when the SNR in the loop bandwidth is above 1.5.

The other significant result of this Report, which can be used to define threshold, is the frequency of skipping cycles. It was shown in Part VI that for a first-order loop with no frequency offset or a second-order loop with very small integrator gain, the

$$\text{frequency of skipping cycles} = (2B_L)/[\pi^2 \alpha I_0^2(\alpha)]$$

which is plotted in Fig. 10. Thus we might set the threshold of the system as the SNR below which the frequency of skipping cycles exceeds a given value. Thus, for example, let $B_L = 20$ cps and the maximum allowable frequency of skipping cycles be once every minute. Then we see from Fig. 10 that the threshold of the system is at $\alpha = 3.6$. Note, however, that when the system operates at $\alpha = 7.2$, 3 db above threshold, the frequency of skipping cycles drops to once every 20 hr reflecting the exponential behavior of this expression. This definition of threshold is most significant for coherent tracking applications wherein the doppler frequency is measured and integrated to obtain relative range information. Loss or gain of a cycle will yield incorrect results.

A third definition of threshold is the SNR for which the absolute value of the loop phase error $|\phi|$ exceeds a given value $\phi_0$ exactly half the time. For the first-order loop with $\omega = \omega_0$, this information is available from the cumulative probability distribution of Fig. 6. For example, if we set $\phi_0$ at $\pi/4$ rad, we find from Fig. 6 that the SNR at which $|\phi|$ exceeds this value exactly half the time is $\alpha = 1.1$. We see also that when the SNR is 3 db above this threshold level (i.e., $\alpha = 2.2$), then $|\phi|$ exceeds $\pi/4$ rad only about three-tenths of the time.

It is felt that the third definition of threshold has the least significance. The definition in terms of skipping cycles is most meaningful for ranging and tracking applications. However, the most useful result is the determination of the threshold of validity of the various models of the phase-locked loop. By comparing the variance of the phase error computed from each of the models with the actual variance for the first-order loop, which is the only case for which an exact solution in closed form is available, we have been able to determine these validity thresholds. The linear model underestimates the variance by less than 20%, for SNR $> 4$ (6 db). Van Trees' model overestimates $\sigma^2$ to within this accuracy for SNR $> 2.5$ (4 db), while Develet's model is accurate to within 10% for SNR $> 1.54$ (1.7 db). It does not necessarily follow that each model will yield equal accuracy for more complicated loops or signals, but these figures do represent lower bounds on the over-all validity. They also provide a ranking on the merits of the three models. It appears that the simpler the expression for variance, the less accurate is the result. If we wish merely to obtain bounds on performance, the results of Fig. 12 suggest that we use the linear model as an upper bound and Van Trees' model as a lower bound. On the other hand, if we are willing to solve a transcendental equation of the type of Eq. (69), it appears that Develet's model produces significantly greater accuracy over a much wider range of SNR.

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## ACKNOWLEDGMENT

The writer is indebted to Prof. J. N. Franklin and Dr. E. C. Posner for several valuable discussions during the preparation of this manuscript.

# Electronic Acknowledgement Receipt

| | |
|---|---|
| **EFS ID:** | 29216234 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 15-MAY-2017 |
| **Filing Date:** | 26-JUN-2014 |
| **Time Stamp:** | 19:56:51 |
| **Application Type:** | Utility under 35 USC 111(a) |

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| 1 | Amendment/Req. Reconsideration-After Non-Final Reject | jm_soam_response.pdf | 341674<br>26b01193679fc4fe28b22bc7f21cc5d8e1b1bde2 | no | 42 |

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| PATENT APPLICATION FEE DETERMINATION RECORD<br>Substitute for Form PTO-875 | Application or Docket Number<br>14/316,489 | Filing Date<br>06/26/2014 | ☐ To be Mailed |
|---|---|---|---|

ENTITY: ☐ LARGE ☑ SMALL ☐ MICRO

## APPLICATION AS FILED - PART I

| FOR | (Column 1) NUMBER FILED | (Column 2) NUMBER EXTRA | | RATE ($) | FEE ($) |
|---|---|---|---|---|---|
| ☐ BASIC FEE (37 CFR 1.16(a), (b), or (c)) | N/A | N/A | | N/A | |
| ☐ SEARCH FEE (37 CFR 1.16(k), (i), or (m)) | N/A | N/A | | N/A | |
| ☐ EXAMINATION FEE (37 CFR 1.16(o), (p), or (q)) | N/A | N/A | | N/A | |
| TOTAL CLAIMS (37 CFR 1.16(i)) | minus 20 = | * | | x $40 = | |
| INDEPENDENT CLAIMS (37 CFR 1.16(h)) | minus 3 = | * | | x $210 = | |
| ☐ APPLICATION SIZE FEE (37 CFR 1.16(s)) | If the specification and drawings exceed 100 sheets of paper, the application size fee due is $310 ($155 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s). | | | | |
| ☐ MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j)) | | | | | |
| * If the difference in column 1 is less than zero, enter "0" in column 2. | | | | TOTAL | |

## APPLICATION AS AMENDED - PART II

| | | (Column 1) | | (Column 2) | (Column 3) | | | |
|---|---|---|---|---|---|---|---|---|
| AMENDMENT | 05/15/2017 | CLAIMS REMAINING AFTER AMENDMENT | | HIGHEST NUMBER PREVIOUSLY PAID FOR | PRESENT EXTRA | | RATE ($) | ADDITIONAL FEE ($) |
| | Total (37 CFR 1.16(i)) | * 6 | Minus | ** 20 | = 0 | | x $40 = | 0 |
| | Independent (37 CFR 1.16(h)) | * 1 | Minus | *** 3 | = 0 | | x $210 = | 0 |
| | ☐ Application Size Fee (37 CFR 1.16(s)) | | | | | | | |
| | ☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | | |
| | | | | | | | TOTAL ADD'L FEE | 0 |

| | | (Column 1) | | (Column 2) | (Column 3) | | | |
|---|---|---|---|---|---|---|---|---|
| AMENDMENT | | CLAIMS REMAINING AFTER AMENDMENT | | HIGHEST NUMBER PREVIOUSLY PAID FOR | PRESENT EXTRA | | RATE ($) | ADDITIONAL FEE ($) |
| | Total (37 CFR 1.16(i)) | * | Minus | ** | = | | x $0 = | |
| | Independent (37 CFR 1.16(h)) | * | Minus | *** | = | | x $0 = | |
| | ☐ Application Size Fee (37 CFR 1.16(s)) | | | | | | | |
| | ☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | | |
| | | | | | | | TOTAL ADD'L FEE | |

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| * If the entry in column 1 is less than the entry in column 2, write "0" in column 3. | LIE |
| ** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20". | sharain E moreland |
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| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

23497 7590 05/11/2017
JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

| EXAMINER | |
|---|---|
| WU, ZHEN Y | |
| **ART UNIT** | **PAPER NUMBER** |
| 2685 | |
| **MAIL DATE** | **DELIVERY MODE** |
| 05/11/2017 | PAPER |

**Please find below and/or attached an Office communication concerning this application or proceeding.**

The time period for reply, if any, is set in the attached communication.

| *Office Action Summary* | **Application No.** 14/316,489 | **Applicant(s)** MARGOLIN, JED | |
|---|---|---|---|
| | **Examiner** ZHEN Y. WU | **Art Unit** 2685 | **AIA (First Inventor to File) Status** Yes |

***-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --***

**Period for Reply**

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE *3* MONTHS FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

**Status**

1)☒ Responsive to communication(s) filed on *02/04/2017*.
☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

**Disposition of Claims***

5)☒ Claim(s) *1-18* is/are pending in the application.
5a) Of the above claim(s) _____ is/are withdrawn from consideration.
6)☒ Claim(s) *6-11 and 15-17* is/are allowed.
7)☒ Claim(s) *1-3,12-14 and 18* is/are rejected.
8)☒ Claim(s) *4 and 5* is/are objected to.
9)☐ Claim(s) _____ are subject to restriction and/or election requirement.

* If any claims have been determined allowable, you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

**Application Papers**

10)☐ The specification is objected to by the Examiner.
11)☐ The drawing(s) filed on _____ is/are: a)☐ accepted or b)☐ objected to by the Examiner.
Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).
Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

**Priority under 35 U.S.C. § 119**

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

**Certified copies:**

a)☐ All b)☐ Some** c)☐ None of the:
1.☐ Certified copies of the priority documents have been received.
2.☐ Certified copies of the priority documents have been received in Application No. _____.
3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

** See the attached detailed Office action for a list of the certified copies not received.

**Attachment(s)**

1) ☒ Notice of References Cited (PTO-892)
2) ☐ Information Disclosure Statement(s) (PTO/SB/08a and/or PTO/SB/08b) Paper No(s)/Mail Date _____.
3) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .
4) ☐ Other: _____.

# DETAILED ACTION

## AIA Status

The present application, filed on or after March 16, 2013, is being examined under the first inventor to file provisions of the AIA.

## *Priority*

Application claims priority to a provisional application 62/005,199 filed on 05/30/2014.

## Claim Status

Claims 1-18 are currently pending for examination.

## *Claim Rejections - 35 USC § 103*

In the event the determination of the status of the application as subject to AIA 35 U.S.C. 102 and 103 (or as subject to pre-AIA 35 U.S.C. 102 and 103) is incorrect, any correction of the statutory basis for the rejection will not be considered a new ground of rejection if the prior art relied upon, and the rationale supporting the rejection, would be the same under either status.

The following is a quotation of 35 U.S.C. 103 which forms the basis for all obviousness rejections set forth in this Office action:

> A patent for a claimed invention may not be obtained, notwithstanding that the claimed invention is not identically disclosed as set forth in section 102, if the differences between the claimed invention and the prior art are such that the claimed invention as a whole would have

been obvious before the effective filing date of the claimed invention to a person having ordinary skill in the art to which the claimed invention pertains. Patentability shall not be negated by the manner in which the invention was made.

The factual inquiries set forth in *Graham v. John Deere Co.*, 383 U.S. 1, 148 USPQ 459 (1966), that are applied for establishing a background for determining obviousness under 35 U.S.C. 103 are summarized as follows:

1. Determining the scope and contents of the prior art.

2. Ascertaining the differences between the prior art and the claims at issue.

3. Resolving the level of ordinary skill in the pertinent art.

4. Considering objective evidence present in the application indicating obviousness or nonobviousness.

Claims 1, 2 and 12 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1).

Regarding claim 1, Haupenthal (383) teaches **a system for detecting the presence of a flame comprising:**

**a. a combustion burner** (Fig. 1)**;**

**b. a flame rod** (Fig. 1, ionization electrodes 3)**;**

**c. a signal source having a selected waveform connected to said flame rod** (Fig. 1, signal source having an ac waveform is connected to the electrode)**;**

**d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through**

**said flame** (Fig. 1, and Col. 4, lines 36-50, "Ionization electrodes 3 or ultraviolet sensors 4,4a are supplied by way of a connecting terminal 1 with the ac voltage signal from a suitable source 5 and supply the signal which is generated by the flame and on which an unwanted alternating current signal is superimposed to the terminal 2 at which an evaluation circuit 6, here a filter member, detects the direct current signal I.sub.F.");

**e. a signal detector having an input connected to the output of said high impedance buffer** (Fig. 1, evaluation circuit 6);

**f. an indicator connected to the output of said signal detector** (Abstract "The direct current signal (I.sub.F) is detected by an evaluation circuit (6) and converted into a first output signal (A), wherein conversion is effected by various further circuit elements (7, 9, 10) in such a way that differently changing output signals (A.sub.1, A.sub.2) are obtained depending on the respective flame intensity.". Indicate the intensity of the flame);

**whereas**

**g. said flame from said combustion burner causes distortion of said signal source having a selected waveform producing a** distorted **signal** (Fig. 5, Col. 7 lines 18-28, "The uppermost diagram shows the direct current signal I.sub.F on which the alternating current signal is superimposed, in which case the alternating current signal is only shown in part for the sake of enhanced clarity.”. The ac source signal is distorted by the direct current generated by the flame)**, and**

**h. said signal detector is configured to detect said** distorted **signal and indicate the results on said indicator** (Fig. 5. Col. 7 line 29-43, detect flame intensity according to the dc component of the superimposed waveform)**.**

Haupenthal (383) teaches a flame monitoring system that detects flame intensity according to the dc current generated by the flame superimposed on the ac source signal instead of the **harmonic** distortion of the ac source signal.

However, in the same field of flame monitoring system, Haupenthal (486) teaches a system that detects the harmonic frequency signal by the flame. See Abstract, “A frequency-selective arrangement (6, 17, 18, 19) detects the presence of mains frequency-harmonic signals in the flame signal (U.sub.1) and activates the flame signal amplifier (40) when there are no mains frequency-harmonic signals in the flame signal (U.sub.1) and deactivates the flame signal amplifier (40) when there is a flame signal (U.sub.1) with periodic signals or no flames signal (U.sub.1) or a test signal (T).”.

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)’s evaluation circuit with Haupenthal (486)’s harmonic detection system to detect harmonic distortion to accurately detect the presence of a flame.

Regarding claim 2, Haupenthal (383) in the combination teaches **the system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave** (Fig. 1, ac voltage source. The ac voltage source is low distortion compare to the superimposed voltage)**.**

Regarding claim 12, recite limitation similar to claim 1. Therefore, claim 12 is rejected with the same rationale and claim 1.

Claims 3, 13 and 14 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 or 12 and further in view of Ngo (Pub. No.: US 2008/0266000 A1).

Regarding claim 3, Haupenthal (486) in the combination teaches **the system of claim 1 whereby said harmonic signal detector comprises** a detectors to detect harmonic but fails to expressly teach **a phase locked loop tuned to the frequency of said harmonic signal.**

However, in the same field of harmonic detection system, Ngo teaches a phase locked loop that is tuned to a harmonic frequency. See para [0005], "Based on an input reference signal, a digital frequency multiplier circuit utilizes a voltage controlled oscillator (VCO), which is tuned to a harmonic of the input frequency signal, along with a frequency divider and a phase-locked loop (PLL) to generate a desired output frequency.”.

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (486)’s harmonic detector with Ngo's phase locked loop to detect a desired harmonic frequency that would accurately detect the presence of a flame.

Regarding claim 13, recite limitation similar to claim 3. Therefore, claim 13 is rejected with the same rationale and claim 3.

Regarding claim 14, the combination teaches **the method of claim 12** but fails to teach **where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.**

However, in the same field of harmonic detection system, Ngo teaches an external clock signal and a control circuit to align the internal signal with external clock signal. See Abstract, “The DCO generates an internal feedback signal. The phase detector detects a phase difference between the internal feedback signal and an external reference clock signal. Coupled between the phase detector and the DCO, the control circuit adjusts the DCO to align the internal feedback signal with the external reference clock signal after a phase difference between the internal feedback signal and the external reference clock signal has been detected.".

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)'s harmonic detector with a clock and a synchronous detector to synchronous various signals to produce an accurate result.

Claim 18 is rejected under 35 U.S.C. 103 as being unpatentable over Sohma (Pat. No.: 5,547,369) in view of Su (Pub. No.: US 2014/0085503 A1).

Regarding claim 18, Sohma teaches **a method for detecting the presence of a flame** (Fig. 1 and Col. 3 lines 13-33, determines the properties of a flame) **comprising the steps of:**

**c. providing a signal detector to detect a mixing signal produced by said two signal sources** (Fig. 1, a camera is used to detect the mixing of light signals)**; and**

**d. providing an indicator to indicate the results of said signal detector** (Col. 3 lines 25-27, "a camera which photographs flames; display means for displaying a picture of the flames by using an output signal from the camera;")**.**

Sohma fails to expressly teach **providing two signal sources to said flame** and **using flame rectification to cause said two signal sources to mix.**

However, in the same field of photo-shooting, Su teaches lights are mixed together from different lights sources, such as the lights sources are mixed with the flame and detected by the camera. See para [0005], "While taking photos, the ambient light while photo-shooting may be a mixture combining lights from different sources (such as natural light, fluorescent tubes, incandescent light bulb, etc.). Lights from different sources may have individual spectral characteristics, such that the ambient light mixed from them may have a different color temperature.".

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Sohma's flame detection system with various ambient lights sources to be mixed with the flame to produce a higher quality picture.

***Allowable Subject Matter***

Claims 4 and 5 objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

The following is a statement of reasons for the indication of allowable subject matter: claims 6-11, 15-17 and dependent claims 4 and 5 are objected to indicated to be allowable as the prior art does not teach or fairly suggest the applicant's claimed invention. The distinguishing elements are claim 4 “**a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising: a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal; b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.**”,

claim 5 “**a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising: a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal; b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal; c. a first absolute value amp having an input connected to the output of said first multiplier; d. a second absolute value amp having an input connected to the output of said second multiplier; e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value**

**amp; f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.**",

Claim 6 "**said flame from said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a first mixing signal at the sum of the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform as well as a second mixing signal at the difference between the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform,**" and

claim 15 "**in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a sum signal at the sum frequency of said first signal source and said second signal source and a difference signal at the difference frequency of said first signal source and said second signal source,**" are allowable subject matter. The various claimed limitations mentioned in the claims are not taught or suggested by the prior art taken either singly or in combination, with emphasize that it is each claim, taken as a whole, including the interrelationships and interconnections between parent claims and various claimed elements make them allowable over the prior art of record.

***Conclusion***

Any inquiry concerning this communication or earlier communications from the examiner should be directed to ZHEN Y. WU whose telephone number is (571)272-5711. The examiner can normally be reached on Monday to Friday, 8AM - 5PM, Alternate Friday, EST.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Hai Phan can be reached on (571) - 272-6338. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/ZHEN Y WU/
Examiner, Art Unit 2685

| *Notice of References Cited* | Application/Control No. 14/316,489 | Applicant(s)/Patent Under Reexamination MARGOLIN, JED | |
|---|---|---|---|
| | Examiner ZHEN Y. WU | Art Unit 2685 | Page 1 of 1 |

**U.S. PATENT DOCUMENTS**

| * | | Document Number Country Code-Number-Kind Code | Date MM-YYYY | Name | CPC Classification | US Classification |
|---|---|---|---|---|---|---|
| * | A | US-2014/0085503 A1 | 03-2014 | Su; Wen-Yueh | G03B7/16 | 348/223.1 |
| * | B | US-5,547,369 A | 08-1996 | Sohma; Kenichi | F23M11/045 | 340/577 |
| | C | US- | | | | |
| | D | US- | | | | |
| | E | US- | | | | |
| | F | US- | | | | |
| | G | US- | | | | |
| | H | US- | | | | |
| | I | US- | | | | |
| | J | US- | | | | |
| | K | US- | | | | |
| | L | US- | | | | |
| | M | US- | | | | |

**FOREIGN PATENT DOCUMENTS**

| * | | Document Number Country Code-Number-Kind Code | Date MM-YYYY | Country | Name | CPC Classification |
|---|---|---|---|---|---|---|
| | N | | | | | |
| | O | | | | | |
| | P | | | | | |
| | Q | | | | | |
| | R | | | | | |
| | S | | | | | |
| | T | | | | | |

**NON-PATENT DOCUMENTS**

| * | | Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages) |
|---|---|---|
| | U | |
| | V | |
| | W | |
| | X | |

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

| Search Notes | Application/Control No. | Applicant(s)/Patent Under Reexamination |
|---|---|---|
| | 14316489 | MARGOLIN, JED |
| | **Examiner** | **Art Unit** |
| | ZHEN Y WU | 2685 |

## CPC- SEARCHED

| Symbol | Date | Examiner |
|---|---|---|
| F23N 5/123, 2023/42, 2023/10 | 1/17/2017 | ZYW |
| G08B 17/125 | 1/17/2017 | ZYW |
| Y02T 50/677 | 5/4/2017 | ZYW |

## CPC COMBINATION SETS - SEARCHED

| Symbol | Date | Examiner |
|---|---|---|
| | | |

## US CLASSIFICATION SEARCHED

| Class | Subclass | Date | Examiner |
|---|---|---|---|
| 340 | 577 | 1/17/2017 | ZYW |

## SEARCH NOTES

| Search Notes | Date | Examiner |
|---|---|---|
| All CPC and USPC classifications listed were searched in combination with keywords in EAST | 1/17/2017 | ZYW |
| Inventor and assignee searches double patenting | 1/17/2017 | ZYW |
| NPL searches (eg. Google, Google scholar) | 1/17/2017 | ZYW |
| Consulted with SPE Hai Phan with claim and allowable subject matter | 1/17/2017 | ZYW |
| Updated searches | 5/4/2017 | ZYW |

## INTERFERENCE SEARCH

| US Class/ CPC Symbol | US Subclass / CPC Group | Date | Examiner |
|---|---|---|---|
| | | | |

| /ZHEN Y WU/<br>Examiner, Art Unit 2685 | |
|---|---|

**EAST Search History**

**EAST Search History (Prior Art)**

| Ref # | Hits | Search Query | DBs | Default Operator | Plurals | Time Stamp |
|---|---|---|---|---|---|---|
| L2 | 367070 | camera with light | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:47 |
| L3 | 1594 | camera with light$3 with mix$3 | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:48 |
| L4 | 5 | camera with light$3 with mix$3 with fire | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:49 |
| L5 | 2172 | camera with light$3 with (fire or flame) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:50 |
| L6 | 6 | take near8 (photo or picture) near8 light$3 with (fire or flame) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:51 |
| L7 | 16 | tak$3 near8 (photo or picture) near8 light$3 with (fire or flame) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:52 |
| L8 | 882 | lighting with photo with camera | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:57 |
| L9 | 270 | lighting near8 photo near8 camera | US-PGPUB; | AND | ON | 2017/05/04 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | 14:57 |
| L10 | 4322 | lights near8 photo near8 camera | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/05/04 14:58 |
| L11 | 58 | lights near8 photo near8 camera | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/05/04 14:58 |
| L12 | 33 | lights near8 photo near8 tak$3 and camera | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | OFF | 2017/05/04 15:01 |
| S2 | 1 | (Margolin near jed).in. and (flame with burner).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 16:05 |
| S4 | 23 | ("1077628" \| "1688126" \| "2112736" \| "2136256" \| "2709799" \| "2804608" \| "3301307" \| "3956080" \| "0307031" \| "4082493" \| "4317487" \| "6404342" \| "8310801" \| "0803684").PN. | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 16:13 |
| S6 | 3 | detect$3 near8 harmonic near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:20 |
| S7 | 89 | sens$3 near4 (resistance or resistivit$3) near4 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:20 |
| S8 | 2 | (sens$3 or detect$3) with harmonic with distortion with flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:21 |

| | | | | | | |
|---|---|---|---|---|---|---|
| S9 | 2 | harmonic near distortion near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S10 | 2 | harmonic near distortion near8 flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S11 | 3 | harmonic near distortion near8 fire | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S12 | 14399 | signal with flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:31 |
| S13 | 256 | two near2 signals with flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:31 |
| S14 | 38 | two near2 signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:32 |
| S15 | 94 | appl$3 with signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:36 |
| S16 | 59 | appl$3 near8 signals near8 flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:37 |
| S17 | 1 | "6486486".pn. | US-PGPUB; USPAT; USOCR | AND | ON | 2017/04/19 12:25 |
| S18 | 2 | "6486486".pn. or "6501383".pn. | US-PGPUB; USPAT; USOCR | AND | ON | 2017/04/19 12:26 |
| S19 | 4323 | 340/577.ccls. F23N5/123 G08B17/125 F23N2023/10 F23N2023/42 Y02T50/677 | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:46 |
| S20 | 1 | S19 and harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; | OR | ON | 2017/04/19 12:47 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S21 | 29 | S19 and mixing with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:47 |
| S22 | 1838298 | S19 and mixing with signal (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:47 |
| S23 | 8 | S19 and mixing with signal with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:47 |
| S24 | 14 | S19 and combin$4 with signal with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:48 |
| S25 | 158 | ("1077628" \| "6486486" \| "4082493" \| "6404342" \| "1688126" \| "2804608" \| "8310801" \| "2136256" \| "4317487" \| "2112736" \| "2709799" \| "3956080" \| "0803684" \| "3301307" \| "0307031" \| "20080266000" \| "6501383").PN. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 12:49 |
| S26 | 26 | ("1077628" \| "6486486" \| "4082493" \| "6404342" \| "1688126" \| "2804608" \| "8310801" \| "2136256" \| "4317487" \| "2112736" \| "2709799" \| "3956080" \| "0803684" \| "3301307" \| "0307031" \| "20080266000" \| "6501383").PN. | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 12:49 |
| S27 | 2 | detect$3 near8 harmonic near8 (flame or fire) and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:00 |
| S28 | 0 | S26 and (combin$3 or mix$3) with signal | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:01 |
| S29 | 4 | S26 and (harmonic) with signal | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:01 |
| S30 | 4 | harmonic near3 distortion near8 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:04 |
| S31 | 5 | harmonic near3 distortion near8 (flame or fire) | US-PGPUB; USPAT; | OR | ON | 2017/04/19 13:04 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S32 | 977 | two near2 signals with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 13:06 |
| S33 | 287 | two near2 signals with (flame or fire) with detect$3 with signal | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/04/19 13:06 |
| S34 | 111 | two near2 signals with (flame or fire) with detect$3 with signal | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:07 |
| S35 | 148 | signal with flame near2 rod | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:12 |
| S36 | 2 | signal with flame near2 rod and harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:13 |
| S37 | 5 | signal with flame near2 rod with mix$3 | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:13 |
| S38 | 14 | mixing with signal with through with (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:26 |
| S39 | 1 | flame near2 rectification with signal with mix$3 | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:30 |
| S40 | 572 | apply with signal with (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S41 | 352 | apply near10 signal near10 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S42 | 2071 | appl$3 near10 signal near10 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S43 | 234 | appl$3 near10 signal near10 through with (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:48 |
| S45 | 147 | appl$3 near10 signal near10 through with (flame or fire) and @ad<"20140530" | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:49 |
| S46 | 26 | appl$3 near10 signal near10 through with (flame or fire) and burner and @ad<"20140530" | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 13:50 |
| S47 | 36 | (Margolin near2 Jed).in. | US-PGPUB; USPAT; USOCR; | AND | ON | 2017/04/19 18:11 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S48 | 1 | S47 and (flame with harmonic).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/04/19 18:11 |
| S49 | 1 | S47 and (flame with mixing with signal).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/04/19 18:12 |
| S50 | 145 | flame near2 rod with electrode | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:15 |
| S51 | 133 | flame near2 rod with electrode and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:15 |
| S52 | 3 | flame near2 rod with electrode with signal and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S54 | 82708 | phase near2 locked near2 loop | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S55 | 38475 | phase near2 locked near2 loop with frequency | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S56 | 389 | phase near2 locked near2 loop with frequency with harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:16 |
| S57 | 1 | phase near2 locked near2 loop with frequency with harmonic and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:17 |
| S58 | 0 | phase near2 locked near2 loop with frequency with harmonic with burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:17 |
| S59 | 23 | phase near2 locked near2 loop with frequency with harmonic with tuned | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:18 |
| S60 | 2 | harmonic near2 detector near10 clock near10 synchronous | US-PGPUB; USPAT; USOCR | OR | ON | 2017/04/19 18:21 |

**EAST Search History (Interference)**

<This search history is empty>

**5/4/2017 4:01:21 PM**
**C:\Users\zwu1\Documents\EAST\Workspaces\14316489 (Flame Sensing system).wsp**

| *Index of Claims* | Application/Control No.<br>14316489 | Applicant(s)/Patent Under Reexamination<br>MARGOLIN, JED |
|---|---|---|
| | Examiner<br>ZHEN Y WU | Art Unit<br>2685 |

| ✓ | Rejected | - | Cancelled | N | Non-Elected | A | Appeal |
|---|---|---|---|---|---|---|---|
| = | Allowed | ÷ | Restricted | I | Interference | O | Objected |

☐ Claims renumbered in the same order as presented by applicant ☐ CPA ☐ T.D. ☐ R.1.47

| CLAIM | | DATE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Final | Original | 01/17/2017 | 05/04/2017 | | | | | | | |
| | 1 | ✓ | ✓ | | | | | | | |
| | 2 | ✓ | ✓ | | | | | | | |
| | 3 | ✓ | ✓ | | | | | | | |
| | 4 | O | O | | | | | | | |
| | 5 | O | O | | | | | | | |
| | 6 | N | = | | | | | | | |
| | 7 | N | = | | | | | | | |
| | 8 | N | = | | | | | | | |
| | 9 | N | = | | | | | | | |
| | 10 | N | = | | | | | | | |
| | 11 | N | = | | | | | | | |
| | 12 | ✓ | ✓ | | | | | | | |
| | 13 | ✓ | ✓ | | | | | | | |
| | 14 | ✓ | ✓ | | | | | | | |
| | 15 | N | = | | | | | | | |
| | 16 | N | = | | | | | | | |
| | 17 | N | = | | | | | | | |
| | 18 | N | ✓ | | | | | | | |

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of Jed Margolin

Serial No.: 14/316,489

Filed: 06/26/2014

For: Flame Sensing System

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

This is in response to the Office Action mailed 01/19/2017.

**1.** The Examiner acknowledged Applicant's traverse filed 11/04/2016 but failed to respond to it or even give it a formal rejection. Nonetheless he withdrew from consideration the claims that Applicant had conditionally withdrawn.

**2.** Applicant filed a Petition to Withdraw Restriction Requirement 01/25/2017. Applicant's Petition was dismissed on 02/01/2017 because the Examiner's rejection of Applicant's traverse had not technically been made final. However, after Applicant's Petition was forwarded to the Examiner, on 2/3/2017 the Examiner called Applicant and left a message saying he would examine all of Applicant's claims.

The following is Applicant's response to the Examiner's Office Action mailed 01/19/2017.

**3.** In the Examiner's Office Action mailed 01/19/2017 he rejected Claims 1, 2 and 12 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1).

**4.** The Examiner rejected Claims 3, 13 and 14 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).

**5.** Claims 4 and 5 were objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

The claims begin on page 3.

Applicant's remarks begin on page 9.

Applicant will note at this point that in addition to Haupenthal '383 and '486 not being relevant to Applicant's invention the Examiner materially misquoted Applicant's claim 1 making the Examiner's rejection of claim 1 improper. Since the Examiner based his rejection of claims 2 and 12 on his rejection of claim 1 his rejection of claims 2 and 12 is improper as well.

Respectfully submitted,

/Jed Margolin/ Date: February 4, 2017

Jed Margolin

Jed Margolin
1981 Empire Rd.
Reno, NV 89521-7430
775-847-7845

## Claims

1. (Original) A system for detecting the presence of a flame comprising:
    a. a combustion burner;
    b. a flame rod;
    c. a signal source having a selected waveform connected to said flame rod;
    d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;
    e. a harmonic signal detector having an input connected to the output of said high impedance buffer;
    f. an indicator connected to the output of said harmonic signal detector;

whereas

    g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and
    h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.

2. (Original) The system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

3. (Original) The system of claim 1 whereby said harmonic signal detector comprises a phase locked loop tuned to the frequency of said harmonic signal.

4. (Original) The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising:
    a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;
    b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

5. (Original) The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

6. ~~(Conditionally Withdrawn)~~ (Original) A system for detecting the presence of a flame comprising:

a. a combustion burner;

b. a flame rod;

c. a first signal source having a selected waveform connected to said flame rod;

d. a second signal source having a selected waveform connected to said flame rod;

e. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

f. a signal detector having an input connected to the output of said high impedance buffer;

g. an indicator connected to the output of said signal detector;

whereas

h. said flame from said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a first mixing signal at the sum of the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform as well as a second mixing signal at the difference between the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform, and

i. said signal detector is configured to detect said first mixing signal or said second mixing signal and indicate the results on said indicator.

7. ~~(Conditionally Withdrawn)~~ (Original) The system of claim 6 whereby said signal detector comprises a phase locked loop tuned to said first mixing frequency or to said second mixing frequency.

8. ~~(Conditionally Withdrawn)~~ (Original) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, and a reference signal having the same frequency as said first mixing signal or said second mixing signal, and said signal detector comprises a simple synchronous detector comprising:

a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

9. ~~(Conditionally Withdrawn)~~ (Original) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, a first reference signal having the same frequency as said first mixing signal or said second mixing signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

10. ~~(Conditionally Withdrawn)~~ (Original) The system of claim 6 whereby said first signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

11. ~~(Conditionally Withdrawn)~~ (Original) The system of claim 6 whereby said second signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

12. (Original) A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;

b. providing a flame rod;

c. providing a signal source having a selected waveform introduced to said flame rod;

d. providing a high impedance buffer to buffer a flame rod signal from said flame rod;

e. providing a harmonic signal detector to receive the output of said high impedance buffer;

f. providing an indicator to receive the output of said harmonic signal detector;

whereas

g. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said signal source having a selected waveform to produce harmonics of the fundamental frequency of said selected waveform,

h. said harmonic signal detector is used to detect the presence of at least one of said harmonics of said selected waveform and indicate the presence of said at least one of said harmonics of said selected waveform on said indicator, and

i. said presence of said at least one of said harmonics of said selected waveform is proof of the presence of said flame.

13. (Original) The method of claim 12 where said step of providing a harmonic signal detector comprises providing a phase locked loop.

14. (Original) The method of claim 12 where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

15. ~~(Conditionally Withdrawn)~~ (Original) A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a first signal source having a selected waveform introduced to said flame rod;
d. providing a second signal source having a selected waveform introduced to said flame rod;
e. providing a high impedance buffer to buffer a flame rod signal from said flame rod;
f. providing a signal detector to receive the output of said high impedance buffer;
g. providing an indicator to receive the output of said signal detector;

whereas

h. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a sum signal at the sum frequency of said first signal source and said second signal source and a difference signal at the difference frequency of said first signal source and said second signal source,
i. said signal detector is used to detect the presence of said sum signal or said difference signal and indicate the presence of said sum signal or said difference signal on said indicator, and
j. said presence of said sum signal or said difference signal is proof of the presence of said flame.

16. ~~(Conditionally Withdrawn)~~ (Original) The method of claim 15 where said step of providing a signal detector comprises providing a phase locked loop.

17. ~~(Conditionally Withdrawn)~~ (Original) The method of claim 15 where said step of providing a signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

18. ~~(Conditionally Withdrawn)~~ (Original) A method for detecting the presence of a flame comprising the steps of:

a. providing two signal sources to said flame;

b. using flame rectification to cause said two signal sources to mix;

c. providing a signal detector to detect a mixing signal produced by said two signal sources; and

d. providing an indicator to indicate the results of said signal detector.

**Applicant's Remarks**

**A.** The Examiner rejected Claims 1, 2 and 12 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No. US 6,501,383 B1) in view of Haupenthal (Pat. No. US 6,486,486 B1).

The Examiner rejected Claims 3, 13 and 14 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).

Applicant will begin by showing what Haupenthal '383 and Haupenthal '486 actually teach and what they do not teach.

## I. Haupenthal '383

In Haupenthal '383 he is concerned that in a flame sensing system using flame rectification to produce a DC voltage, a component (such as a capacitor) in the filter section could fail so that the system could indicate the presence of a flame when there isn't one.

In Haupenthal's description of prior art:

> 2. Description of the Prior Art
>
> Monitoring gas flames frequently entails the use of flame monitors which utilize the rectifier effect of the flame, that is to say which operate on the basis of what is known as the ionization principle. In that procedure an ac voltage is applied between two electrodes. The volume which is filled by the flame depends on the instantaneous output of the burner. The direct current which can be produced can be very low at a low level of burner output and if the geometry of the electrodes is not the optimum, while the alternating current can be substantially greater in dependence on the capacitance of the sensor line. The flame signal amplifier must therefore be capable of filtering off the low direct current component in the overall sensor circuit current, without the alternating current being able to simulate a flame signal as a result of the inevitable rectifier effects in the amplifier input. Therefore the magnitude of the direct current component gives a measurement in respect of the intensity of the flame, in which respect the absence of a flame corresponds to the intensity of zero, the detection of which must be established reliably and very close to real time in order to avoid unburnt gas or oil from flowing out into the burner chamber.

{Emphasis added}

But:

> In principle filtering of the direct current component can be implemented by an evaluation circuit which is connected upstream of the flame signal amplifier, such as for example a low

> pass filter with a sufficiently low limit frequency. If however the filter capability of the low pass filter is lost, for example because of a failure of a filter capacitor, the alternating current could simulate the presence of a flame, even when the flame is not present.

{Emphasis added}

Note the emphasis on "direct current" and "direct current component". Applicant's invention does not use flame rectification to produce a direct current, a practice which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

Haupenthal proposes to solve the problem caused by the failure of a filter as follows:

> Therefore the object of the present invention is to provide a method and an apparatus for monitoring a flame which serves as a flame monitoring method and circuit respectively, the response sensitivity of which is substantially improved in comparison with the state of the art without detracting from compatibility for line capacitance, whose switch-off capability can be periodically checked during burner operation and also supplies an output signal representing a measurement in respect of flame intensity. The invention further seeks to provide that the method ensures continuous checking of the monitoring action.
>
> According to a first aspect of the present invention, there is provided a method of monitoring a flame, wherein: in dependence on the presence or intensity of the flame there is produced from a first electrical signal a second electrical signal of different magnitude, the second electrical signal is applied to an evaluation circuit and converted into a first output signal, and the evaluation circuit is acted upon by a monitoring signal which upon failure of the evaluation circuit leads to a second output signal.

{Emphasis added}

Unfortunately, this is so vague that we are required to decipher what he means by "a first electrical signal" and "a second electrical signal".

But then he says:

> The method according to the invention of monitoring a flame makes use of the known principle that in dependence on the presence or the intensity of the flame there is produced from a first electrical signal (for example an ac voltage signal) a second electrical signal of different magnitude (for example a dc signal) (I.sub.F) . A preferred embodiment uses ionization electrodes or ultraviolet sensors with series-connected diode which in dependence on flame intensity supply a corresponding dc signal. No dc signal is produced when the flame is extinguished. The second electrical signal (I.sub.F) is detected by an evaluation circuit to which the ionization electrodes or the ultraviolet sensors are connected, and converted into a first output signal (A), wherein conversion is effected by various further circuit elements in such a

> way that differently dynamic output signals are obtained, depending on the respective flame intensity involved. Therefore with changing flame intensities the output signal (A) is an output signal which changes in terms of its dynamics.

{Emphasis added}

The first electrical signal may be an AC voltage signal and the second electrical may be a DC signal, and the first electrical signal (an AC signal) produces the second electrical signal (a DC signal).

Since Haupenthal is concerned that in a flame sensing system using flame rectification to produce a DC voltage a component (such as a capacitor) in the filter section could fail so that the system could indicate the presence of a flame when there isn't one, the first electrical signal is the AC applied to the flame sensor (which is subject to flame rectification) and the second electrical signal is the dc voltage produced by filtering. However, in addition, "A preferred embodiment uses ionization electrodes or ultraviolet sensors"

Unless the "or" is a mistranslation of the original German (or a typo) and Haupenthal really does mean "or" and not "and" then his patent is for two different inventions, both of which were already known at the time he filed his application. There are:

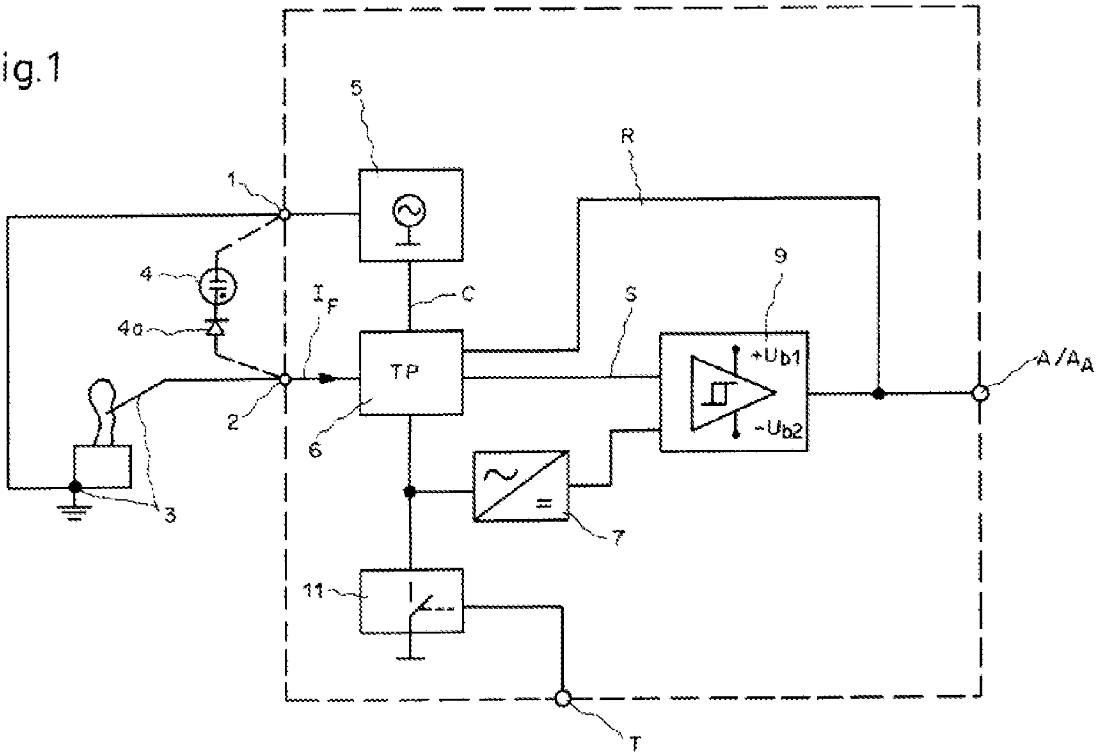
1. Flame rectification of an AC voltage which after filtering provides a DC voltage. U.S. Patent 2,112,736 **Flame Detector** issued March 29, 1938 to William D. Cockrell, assigned to General Electric *{Applicant's IDS Cite 2}*. This patent teaches using flame rectification for providing flame proof. Cockrell Figure 1 shows an embodiment using one electrode (22) with the burner (2) used as the return. See Page 1, left column, line 41 - Page 2, right column, line 15.

2. A UV sensor that detects the UV radiation produced by a flame.

> From Haupenthal DESCRIPTION OF THE PREFERRED EMBODIMENT:
>
> FIG. 1 is a diagrammatic view of a preferred embodiment of apparatus according to the invention. <u>Ionization electrodes 3 or ultraviolet sensors 4,4a</u> are supplied by way of a connecting terminal 1 with the ac voltage signal from a suitable source 5 and supply the signal which is generated by the flame and on which an unwanted alternating current signal is superimposed to the terminal 2 at which an evaluation circuit 6, here a filter member, detects the direct current signal I.sub.F. The control signal S is passed to the trigger stage 9 which outputs the output signal A, A.sub.A. A reset line R serves to reset the evaluation circuit 6 so that an oscillating signal appears at the output of the trigger stage 9. If the evaluation circuit 6 comprises a low pass member TP with capacitor C1 and resistor R1, it has to be regularly reset.

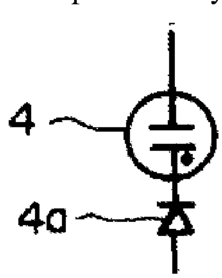
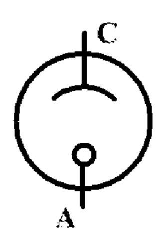
Here is Haupenthal Figure 1:

Fig.1




Components 4 and 4a are characterized as “ultraviolet sensors 4,4a” and their (or its) output is added to the signal produced by flame rectification which come from component 3 (a flame electrode and the body of the combustion burner) so Haupenthal must mean flame rectification **<u>and</u>** the use of a UV sensor.

The UV sensor that Hauphenthal uses appears to be a UV phototube.

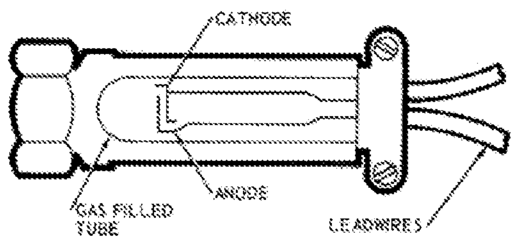
| Haupenthal’s symbol | Standard symbol for a phototube |
| --- | --- |
|  |  |

See *Ref. 1:* **Phototubes** by Hamamatsu, Figure 2 page 6.

From Column 5, lines 5 -10:

> The flame monitoring circuit is fed in bipolar mode by two operating voltages +Ub1 and -Ub2 defined with respect to a reference potential m. It has two terminals 1 and 2 which can be connected either to two ionization electrodes 3 or to the two terminals of an ultraviolet sensor comprising a gas-filled ultraviolet cell 4 and a diode 4a connected in series therewith.

This is a phototube:




From *Ref. 2*: **Phototube** at Wikipedia:

> A phototube or photoelectric cell is a type of gas-filled or vacuum tube that is sensitive to light. Such a tube is more correctly called a 'photoemissive cell' to distinguish it from photovoltaic or photoconductive cells. Phototubes were previously more widely used but are now replaced in many applications by solid state photodetectors. The photomultiplier tube is one of the most sensitive light detectors, and is still widely used in physics research.

and

> Phototubes operate according to the photoelectric effect: Incoming photons strike a photocathode, knocking electrons out of its surface, which are attracted to an anode. Thus current is dependent on the frequency and intensity of incoming photons. Unlike photomultiplier tubes, no amplification takes place, so the current through the device is typically of the order of a few microamperes.[1]
>
> The light wavelength range over which the device is sensitive depends on the material used for the photoemissive cathode. A caesium-antimony cathode gives a device that is very sensitive in the violet to ultra-violet region with sensitivity falling off to blindness to red light. Caesium on oxidised silver gives a cathode that is most sensitive to infra-red to red light, falling off towards blue, where the sensitivity is low but not zero.[2]

The use of an ultraviolet sensor to detect the presence of a flame goes back to at least 1977 in U.S. Patent 4,039,844 **Flame monitoring system** issued August 2, 1977 to MacDonald (*Ref. 3*). From Column 6, lines 6 - 27:

> In operation, the burner 16A in proper operation provides a flame condition with fluctuating components in zone 22A. The sensor circuit 70 senses that fluctuating component and steady

> state components in zone 24 of flame 20 as well as in background radiation and produces an AC signal which coupled by capacitor 76 to the band pass amplifier 80 which amplifies that AC signal. As long as that AC signal above a minimum threshold is present, filter 128 periodically causes comparator 136 to trigger one shot 148 to produce a forty microsecond pulse at output terminal 178. Those output pulses are compatible with operating circuitry designed to respond to an <u>ultraviolet flame sensor,</u> for example. Should the magnitude of the output signal from the band pass amplifier fall sufficiently to switch comparator 198, however, the pulse generating circuit is clamped off and the threshold level is shifted by the feedback loop of comparator 198 to require a substantially greater magnitude of flame signal at terminal 62' to reinitiate the generation of output pulses at terminal 178 than was required to maintain application of those pulses at that terminal.

{Emphasis added}

What we learn from this is that the ultraviolet produced by a flame contains fluctuating components. MacDonald separates these fluctuating components from the DC component and uses them as flame proof.

These fluctuating components are also an important part of U.S. Patent 5,073,769 **Flame detector using a discrete fourier transform to process amplitude samples from a flame signal** issued December 17, 1991 to Kompelien (*Ref. 4*). From Column 1, lines 5 - 21:

> In fuel burners such as furnaces where the main burner is lit by a pilot burner, it is necessary for obvious reasons to assure that the pilot burner is lit before the main burner fuel valve is opened. This is true whether a standing pilot or intermittent pilot is involved. While there are many different types of sensing operations which can reliably detect presence of a pilot flame, one which is preferred senses the flicker frequency of typical pilot flames. This flicker is a periodic variation of the intensity or amplitude of the infrared, visible, or ultraviolet radiation produced by the burning of the fuel sustaining the pilot flame. The flicker frequency of this radiation in most cases has a component in the range of 13-17 hz. This characteristic is fairly independent of the fuel and the size of the pilot flame.

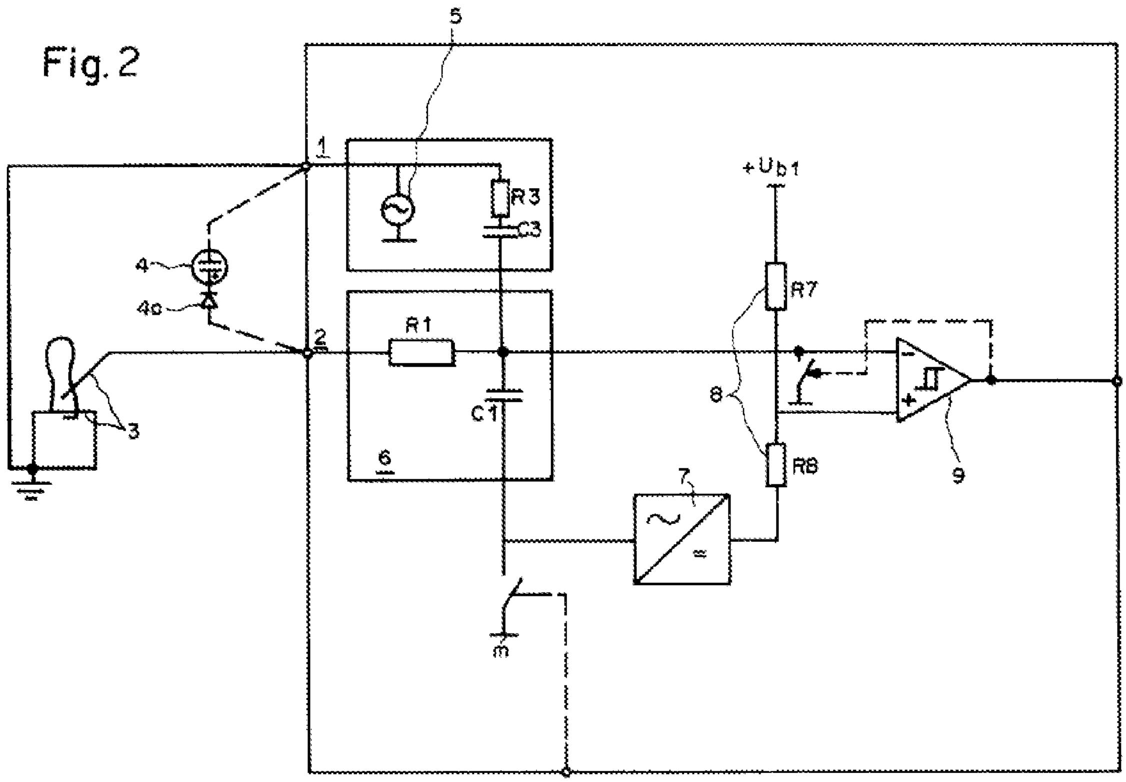
However, Haupenthal's Figure 5 does not appear to have accounted for the 13-17 Hz undulation.

Haupenthal states:

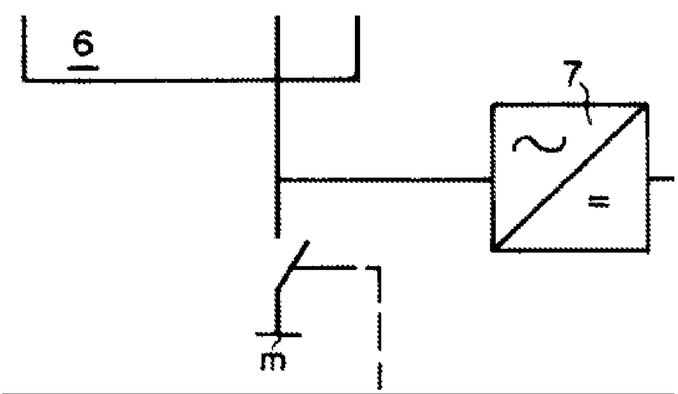
> The flame begins to burn at the time t.sub.1, and it is possible to see a direct current signal which rises to the time t.sub.2. Until t.sub.3 the flame intensity remains constant and then falls to t.sub.4 in order there to remain at a lower level in order finally to rise again from the time t.sub.5 and remain at a higher level from time t.sub.6.

Haupenthal's UV Sensor is connected in parallel with the flame rod and combustion burner so the current through the UV Sensor is added to the current produced by flame rectification.

There is a problem with Haupenthal's circuit. AC source (5) is grounded to circuit ground (m) - which is also known as circuit common. This is shown in Haupenthal Figure 2. (He left it out of Figure 1 even though it is the same part of the circuit.)



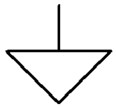

Since it might not be apparent where circuit ground (m) is this is a zoomed in picture:




Haupenthal uses the symbol

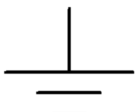
to indicate circuit ground.

Another symbol that is commonly used for circuit ground is:



There does not seem to be an international standard for circuit ground.

However, there is an international electrical symbol for earth ground: IEC 5017.

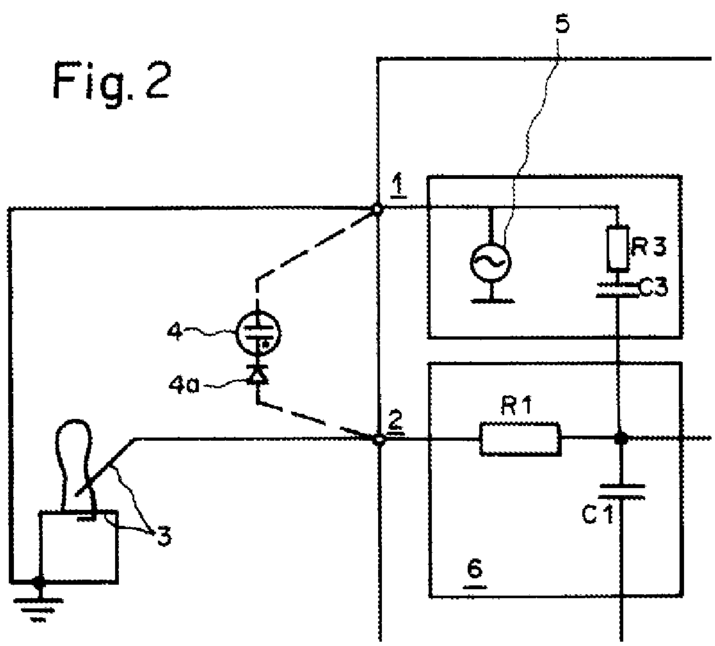


For the ANSI/IEC standard for the symbol see *Ref. 5*. It is characterized as:

1) A direct conducting connection to the earth or body of water that is a part thereof.

The problem is that while one side of AC source (5) is connected to circuit common (m) the hot side terminal (1) is connected to earth ground. This is because the combustion burner must be directly attached to the furnace cabinet which must be grounded to earth ground for safety reasons (it is an exposed metal surface). Another reason the furnace cabinet must be connected to earth ground is that this is a gas furnace, and the gas line must be grounded to earth ground.

This shows that the AC source (5) hot terminal (1) is connected to earth ground.



If AC source (5) were the AC Mains this would short the AC Mains hot to earth ground producing large ground currents. This cannot be allowed to happen.

Suppose AC source (5) is isolated from the Mains. This would work if the circuit ground (m) were kept isolated from earth ground. If it isn't, then AC source (5) would be shorted out.

But remember that Haupenthal's flame sensor is for a furnace. The furnace will be controlled by a thermostat. The thermostat will need to be located somewhere other than the furnace. Otherwise the heat from the furnace will affect the thermostat readings. And who wants the temperature of their bedroom determined by the temperature in their garage where the furnace might be located?

The thermostat will probably be connected to the furnace by a cable of wires. This means that care must be taken so that no internal conducting part of the thermostat can come into contact with earth ground either directly or through a person. It is unlikely that any safety organization would approve a furnace using Haupenthal's flame sensor.

Be that as it may, Haupenthal's invention uses flame rectification to convert an AC voltage to a DC voltage which is augmented by an ultraviolet flame sensor.

Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

## <u>II. Haupenthal '486</u>

Haupenthal '486 is for a flame sensor that detects the ultraviolet radiation produced by a flame. Haupenthal does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is no flame rod. There is no selected signal. The only things that '486 has in common with Applicant's invention are:

They are both flame sensors; and

Both use the word "harmonics" somewhere.

They achieve their results by completely different means.

Haupenthal is concerned that lighting sources powered by the Mains could be picked up by the UV sensor and cause the UV sensor to report the presence of a flame when there isn't one.

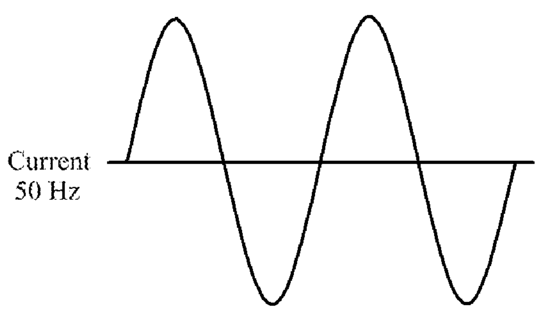
When could this happen? Isn't the combustion compartment sealed? The answer is that there are times when the furnace covers must be removed such as for diagnosing furnace problems.

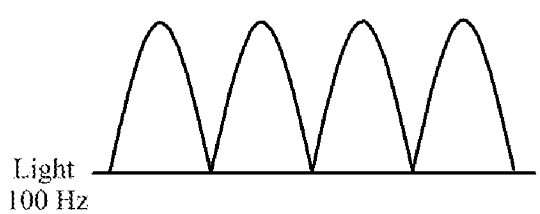
Haupenthal states (Column 2, line 20 - 27):

> The object of the present invention is to provide a flame monitoring system and a method of monitoring a flame, which has immunity in relation to mains frequency-harmonic input signals with a very low level of flame signal information loss and which is suitable for use in relation to burners in a continuous mode of operation.

At the time Haupenthal made his invention (priority comes from around 1998) the major sources of artificial lighting were incandescent lights and fluorescent lights powered by the Mains.

The light produced by an incandescent bulb does not care about the polarity of the current so a Mains current of 50 Hz (which is the Mains frequency in Europe where Haupenthal made his invention) would produce light at twice the Mains frequency, which would be 100 Hz.



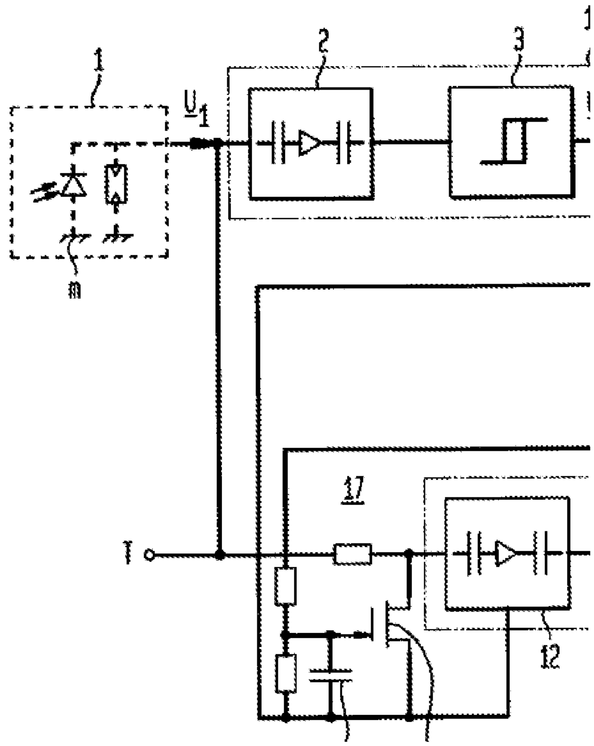




Incandescent bulbs have a large amount of thermal inertia so the light output will be more-or-less steady and not as shown.

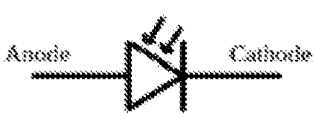
However, fluorescent lights have no thermal inertial so the light output will be as shown.

This is the source of the "mains frequency-harmonic input signals".

Here is the front end of Haupenthal's system showing the UV sensor 1. (Figure 1)




Haupenthal is using the standard symbol for a photodiode.




See *Ref. 6:* **Photodiode** from Wikipedia.

The UV Sensor is labeled "**1**". Input "**T**" is an input for a test signal. From Column 6, lines 5 - 8:

> FIG. 1 also shows a control input, by way of which a test signal T can be superimposed on the signal voltage U.sub.1. Such a test signal T is for example a 100 Hz signal which simulates a light source operated with alternating current.

{Emphasis added}

Further, from Column 2, lines 20 - 59:

> In accordance with a first aspect of the invention, there is provided a flame monitoring system comprising: a flame sensor which converts the radiation emanating from a flame into a flame signal; a flame signal amplifier which converts the flame signal into an output signal; and a frequency-selective arrangement which detects the presence of mains frequency-harmonic

signals in the flame signal; wherein: the frequency-selective arrangement activates the flame signal amplifier when there are no mains frequency-harmonic signals in the flame signal; and the frequency-selective arrangement deactivates the flame signal amplifier when there is a flame signal with mains frequency-harmonic signals or no flame signal or a test signal.

In accordance with a second aspect of the invention, there is provided a method of monitoring a flame, comprising: converting radiation emanating from the flame into a flame signal which is converted into an output signal; and detecting the presence of mains frequency-harmonic signals in the flame signal by using a frequency-selective arrangement; wherein: the flame signal is converted into an output signal when there are no mains frequency-harmonic signals in the flame signal; and the flame signal is converted into a zero signal where there is a flame signal with mains frequency-harmonic signals or no flame signal or a test signal.

In both aspects the flame signal amplifier is activated when there are no mains frequency harmonics (from ambient lighting) and is deactivated when there are mains frequency harmonics (from ambient lighting).

Haupenthal does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is no flame rod. There is no selected signal.

Applicant observes that both incandescent and fluorescent bulbs produce little or no ultraviolet energy. If they did, they would be considered hazardous. (There are fluorescent bulbs designed to produce ultraviolet energy for specific purposes like germocidal lamps but they are not used for general lighting.)

Applicant also observes that fluorescent bulbs using an electronic ballast operate at ultrasonic frequencies. This includes modern compact fluorescent lights (CFLs). Haupenthal's invention would not work as intended with these lights.

It is possible that Haupenthal was working with a general light sensor instead of one that was responsive only to ultraviolet.

The result is that Haupenthal '486 is for a flame sensor that detects the ultraviolet radiation produced by a flame. He detects the second harmonic of the mains power caused by ambient lighting operating at the mains power frequency (and whose operation effectively doubles the frequency of the mains power) and disables the flame sensor when this second harmonic is detected by the ultraviolet sensor. Haupenthal does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is not even a flame rod.

Combining Haupenthal ‘383 with Haupenthal ‘486 results in a flame sensing system that:

1. Uses flame rectification to produce a DC voltage when a flame is present;
2. Also uses an ultraviolet sensor to detect the ultraviolet light from the flame; and
3. Turns off the flame sensor when the ultraviolet sensor detects ambient light operating at the Mains power frequency.

Applicant’s invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

And when Haupenthal detects his harmonic it means his ultraviolet sensor might be being fooled by ambient light so the flame might be bad. When Applicant detects his harmonic it means the flame is good.

**B.** For the above reasons the Examiner's rejection of Applicant's claims 1, 2 and 12 is not supportable. The Examiner's reasons are as follows:

> Claims 1, 2 and 12 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1).
>
> Regarding claim 1, Haupenthal (383) teaches a **system for detecting the presence of a flame comprising:**
>
> **a. a combustion burner** (Fig. 1);
>
> **b. a flame rod** (Fig. 1, ionization electrodes 3);
>
> **c. a signal source having a selected waveform connected to said flame rod** (Fig. 1, signal source having an ac waveform is connected to the electrode);
>
> **d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame** (Fig. 1, and Col. 4, lines 36-50,
>
> > "Ionization electrodes 3 or ultraviolet sensors 4, 4a are supplied by way of a connecting terminal 1 with the ac voltage signal from a suitable source 5 and supply the signal which is generated by the flame and on which an unwanted alternating current signal is superimposed to the terminal 2 at which an evaluation circuit 6, here a filter member, detects the direct current signal I.sub.F.");

As Applicant has noted Haupental (383) shows a series path through the combustion burner requiring unsafe grounding practices while Applicant uses a parallel path which allows standard (and safe) grounding practices to be used.

But the real story is that Haupenthal (383) uses flame rectification to produce a direct current, which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components.

The Examiner continues:

> **e. a signal detector having an input connected to the output of said high impedance buffer** (Fig. 1, evaluation circuit 6);

The Examiner has misquoted Applicant's claim 1(e) which actually says:

**e. a harmonic signal detector having an input connected to the output of said high impedance buffer;**

Haupenthal's Fig. 1 (383) evaluation circuit 6 is not a harmonic signal detector. The word "harmonic" does not appear anywhere in Haupenthal (383). Haupental uses flame rectification to produce a direct current, which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components. Haupenthal's indicator indicates the presence of a direct current produced by flame rectification. Applicant's indicator indicates the presence of either a harmonic of a selected waveform caused by flame rectification or sum and difference frequency components produced when flame rectification causes two selected waveforms to mix.

The Examiner continues:

**f. an indicator connected to the output of said signal detector** (Abstract:

"The direct current signal (I.sub.F) is detected by an evaluation circuit (6) and converted into a first output signal (A), wherein conversion is effected by various further circuit elements (7, 9, 10) in such a way that differently changing output signals (A.sub.1, A.sub.2) are obtained depending on the respective flame intensity. ".

Indicate the intensity of the flame);

The Examiner has misquoted Applicant's claim 1(f) which actually says:

**f. an indicator connected to the output of said harmonic signal detector;**

Haupental uses flame rectification to produce a direct current, which is well known in the art. Applicant's invention uses flame rectification as a mixer to cause harmonic distortion of a selected waveform or to cause two selected waveforms to mix, creating sum and difference frequency components. Haupenthal's indicator indicates the presence of a direct current produced by flame rectification. Applicant's indicator indicates the presence of either a harmonic of a selected waveform caused by flame rectification or sum and difference frequency components produced when flame rectification causes two selected waveforms to mix.

The Examiner continues:

**whereas**

**g. said flame from said combustion burner causes distortion of said signal source having a selected waveform producing a a distorted signal** (Fig. 5, Col. 7 lines 18-28,

> "The uppermost diagram shows the direct current signal I.sub.F on which the alternating current signal is superimposed, in which case the alternating current signal is only shown in part for the sake of enhanced clarity.".

The ac source signal is distorted by the direct current generated by the flame), and

The Examiner has misquoted Applicant's claim 1(g) which actually says:

**g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and**

As Applicant has explained, he does not use flame rectification to produce a direct current signal. The Examiner's assertion that "The ac source signal is distorted by the direct current generated by the flame" is an interesting conjecture but is not relevant here. Is the Examiner referring to the flame battery referred to in Applicant's specification paragraph 029 ?

> Figure 1 shows a representative Combustion Burner 1, Flame 2, and Flame Rod 3. Figure 2 is a representative electrical model of the electrical properties of Figure 1. Experiments will show that this is an AC model and that the flame battery is an integral part of Flame Diode D (23).

Although the flame does generate a small current by itself (the flame battery) which is probably part of the process that produces flame rectification, the use of flame rectification requires an external current in order to produce its effect.

And the alternating current that is superimposed on the direct current signal I.sub.F comes from coupling capacitance in Haupenthal's sensor lines. From Column 5, lines 33 - 40:

> Only a direct current flows in the sensor circuit between the ionization electrodes 3 because of the rectifying effect of the flame or in the ultraviolet cell 4 because of the diode 4a, more specifically only when the flame is actually burning. However an unwanted alternating current also constantly flows between the terminals 1 and 2, because of the inevitable capacitance of the sensor lines, and that alternating current is superimposed on the direct current.

Since Applicant's invention detects the presence of either a harmonic of a selected waveform caused by flame rectification (or sum and difference frequency components produced when flame rectification causes two selected waveforms to mix) it is already relatively insensitive to any capacitive coupling between the sensor line and ground, which is Applicant's return current path between the combustion burner and the flame rod. Any effect that capacitive coupling between the sensor line and ground has on the DC produced by flame rectification is irrelevant because Applicant does not use the DC produced by flame rectification. In addition, the capacitance between Haupenthal's sensor lines is a linear capacitance and does not introduce distortion.

The Examiner continues:

> **h. said signal detector is configured to detect said distorted signal and indicate the results on said indicator** (Fig. 5. Col. 7 line 29-43, detect flame intensity according to the dc component of the superimposed waveform).

The Examiner has misquoted Applicant's claim 1(h) which actually says:

> **h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.**

Applicant 's indicator does not detect flame intensity according to the DC component of the superimposed waveform. Applicant's indicator indicates the presence of either a harmonic of a selected waveform caused by flame rectification or the sum and/or difference frequency components produced when flame rectification causes two selected waveforms to mix.

The Examiner has omitted words and substituted his own words for the claim filed by Applicant. This is in violation of MPEP 2143.03.

> **2143.03 All Claim Limitations Must Be Considered [R-08.2012]**
>
> "All words in a claim must be considered in judging the patentability of that claim against the prior art." *In re Wilson,* 424 F.2d 1382, 1385, 165 USPQ 494, 496 (CCPA 1970). If an independent claim is nonobvious under 35 U.S.C. 103, then any claim depending therefrom is nonobvious. *In re Fine,* 837 F.2d 1071, 5 USPQ2d 1596 (Fed. Cir. 1988).

By materially misquoting Applicant's claim 1 the Examiner has made an improper rejection. Since the Examiner's rejection of claims 2 and 12 are based on his rejection of claim 1 his rejection of claims 2 and 12 is improper as well.

The Examiner continues:

> Haupenthal (383) teaches a flame monitoring system that detects flame intensity according to the dc current generated by the flame superimposed on the ac source signal instead of the **harmonic** distortion of the ac source signal.

> However, in the same field of flame monitoring system, Haupenthal (486) teaches a system that detects the harmonic frequency signal by the flame. See Abstract,
>
> > "A frequency-selective arrangement (6, 17, 18, 19) detects the presence of mains frequency-harmonic signals in the flame signal (U.sub.1) and activates the flame signal amplifier (40) when there are no mains frequency-harmonic signals in the flame signal (U.sub.1) and deactivates the flame signal amplifier (40) when there is a flame signal (U.sub.1) with periodic signals or no flames signal (U.sub.l) or a test signal (T) .".
>
> Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)'s evaluation circuit with Haupenthal (486)'s harmonic detection system to detect harmonic distortion to accurately detect the presence of a flame.

As Applicant has shown in his discussion of Haupenthal '486, the '486 patent is for a flame sensor that detects the ultraviolet radiation produced by a flame. It does not detect harmonics produced by the flame. Haupenthal is concerned that lighting sources powered by the Mains could be picked up by the UV sensor and cause the UV flame sensor to report the presence of a flame when there isn't one. At the time Haupenthal made his invention (priority comes from around 1998) the major sources of artificial lighting were incandescent lights and fluorescent lights powered by the Mains. The light produced by incandescent bulbs and fluorescent lights does not care about the polarity of the current so a Mains current of 50 Hz (which is the Mains frequency in Europe where Haupenthal made his invention) would produce light at twice the Mains frequency, which would be 100 Hz. It is the Mains frequency harmonic produced by ambient light that '486 is designed to detect. When it detects this harmonic it deactivates the flame sensor.

Haupenthal '486 does not detect the harmonic distortion caused by flame rectification of a selected signal. He does not use flame rectification. There is no flame rod. There is no selected signal. The only things that '486 has in common with Applicant's invention is that:

They are both flame sensors; and

Both use the word "harmonic" somewhere.

They achieve their results by completely different means.

The Examiner finishes the section with:

> Regarding claim 2, Haupenthal (383) in the combination teaches **the system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave** (Fig. 1, ac

> voltage source. The ac voltage source is low distortion compare to the superimposed voltage).
>
> Regarding claim 12, recite limitation similar to claim 1. Therefore, claim 12 is rejected with the same rationale and claim 1.

In the Examiner's statement that "The ac voltage source is low distortion compare to the superimposed voltage" Haupenthal's term "superimposed voltage" means the voltage produced by capacitive coupling between Haupenthal's sensor lines. From Column 5, lines 33 - 40:

> Only a direct current flows in the sensor circuit between the ionization electrodes 3 because of the rectifying effect of the flame or in the ultraviolet cell 4 because of the diode 4a, more specifically only when the flame is actually burning. However an unwanted alternating current also constantly flows between the terminals 1 and 2, because of the inevitable capacitance of the sensor lines, and that alternating current is superimposed on the direct current.

The superimposed voltage is a voltage that comes from Haupenthal's AC source (5) through capacitive coupling in the sensor lines. It will have the same percentage of presumed distortion that may be present in AC source (5). It cannot be lower or higher. Therefore the assertion that "The ac voltage source is low distortion compare to the superimposed voltage" is untrue.

Besides, Applicant's claim 2 is a dependent claim that is dependent on claim 1.

Applicant quotes MPEP 2143.03:

> **2143.03 All Claim Limitations Must Be Considered [R-08.2012]**
>
> "All words in a claim must be considered in judging the patentability of that claim against the prior art." *In re Wilson,* 424 F.2d 1382, 1385, 165 USPQ 494, 496 (CCPA 1970). If an independent claim is nonobvious under 35 U.S.C. 103, then any claim depending therefrom is nonobvious. *In re Fine,* 837 F.2d 1071, 5 USPQ2d 1596 (Fed. Cir. 1988).

Applicant has shown that the Examiner's rejection of claim 1 is in error and that claim 1 should be allowed. Therefore, claim 2 must be allowed. And since the Examiner's rejection of claim 1 is in error, so is the Examiner's rejection of claim 12.

**C.** The Examiner rejected Claims 3, 13 and 14 under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).

> Claims 3, 13 and 14 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 Bi) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 Al).
>
> Regarding claim 3, Haupenthal (486) in the combination teaches **the system of claim 1 whereby said harmonic signal detector comprises a** detectors to detect harmonic but fails to expressly teach a **phase locked loop tuned to the frequency of said harmonic signal.**
>
> However, in the same field of harmonic detection system, Ngo teaches a phase locked loop that is tuned to a harmonic frequency. See para [0005], "Based on an input reference signal, a digital frequency multiplier circuit utilizes a voltage controlled oscillator (VCO), which is tuned to a harmonic of the input frequency signal, along with a frequency divider and a phase-locked loop (PLL) to generate a desired output frequency.".
>
> Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (486)'s harmonic detector with Ngo's phase locked loop to detect a desired harmonic frequency that would accurately detect the presence of a flame.
>
> Regarding claim 13, recite limitation similar to claim 3. Therefore, claim 13 is rejected with the same rationale and claim 3.
>
> Regarding claim 14, the combination teaches **the method of claim 12** but fails to teach **where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.**
>
> However, in the same field of harmonic detection system, Ngo teaches an external clock signal and a control circuit to align the internal signal with external clock signal. See Abstract,
>
>> "The DCC generates an internal feedback signal. The phase detector detects a phase difference between the internal feedback signal and an external reference clock signal. Coupled between the phase detector and the DCC, the control circuit adjusts the DCC to align the internal feedback signal with the external reference clock signal after a phase difference between the internal feedback signal and the external reference clock signal has been detected.".
>
> Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)'s harmonic detector with a clock and a synchronous detector to synchronous various signals to produce an accurate result.

Applicant again quotes MPEP 2143.03:

> **2143.03 All Claim Limitations Must Be Considered [R-08.2012]**
>
> "All words in a claim must be considered in judging the patentability of that claim against the prior art." *In re Wilson,* 424 F.2d 1382, 1385, 165 USPQ 494, 496 (CCPA 1970). If an independent claim is nonobvious under 35 U.S.C. 103, then any claim depending therefrom is nonobvious. *In re Fine,* 837 F.2d 1071, 5 USPQ2d 1596 (Fed. Cir. 1988).

**1.** Applicant's claim 3 is a dependent claim that is dependent on claim 1. As such, claim 3 contains all of the limitations of claim 1. Applicant has shown that Haupenthal '383 and '486 are irrelevant to Applicant's invention so that claim 1 should be allowed. Thus claim 3 must also be allowed.

Applicant's claim 13 is a dependent claim that is dependent on claim 12. As such, claim 13 contains all of the limitations of claim 12. Applicant has shown that Haupenthal '383 and '486 are irrelevant to Applicant's invention so that claim 12 should be allowed. Thus claim 13 must also be allowed.

Applicant's claim 14 is a dependent claim that is dependent on claim 12. As such, claim 14 contains all of the limitations of claim 12. Applicant has shown that Haupenthal '383 and '486 are irrelevant to Applicant's invention so that claim 12 should be allowed. Thus claim 14 must also be allowed.

Furthermore, claim 14 provides that a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector. This is not a phase locked loop described by Ngo. It is a synchronous detector.

**2.** Ngo (Pub. No.: US 2008/0266000) is for a digitally controlled phase-locked loop. From paragraph 7:

> [0007] In accordance with a preferred embodiment of the present invention, a digital frequency multiplier circuit includes a digitally controlled oscillator (DCO), a phase detector and a control circuit. The DCO generates an internal feedback signal. The phase detector detects a phase difference between the internal feedback signal and an external reference clock signal. Coupled between the phase detector and the DCO, the control circuit adjusts the DCO to align the internal feedback signal with the external reference clock signal after a phase difference between the internal feedback signal and the external reference clock signal has been detected. The control circuit also locks a modulation frequency of the DCO and monitors the state of the digital frequency multiplier circuit in order to maintain the lock.

See Ngo Figure 1.

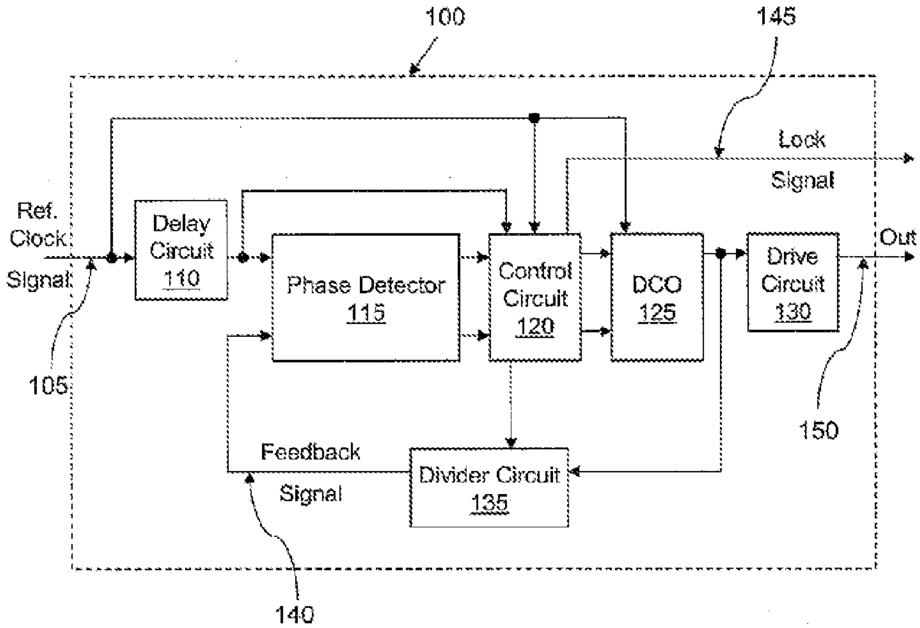



**FIG. 1**

**a.** The divider (135) is in the feedback loop in order to act as a frequency multiplier. Thus, the output of Ngo's PLL is tuned to a multiple of the input reference.

**b.** Instead of controlling the frequency of the oscillator with an analog VCO Ngo uses a digitally controlled oscillator (DCO 125).

**c.** Ngo produces two outputs: a signal that is the reference clock multiplied by a digitally selected ratio and a lock signal that indicates that the output signal is being produced at a selected multiple of the input reference signal.

Applicant's use of a PLL is only to detect an input signal at a particular frequency and produce a lock signal when that input signal is detected, not to produce a multiple of the frequency of the input reference signal. As such Ngo's PLL would be a poor choice to use as Applicant's PLL.

**d.** As noted, claims 3 and 13 are dependent claims. Applicant does not claim to have invented the phase locked loop. The principles of the phase locked loop were described in 1932, in a paper by Henri de Bellescize, in the French journal L'Onde Électrique. See *Ref. 7.*

A good explanation of the modern phase locked loop can be found in Technical Report No. 32-427 **Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques** by A.J.

Viterbi, published by the Jet Propulsion Laboratory, March 29, 1963 in the section **I. Introduction** (*Ref. 8*, PDF page 5).

Also as noted, claim 14 is a dependent claim that provides for the step of using a synchronous detector. Applicant does not claim to have invented the synchronous detector. Synchronous detectors have been used since the early 20th century.

For the above reasons the Examiner's rejection of dependent claims 3, 13, and 14 is not supportable, is contrary to MPEP 2143.03, and must be withdrawn.

**D.** Claims 4 and 5 were objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

The Examiner's rejection of claim 1 does not hold up to scrutiny of his references and by misquoting Applicant's base claim his rejection is improper. Therefore dependent claims 4 and 5 must be allowed under MPEP 2143.03 .

**E. Conclusion**

For the above reasons Applicant requests an allowance of all of his claims.

**References**

Ref. 1 - **Phototubes** by Hamamatsu;
from http://www.hamamatsu.com/resources/pdf/etd/Phototubes_TPT1001E.pdf

Ref. 2 - **Phototube**; Wikipedia; from https://en.wikipedia.org/wiki/Phototube

Ref. 3 - U.S. Patent 4,039,844 **Flame monitoring system** issued August 2, 1977 to MacDonald.

Ref. 4 - U.S. Patent 5,073,769 **Flame detector using a discrete fourier transform to process amplitude samples from a flame signal** issued December 17, 1991 to Kompelien

Ref. 5 - ANSI/IEC Standard symbol for Earth Ground

Ref. 6 - **Photodiode** from Wikipedia; from https://en.wikipedia.org/wiki/Photodiode

Ref. 7 - Phase Locked Loop; Wikipedia; History;
from https://en.wikipedia.org/wiki/Phase-locked_loop#History

Ref. 8 - Technical Report No. 32-427 **Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques** by A.J. Viterbi, published by the Jet Propulsion Laboratory, March 29, 1963 in the section **I. Introduction** (*Ref. 11*, PDF page 5).
from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19630005005.pdf

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# References

References

# Reference 1

Reference 1

# Phototubes

HAMAMATSU
PHOTON IS OUR BUSINESS

# ■FEATURES AND APPLICATIONS

## FEATURES

| | |
|---|---|
| High sensitivity and high stability | High sensitivity and high stability make phototubes very useful in chemical and medical analytical instruments which require high reliability. |
| Wide dynamic range | Phototubes feature a wide dynamic range from several picoamperes to several microamperes, providing signal output with excellent linearity. |
| Superior temperature stability | Phototubes show virtually no fluctuation with changes in the ambient temperature. |
| Large photosensitive area | Compared to semiconductor sensors, phototubes offer larger photosensitive area. |
| Low voltage operation | Phototubes are designed to operate at a low voltage. |

## SPECTRAL RESPONSE RANGE AND APPLICATIONS

| Spectral Range | Photocathode | Window Material | Spectral Response | | Typical Applications | Applicable Phototube Type No. |
|---|---|---|---|---|---|---|
| Spectral response in vacuum UV region only | Cs-I | $MgF_2$ | 115 nm to 200 nm | ① | Vacuum UV spectrophotometer | R1187 |
| | | Quartz | 160 nm to 200 nm | ② | | R5764 |
| Vacuum UV region only | Diamond | $MgF_2$ | 115 nm to 220 nm | ③ | 172 nm monitor for excimer lamp | R6800U-26 |
| | | Quartz | 160 nm to 220 nm | ④ | 185 nm monitor for sterilizing mercury lamp | R6800U-16 |
| Solar blind spectral response | Au (single metal) | Quartz | 160 nm to 240 nm | ⑤ | 185 nm monitor for sterilizing mercury lamp | R4044 |
| | Cs-Te | Quartz | 160 nm to 350 nm | ⑥ | Monitor for 185 nm, 254 nm mercury line spectrum | R765, R6800U-11 |
| | | UV glass | 185 nm to 350 nm | ⑦ | Ozone monitor | R1107, R1228, R6800U-01 |
| Wide spectral response from UV to infrared | Sb-Cs | UV glass | 185 nm to 650 nm | ⑧ | Spectrophotometer | R840, R727 |
| | | Borosilicate | 300 nm to 650 nm | ⑨ | Blood analyzer | R414 |

# ■GLOSSARY OF TERMS

**●Spectral response characteristic:**
When light (photons) enters the photocathode, it is converted into electrons emitting from the photocathode at a certain ratio. This ratio depends on the wavelength of incident light. The relationship between the ratio and the wavelength is called spectral response characteristic.

**●Peak wavelength:**
The wavelength gives the maximum sensitivity to the photocathode. In this catalog, the peak wavelength for radiant sensitivity (A/W) is listed.

**●Absolute maximum ratings:**
The limiting values of the operating and environmental conditions applied to a phototube. Any conditions shall not exceed these ratings even instantaneously.

**●Anode supply voltage:**
The voltage applied across the anode and the cathode. Normally, the cathode is used at ground potential, so the anode supply voltage equals the potential difference between the anode and ground.

**●Peak cathode current:**
The peak current that can be allowed from the cathode when it is of pulse waveform.

**●Average cathode current:**
The average current that can be allowed from the cathode. Normally, it is the average for 30 seconds.

**●Average cathode current density:**
The average cathode current per unit surface area on the photocathode.

**●Luminous sensitivity:**
The ratio of photocurrent in amperes (A) flowing in the photocathode to the incident luminous flux in lumens (lm).

$$\text{Luminous sensitivity (A/lm)} = \frac{\text{Current (A)}}{\text{Luminous flux (lm)}}$$

**●Radiant sensitivity:**
The ratio of photocurrent in amperes (A) flowing in the photocathode to the intensity of the incident light in watts (W).

$$\text{Radiant sensitivity (A/W)} = \frac{\text{Current (A)}}{\text{Light intensity (W)}}$$

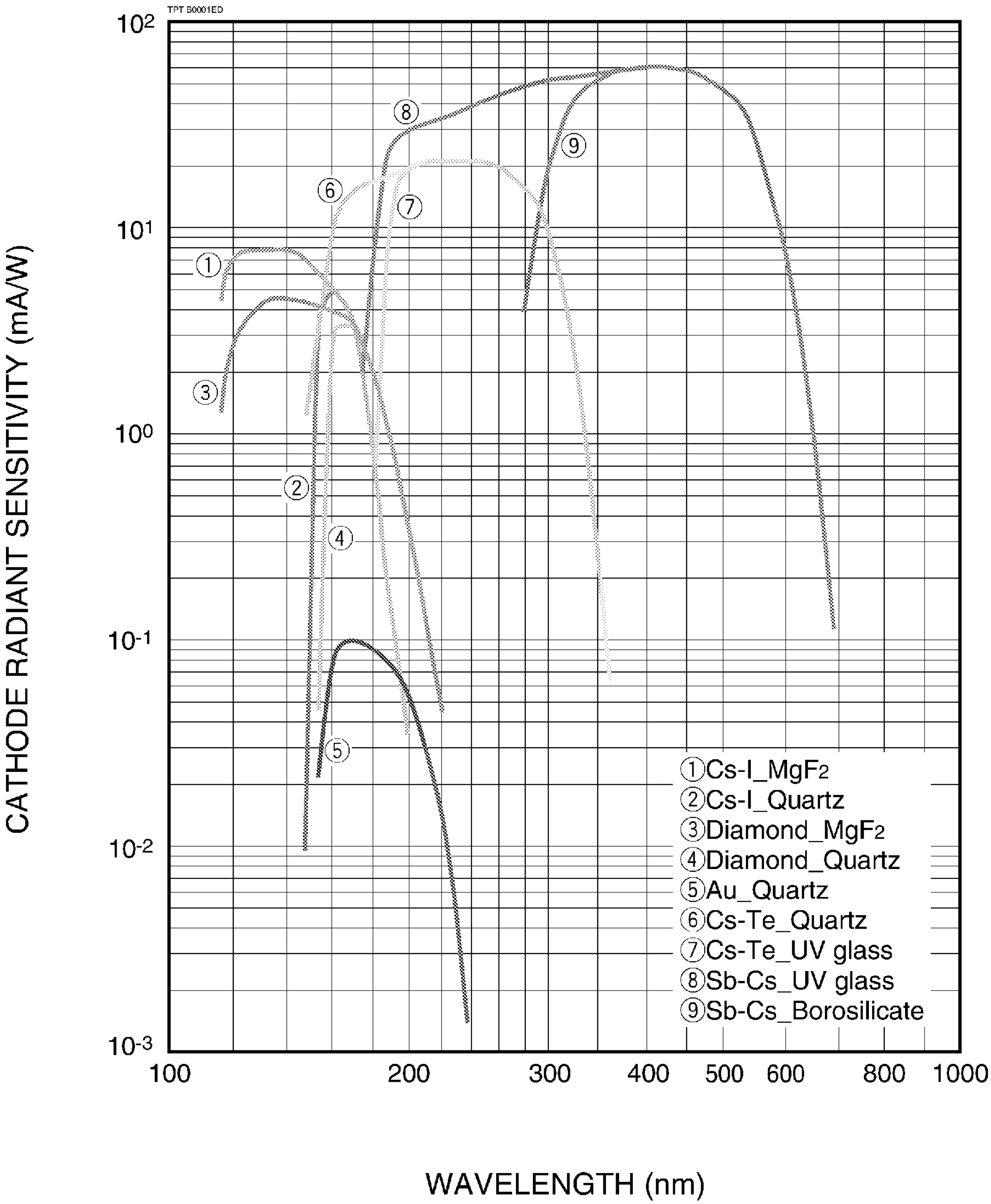
**●Dark Current:**
The current flowing between the anode and the cathode when light is removed.

**●Interelectrode capacitance:**
The electrostatic capacitance between the anode and the cathode.

**●Recommended operating voltage:**
The lifetime of a phototube tends to become shortened as the supply voltage increases. The supply voltage should be made as low as possible as compared to the maximum ratings, in order to lengthen useful life. However, if the supply voltage is too low, the voltagecurrent characteristics fall outside the saturation region, and undersirable phenomena such as hysteresis (Note 1) may occur. Considering these effects, the recommended operating voltage for each type of phototube is listed in this catalog.

(Note 1) Hysteresis: The temporary instability in output signal when light is applied to a phototube, showing "overshoot" or "undershoot" without being proportional to light input.

## ■SPECTRAL RESPONSE CHARACTERISTICS



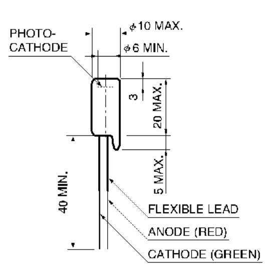
## ■CHARACTERISTICS

| Type No. | Ⓐ Spectral Response (nm) | Peak Wave-length (nm) | Outline Diagram No. | Tube Diameter (mm) | Photocathode Area Min. (mm) | Input Window Material | Absolute Maximum Ratings: Anode Supply Voltage (V) | Peak Cathode Current (μA) | Ⓑ Average Cathode Current Density (μA/cm²) | Average Cathode Current (μA) | Ⓒ Ambient Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **●GLASS BULB TYPE** | | | | | | | | | | | |
| **For Vacuum UV (Cs-I Photocathode)** | | | | | | | | | | | |
| R1187 | 115 to 200 | 130 | ❸ | φ15 | φ8 | $MgF_2$ | 100 | 1 | 0.5 | 0.1 | -80 to +50 |
| R5764 | 160 to 200 | 161 | ❸ | φ15 | φ8 | Quartz | 100 | 1 | 0.5 | 0.1 | -80 to +50 |
| **For UV / High Power (Au Single Metal Photocathode)** | | | | | | | | | | | |
| R4044 | 160 to 240 | 185 | ❸ | φ15 | φ8 | Quartz | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| **For UV / General Purpose (Cs-Te Photocathode)** | | | | | | | | | | | |
| R1107 | 185 to 350 | 240 | ❶ | φ10 | φ6 | UV glass | 100 | 0.5 | 5 | 0.15 | -80 to +50 |
| R765 | 160 to 350 | 240 | ❷ | φ15 | φ8 | Quartz | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| R1228 | 185 to 350 | 240 | ❷ | φ15 | φ8 | UV glass | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| **For UV to Visible (Sb-Cs Photocathode)** | | | | | | | | | | | |
| R414 | 300 to 650 | 400 | ❶ | φ10 | φ6 | Borosilicate glass | 100 | 1 | 5 | 0.3 | -80 to +50 |
| R840 | 185 to 650 | 340 | ❷ | φ15 | φ8 | UV glass | 100 | 2 | 5 | 0.5 | -80 to +50 |
| R727 | 185 to 650 | 340 | ❹ | φ20 | φ15 | UV glass | 100 | 6 | 5 | 2 | -80 to +50 |
| **●METAL PACKAGE TYPE** | | | | | | | | | | | |
| **For Vacuum UV (Diamond Photocathode)** | | | | | | | | | | | |
| R6800U-26 | 115 to 220 | 135 | ❺ | φ16 | φ6 | $MgF_2$ | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| R6800U-16 | 160 to 220 | 165 | ❺ | φ16 | φ6 | Quartz | 100 | 10 | 50 | 4 | -80 to +50 |
| **For UV / General Purpose (Cs-Te Photocathode)** | | | | | | | | | | | |
| R6800U-11 | 160 to 350 | 240 | ❻ | φ16 | φ8 | Quartz | 100 | 1.2 | 5 | 0.4 | -80 to +50 |
| R6800U-01 | 185 to 350 | 240 | ❼ | φ16 | φ8 | UV glass | 100 | 1.2 | 5 | 0.4 | -80 to +50 |

**NOTE:** ⒶSee spectral response characteristics on page 2. ⒷOutput current averaged over 1 second time interval. The whole photocathode is uniformly illuminated. ⒸWhen a tube is operated below -35 °C see page 6, "Caution".

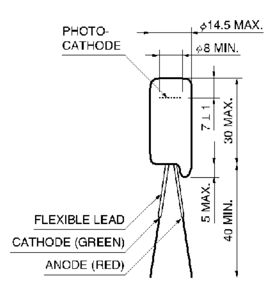
## ■DIMENSIONAL OUTLINES (Unit: mm)

**❶ R414, R1107**



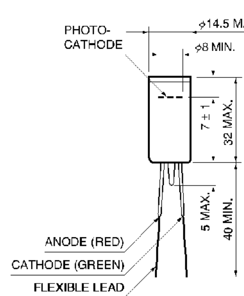

TPT A0002EA

**❷ R765, R1228, R840**



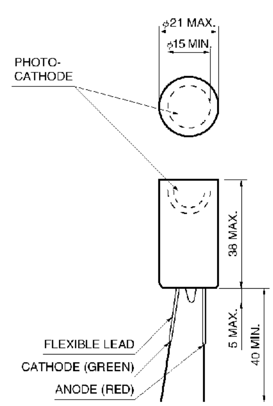

TPT A0003EB

**❸ R5764, R4044, R1187**




TPT A0014EC

**❹ R727**

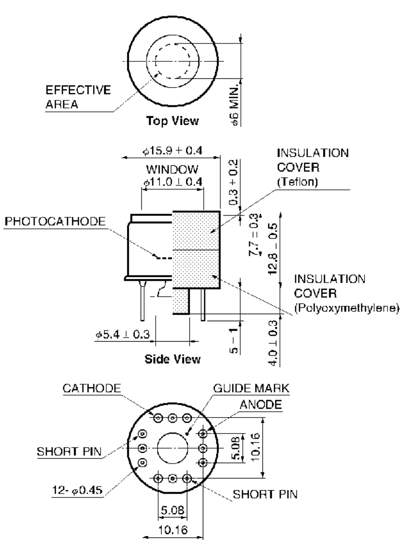



TPT A0006EB

| Characteristics at 25 °C | | | | | | | | | | | Type No. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Luminous Sensitivity ❹ | | Radiant Sensitivity | | | | | | Dark Current | Recommended Operating Voltage | Interelectrode Capacitance | |
| | | 122 nm | | 254 nm | | Pt Peak ❺ | | | | | |
| Typ. (µA/lm) | Min. (µA/lm) | Typ. (mA/W) | Min. (mA/W) | Typ. (mA/W) | Min. (mA/W) | Typ. (mA/W) | Min. (mA/W) | Max. (pA) | (V) | (pF) | |
| — | | 8 | 2 | — | | — | | 2 | 15 | 2.4 | R1187 |
| — | | — | | — | | 5 | 1 | 2 | 15 | 2.4 | R5764 |
| — | | — | | — | | 0.1 | 0.02 | 1 | 15 | 2.4 | R4044 |
| — | | — | | 15 | 10 | — | | 2 | 15 | 2.0 | R1107 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 2.4 | R765 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 2.4 | R1228 |
| 80 | 40 | — | | — | | — | | 5 | 15 | 2.0 | R414 |
| 80 | 40 | — | | — | | — | | 2 | 15 | 2.4 | R840 |
| 110 | 40 | — | | — | | — | | 2 | 15 | 2.0 | R727 |
| — | | 3 | 1 | — | | — | | 1 | 15 | 3 | R6800U-26 |
| — | | — | | — | | 3 | 1 | 1 | 15 | 3 | R6800U-16 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 3 | R6800U-11 |
| — | | — | | 20 | 10 | — | | 1 | 15 | 3 | R6800U-01 |

❹The photocurrent from the photocathode per incident light flux ($10^{-5}$ to $10^{-2}$ lumens) from a tungsten filament lamp operated at a distribution temperature of 2856 K. ❺See peak wavelength.

### ❺ R6800U-16, -26

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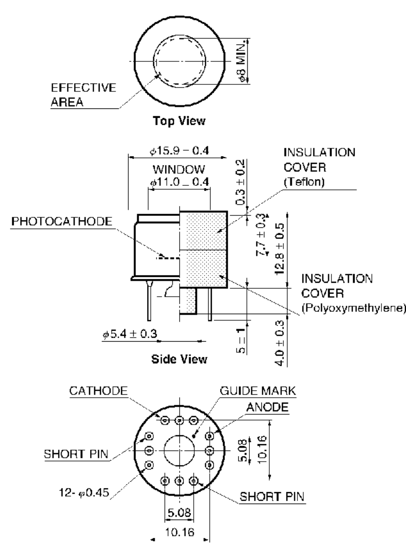
### ❻ R6800U-11

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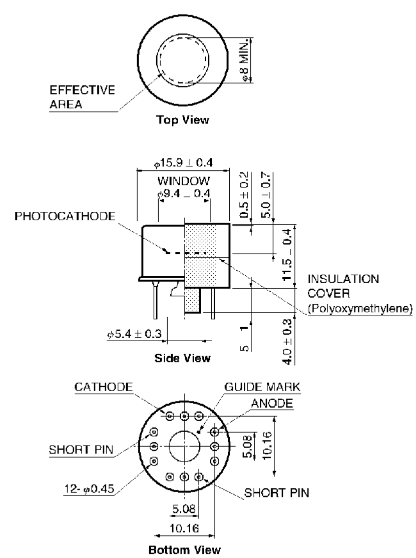
### ❼ R6800U-01




TPT A0022EC



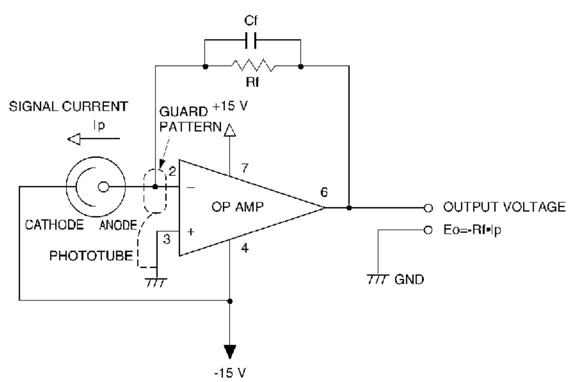
NOTE: Don't use pins excepting ANODE and CATHODE pins.

# ■EXAMPLE OF OPERATING CIRCUITS

## OPERATING CIRCUITS FOR PHOTOTUBES

Figure 1 shows an operating circuit example using the phototube bias voltage also for the power to an operational amplifier. The feedback resistance Rf should be chosen so that the output voltage becomes 0.1 V to 1 V. Cf must be placed for stable operation and should be between 10 pF and 100 pF. It is recommended to use a low-bias, low-offset-current FET input operational amplifier. For the input terminal (pin 2), a guard pattern should be provided on the printed circuit board or a stand-off terminal made of Teflon should be used.

Figure 1: When Pulse / Minus Powers Are Available

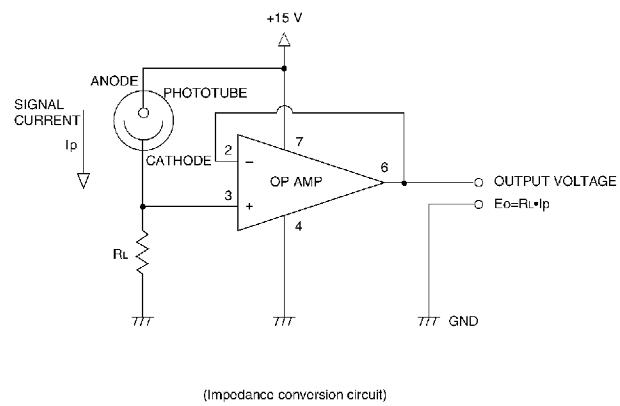



(Inverting current-voltage conversion circuit)

TPT C0001EC

Figure 2 shows an operating circuit in which a low-impedance voltage is output from an operation amplifier after the signal current has been converted into a voltage through the road resistance RL. The operational amplifier should be a low-bias, low-offset-current type which can be operated on a single power.

Figure 2: Operating Circuit Operating on Signal Power




(Impedance conversion circuit)

TPT C0002EC

**NOTE:** The operational amplifiers that can be used in these circuits differ in such factors as operating temperature range, bias current, phase compensation, and offset adjustment method, depending on the type used. Please refer to the catalog or data sheet available from the manufacturer.
Sample circuits listed in this catalog introduce typical applications and do not cover any guarantee of the circuit design. No patent rights are granted to any of the circuits described herein.

## ■ ⚠ CAUTIONS

● **Maximum ratings**
Always operate the phototube within the maximum rating listed in this catalog.

● **The light input surface area should be as large as possible**
The output current available from a phototube is determined by the maximum average cathode current and maximum average cathode current density. If the light input surface area is small, even if the output current is below the maximum average cathode current, the maximum average cathode current density may be exceeded. Therefore, the light input surface area should be as large as possible to decrease the cathode current per unit surface area. This is important also, from the standpoint of photocathode uniformity (i.e., variation in sensitivity with respect to incident light position).

● **Handle tubes with extreme care**
Phototubes have evacuated glass envelopes. Allowing the glass to be scratched or to be subjected to shock can cause cracks. Extreme care should be taken in handling, especially for tubes with graded sealing of synthetic silica.

● **Avoid mechanical vibration**
Mechanical vibration can cause microphonic noise (sensitivity fluctuation caused by vibration of the electrode.) and variation in sensitivity caused by displacement of the incident light position.

● **keep faceplate and base clean**
Do not touch the faceplate and base with bare hands. Dirt and fingerprints on the faceplate cause loss of transmittance and dirt on the base may cause ohmic leakage. Should they become soiled, wipe it clean using alcohol.

● **Avoid direct sunlight and other high-intensity light**
Avoid subjecting the phototube to direct sunlight or other high-intensity light, as this can adversely affect the photocathode, causing not only loss of sensitivity but instability as well.

● **Handling of tubes with a glass base**
A glass base (also called button stem) is weak, so care should be taken in handling this type of tube.

● **Cooling of tubes**
When cooling a phototube, the photocathode section is usually cooled. However, if you suppose that the base is also cooled down to -35 °C or below, please consult our sales office in advance.

● **Helium permeation through silica bulb**
Helium will permeate through the silica bulb, leading to an increase in noise. Avoid operating or storing tubes in an environment where helium is present.

Data and specifications listed in this catalog are subject to change due to product improvement and other factors. Before specifying any of the types in your production equipment, please consult our sales office.

## ■WARRANTY

In general, Hamamatsu products listed in this catalog are warranted for a period of one year from time of delivery. This warranty is limited to replacement for the defective product. Note, however, that this warranty will not apply to failures caused by natural calamity or misuse.

## ■CE MARKING

This catalog contains products which are subject to CE Marking of European Union Directives. For further details, please consult Hamamatsu sales offices.

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MAY 2016 IP

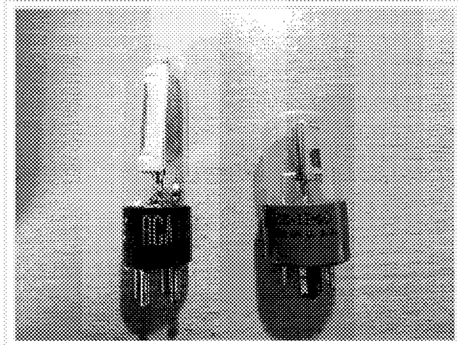
# Reference 2

Reference 2

# Phototube

From Wikipedia, the free encyclopedia

A **phototube** or photoelectric cell is a type of gas-filled or vacuum tube that is sensitive to light. Such a tube is more correctly called a 'photoemissive cell' to distinguish it from photovoltaic or photoconductive cells. Phototubes were previously more widely used but are now replaced in many applications by solid state photodetectors. The photomultiplier tube is one of the most sensitive light detectors, and is still widely used in physics research.



Two different types of phototubes

## Operating principles

Phototubes operate according to the photoelectric effect: Incoming photons strike a photocathode, knocking electrons out of its surface, which are attracted to an anode. Thus current is dependent on the frequency and intensity of incoming photons. Unlike photomultiplier tubes, no amplification takes place, so the current through the device is typically of the order of a few microamperes.[1]

The light wavelength range over which the device is sensitive depends on the material used for the photoemissive cathode. A caesium-antimony cathode gives a device that is very sensitive in the violet to ultra-violet region with sensitivity falling off to blindness to red light. Caesium on oxidised silver gives a cathode that is most sensitive to infra-red to red light, falling off towards blue, where the sensitivity is low but not zero.[2]

Vacuum devices have a near constant anode current for a given level of illumination relative to anode voltage. Gas filled devices are more sensitive but the frequency response to modulated illumination falls off at lower frequencies compared to the vacuum devices. The frequency response of vacuum devices is generally limited by the transit time of the electrons from cathode to anode.

## Applications

One major application of the phototube was the reading of optical sound tracks for projected films. Phototubes were used in a variety of light-sensing applications until they were superseded by photoresistors and photodiodes.

## References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Categories: Optical devices | Sensors | Vacuum tubes

# Reference 3

Reference 3

# United States Patent [19]

**MacDonald**

[11] **4,039,844**

[45] **Aug. 2, 1977**


[54] **FLAME MONITORING SYSTEM**


[75] Inventor: **Malcolm F. MacDonald,** Chelmsford, Mass.

[73] Assignee: **Electronics Corporation of America,** Cambridge, Mass.



[21] Appl. No.: **560,569**

[22] Filed: **Mar. 20, 1975**

[51] **Int. Cl.**[2] .......... **G01N 21/58**

[52] **U.S. Cl.** .......... **250/554;** 250/214 AG; 250/214 RC; 340/228.2

[58] **Field of Search** .......... 250/206, 554, 214, 214 AG, 250/214 RC; 340/228.1, 228.2; 23/254 EF



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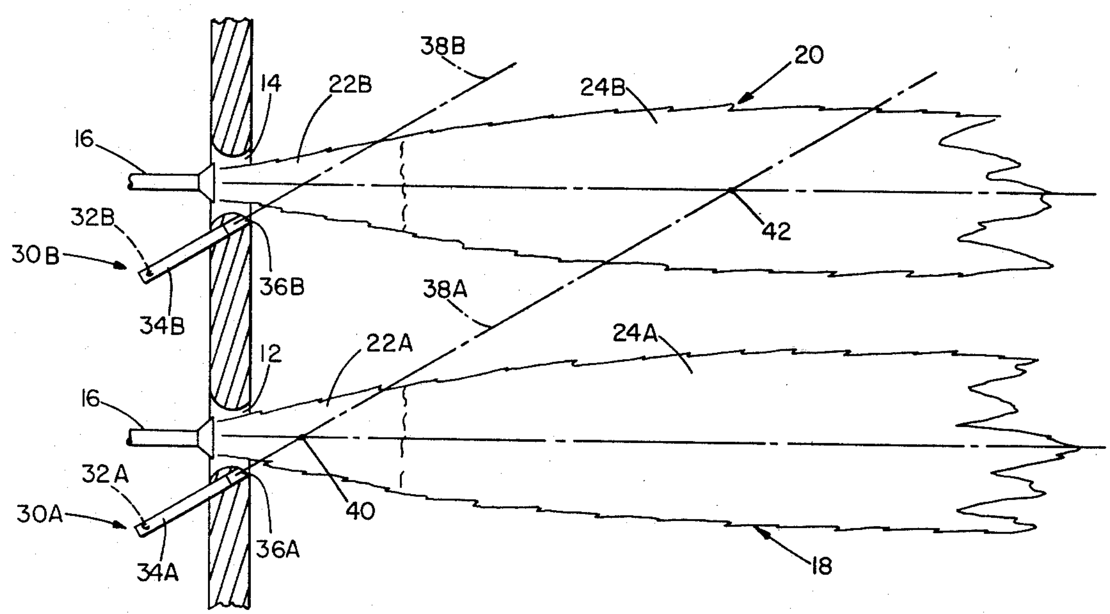
*Primary Examiner*—David C. Nelms

[57] **ABSTRACT**


A flame monitoring system includes a flame sensor for producing a flame signal as a function of flame conditions in a monitored environment and flame signal enhancing circuitry coupled to the flame sensor. The flame signal enhancing circuitry has a first response as a function of a first characteristic of the flame signal and a second response different from the first response as a function of a second characteristic of the flame signal and is arranged to combine the first and second responses to provide an enhanced flame signal representative of the monitored flame.


**24 Claims, 4 Drawing Figures**



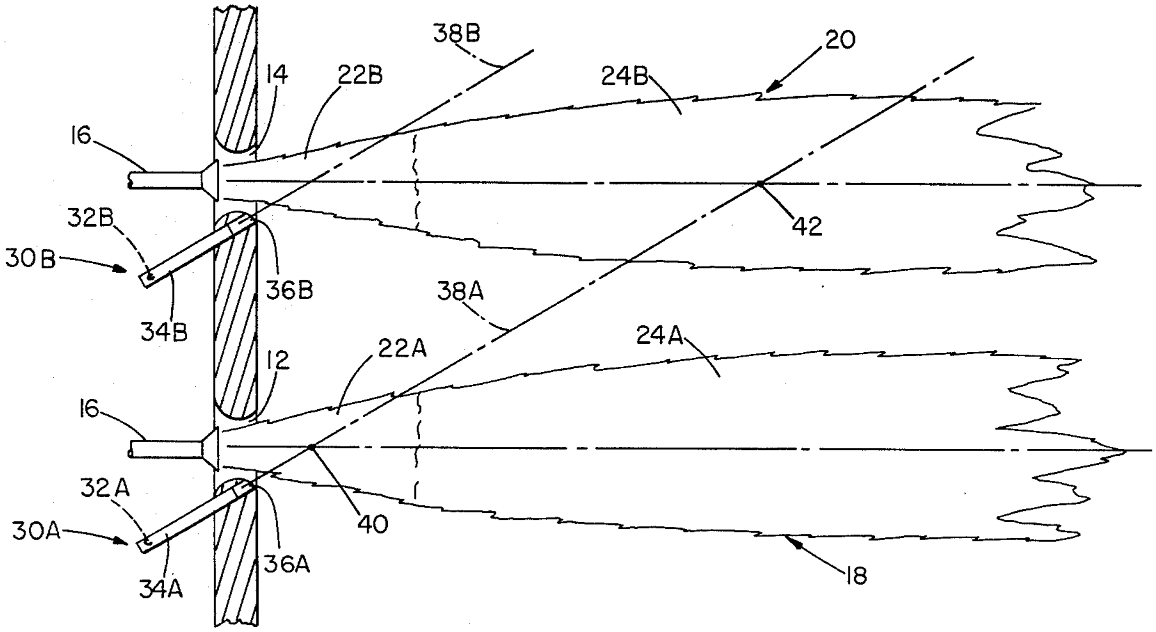



FIG 1

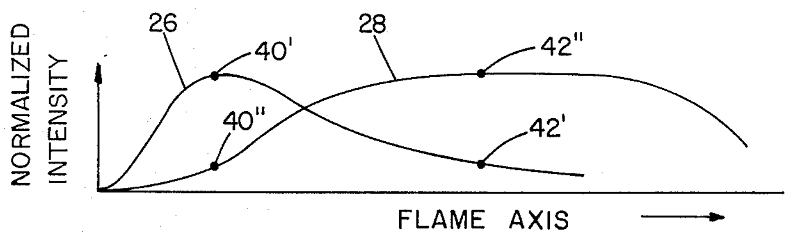



FIG 2

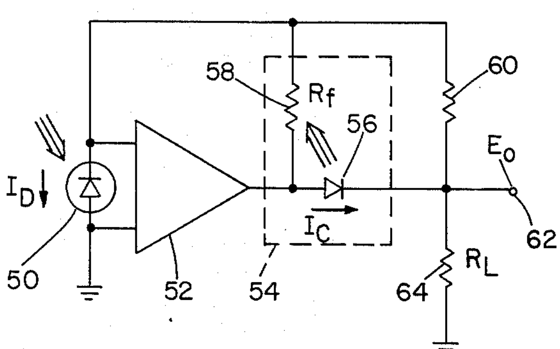
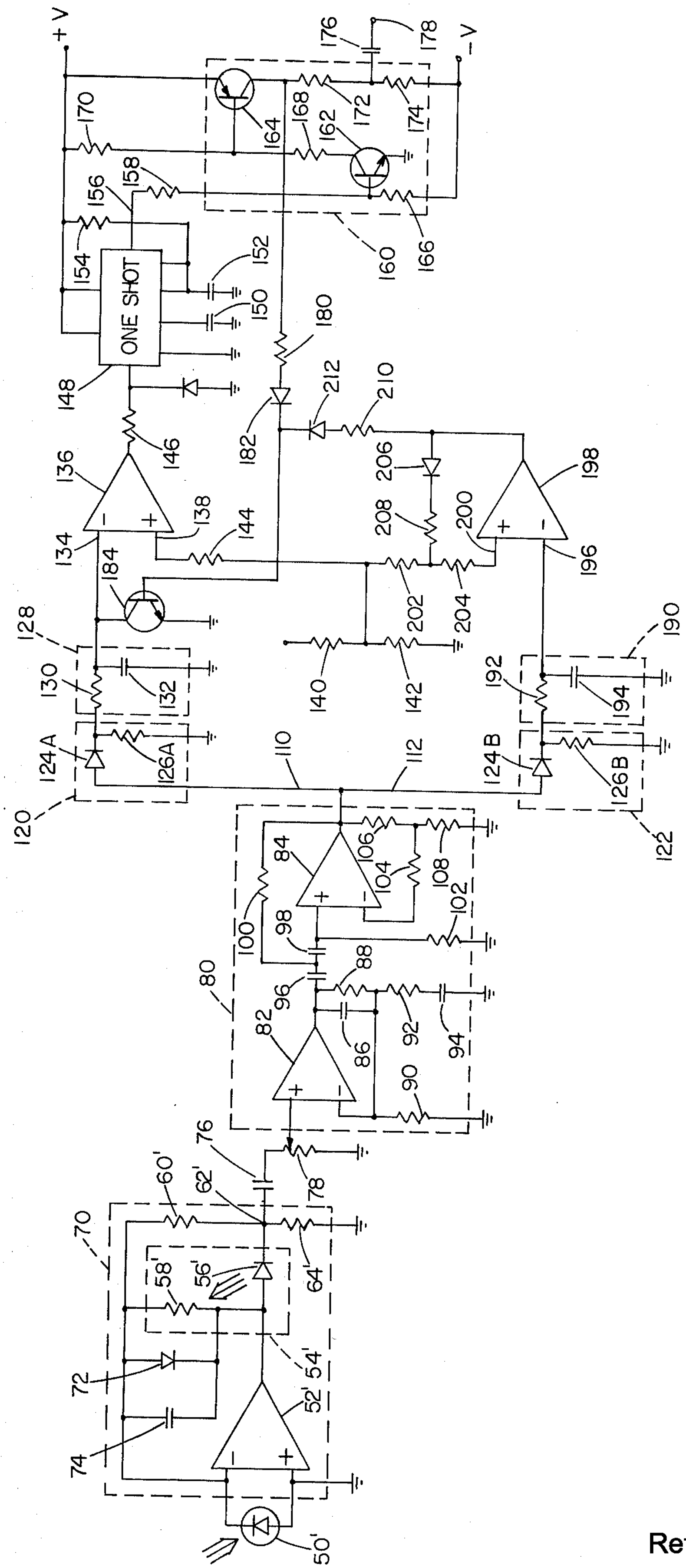



FIG 3

FIG 4



# FLAME MONITORING SYSTEM

## SUMMARY OF INVENTION

This invention relates to flame monitoring systems and more particularly to systems adapted for monitoring flames in multi-burner furnaces, such as boilers for large electrical power generating stations.

There is demand in modern steam generating stations, process systems and similar apparatus for the individual monitoring of burner flames so that immediate warning of flame failure can be given. The desirability of automatically monitoring flames in a furnace has long been recognized. When fuel continues to be supplied to a burner after the flame has been extinguished, the fuel may reignite explosively. While many flame detection systems responsive to flame radiation have been devised, such systems may give false indications that flame is present when they receive radiation from another source of comparable brightness, such as the furnace wall or an adjacent flame. In an effort to overcome such limitations, detector systems have been proposed which position plural detectors to view different areas of the same burner flame or which cross-correlate the signals from plural detectors positioned to view the same area of the burner flame. Certain flame detection systems utilize a flame responsive electrical output signal that has an alternating component, in some cases the utilized alternating component being in the order of 1-10 Hertz, while in other cases the utilized alternating component being of somewhat higher frequency, for example in the order of 100 Hertz.

The burner is frequently required to be monitored accurately at both low firing rates where the flame sensor must provide a useful signal when sensing radiation of low intensity, and at maximum firing rates where high radiation intensity on the flame sensor tends to mask components of higher frequency.

The source of alternating components of sensed flame radiation is not entirely clear but has been at times attributed to turbulence in the flame and/or to fluctuations in fuel supply. At the root or base of the flame, turbulence appears to distort the flame front, which distortions, it has been suggested, give rise to large variations in speed and direction of propagation of the combustion process and this may be the source of higher frequency alternating components. Lower frequency components exist in the flame region more remote from the base of the flame. With large turbulence, some unburned fuel may be carried periodically into the hotter regions of the flame where it suddenly ignites, propagating a region of hotter gas along the length of the flame. In practice, the magnitude of the higher frequency alternating component is low relative to the magnitude of the lower frequency or steady state component.

In accordance with an aspect of the invention, there is provided flame monitoring equipment for indicating the state of a burner flame by coordinating response of a single flame sensor or scanner to radiation components of different (e.g. higher and lower) frequencies that are sensed along a line of sight which passes through the root portion of the flame being monitored. The term "lower frequency components" is used herein to denominate steady and slowly varying components (up to a maximum of about 100 Hertz) while the term "higher frequency components" is used herein to denominate components that have a frequency above about 100 Hertz and up to 1000 Hertz and above.

Flame signal enhancing circuitry coupled to the flame sensor has a first response as a function of a first characteristic of the flame signal and a second response different from the first response as a function of a second characteristic of the flame signal and is arranged to combine the first and second responses to provide an enhanced flame signal representative of the monitored flame as an output signal. In preferred embodiments selective attenuation circuitry is coupled to the flame signal enhancing circuitry and has a low frequency cutoff that excludes all signals in the range of the second characteristic, a typical low frequency cutoff being about 200 Hertz. Gain adjustment means is provided for varying the magnitude of the enhanced flame signal.

The flame scanner conveniently comprises a photosensor mounted in tubular structure which serves to collimate the scanner path. The photosensor in practice may be mounted in a long tube which extends into the refractory wall of the combustion chamber; such a tube may be, for example, several feet in length to give protection for the sensor. The scanner path intersects the axis of its burner system at a selected point forward of the throat tile, a normal flame at selected point having a higher frequency component of significant intensity and the appropriate location of such point typically depending to some extent on conditions such as the nature of the fuel being fired. The root portion of a normal flame has a substantial higher frequency component while in portions of such flames more remote from the burner nozzle the magnitude of higher frequency components relative to lower frequency components is reduced. Background radiation conditions also have lower frequency characteristics. In a multi-burner system the scanner path may extend into more remote areas of the other flames (that is, areas of flames further spaced from the refractory wall than the monitored area of its flame). The ratio of lower to higher frequency components in such more remote areas is significantly greater than the lower/higher frequency component ratio in the monitored root portion of the supervised flame. Where the invention is utilized in such systems, it is not necessary that care be taken to direct the scanner away from the adjacent burners and towards a dark surface.

In preferred embodiments the signal processing circuitry produces an output that bears a direct relation to the higher frequency component and an inverse relation to the lower frequency component. While such direct and inverse relations may be obtained in various manner as, for example the higher frequency components being additively related and the lower frequency components subtractively related to the output signal, in particular embodiments the output signal is a ratio of the sensed higher and lower frequency components.

In a particular embodiment the photosensor is a silicon photodiode that has a high frequency response characteristic and a signal processing network coupled to the photodiode includes a radiation source that also has a high frequency response characteristic. A feedback circuit that includes a radiation responsive impedance element is optically coupled to the radiation source. The impedance of that impedance element changes as a function of radiation incident thereon at a rate that is much slower than the speed of response of the photodiode and of the radiation source. The feedback circuit moderates the output signal in proportion to the reciprocal of a fractional power of the low frequency component of the sensed radiation. It will be apparent that discrimination between the higher and lower frequency components of the sensed flame may be obtained in other manners, for example through use of a radiation source that has a damped output response or by separately extracting higher and lower frequency component signals and applying the extracted signals to a multiplier circuit. The alternating output signal of the signal processing network is applied to a band pass amplifier that has a pass band of about 400 Hertz and a low frequency cutoff at about 200 Hertz. The invention provides a simplified and more versatile monitoring system that is capable of providing enhanced discrimination between flames and also between flame and non-flame radiation sources in a combustion chamber. The system is useful in monitoring the quality as well as the presence of the supervised flame.

Other objects, features and advantages of the invention will be seen as the following description of a particular embodiment progresses, in conjunction with the drawings, in which:

FIG. **1** is a diagrammatic view of a flame monitoring arrangement for a multi-burner furnace;

FIG. **2** is a graph indicating the normalized relation of higher frequency and lower frequency components in a flame along the length of the flame;

FIG. **3** is a schematic diagram of a flame sensor circuit in accordance with features of the invention; and

FIG. **4** is a circuit diagram illustrating a flame monitoring system in accordance with the invention.

## DESCRIPTION OF PARTICULAR EMBODIMENT

There is shown in FIG. **1** a furnace structure having a refractory wall **10** with a plurality of burner throat apertures, two of which (**12, 14**) are shown. Conventional fuel supply and igniter structure **16** is associated with each burner system for establishing flames **18, 20.** Each flame has a primary combustion zone **22** adjacent to its burner throat aperture which contains a large proportion of unburned fuel. The brightness of this region is relatively low and high velocity air introduced through the burner throat creates turbulence in this primary combustion zone. As the flame extends further into the combustion chamber, combustion becomes complete with increased brightness in this secondary combustion zone **24,** and the high frequency modulation decreases in this region. Thus the primary zone **22** has a lower brightness and a significant proportion of higher frequency components, while the secondary zone **24** is brighter and has a lesser proportion of the higher frequency components.

The graph in FIG. **2** is an indication of the proportion of the higher and lower frequency components along the flame axis, the curves **26** and **28** being normalized as a typical average magnitude of the higher frequency component (represented by curve **26**) is in the order of 3–5 percent of the magnitude of the lower frequency component (represented by curve **28**).

A scanner system **30** is associated with each burner and includes a sensor **32** mounted in an elongated tube **34** that extends to a port **36** in the refractory wall **10** and that defines a line of sight **38.** Sensor **30A** is arranged to sense flame **18,** while sensor **30B** is arranged to sense flame **20.** Line of sight **38A** passes through the primary combustion zone **22A** of flame **18** (e.g. at point **40**) and the secondary combustion zone **24B** of flame **20** (e.g. at point **42**). The relative intensities of the higher and lower frequency components at points **40** and **42** along line of sight **38A** are indicated at **40'** and **40''**, and **42'** and **42''** respectively in FIG. **2.**

In particular embodiments a silicon photosensor is employed, its output response to sensed radiation components varying over the range of 1 to 500 microamperes. A circuit that accommodates the large dynamic range of sensed flame conditions and also produces an output that is directly related to the sensed higher frequency components and inversely related to the sensed lower frequency (including DC) components is shown in FIG. **3.** That circuit employs a silicon photodiode **50** which senses radiation energy of the flame in the rear infrared and visible red portions of the spectrum and has a speed of response that follows the second higher frequency components of the flame. The output of diode **50** is applied to operational amplifier **52** that is connected for current to voltage conversion and that has an optical coupler unit **54** connected to its output. That optical coupler includes a light emitting diode **56** optically coupled to a photoresistor **58** (e.g. cadmium sulfide) of slower response such that its response corresponds to the average current signal through diode **56.** Resistor **60** connected in parallel with photoresistor **58** in the feedback path of operational amplifier **52** limit the maximum gain of the circuit.

The transfer function for this circuit is of the form:

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $n$ has been found to be in the range of 0.6–0.8.

Thus, the AC output signal ($E_0$(AC)) is directly proportional to the AC component of the current ($I_D$) flowing through photodiode **50** and inversely proportional to a fractional power of the DC component of the current flowing through diode **50.** As $I_C$ (the output current) increases, the illumination of $R_f$ increases and causes its resistance value to decrease. The effect is to decrease the gain of the circuit. The frequency response of photosensor **58** in the optical coupler is less than 100 Hertz, lower than the response of photosensor **50** and so slow that it does not affect the high frequency component of the signal of interest.

This detection system senses the presence of flame of the particular burner it is supervising by sensing the presence of the higher frequency component of the signal, which signal presence is moderated by the effect of the second lower frequency component. Thus if there is either a significant decrease of the higher frequency signal or the lower frequency signal increases significantly more than the higher frequency signal, the output voltage will be reduced providing a flame out indication. The relationship between the higher and lower frequency components of a sensed flame is also useful in monitoring the quality of that flame.

The relationship between higher and lower frequency components of the radiation conditions along the sensed path in the combustion chamber may be usefully provided in various forms, for example a ratio of the higher to the lower frequency components or a diference between normalized values of the higher and lower frequency components, and by circuit arrangements other than that shown in FIG. **3.**

A schematic diagram of a particular embodiment is shown in FIG. **4.** That circuit includes a flame sensor **50'** connected across the input terminals of operational amplifier 52'. Sensor 50' is a silicon diode that is connected to operate in a photoconductive mode as a current source so that the sensed radiation intensity modifies the diode current flow as a function of the radiation incident on the diode. Connected to the output of amplifier 52' is a photocoupler 54' that includes a silicon light emitting diode 56' optically coupled to a cadmium sulfide photoresistor 58'. Supplemental resistor 60' is connected in the feedback path and diode 72 and capacitor 74 are connected across photoresistor 58'. This input stage 70 produces an output signal that is a direct function of the higher and an inverse function of the lower frequency components of the sensed radiation condition.

That output signal is coupled by capacitor 76 to a gain control potentiometer 78. Potentiometer 78 provides gain adjustment for band pass filter 80 that includes operational amplifiers 82 and 84. The band pass filter components are selected to provide a center frequency of about 400 Hertz and a pass band of 400 Hertz. The resulting output signal is applied on lines 110 and 112 to detector networks 120, 122, each of which includes a diode 124 and a resistor 126.

The signal from detector 120 is applied to high speed filter 128 that includes resistor 130 and capacitor 132 and has a time constant of about 50 milliseconds. The output of the filter 128 is applied to terminal 134 of operational amplifier 136 which is connected to function as a comparator. The voltage at reference terminal 138 of comparator 136 is supplied from a divider network includes resistors 140 and 142 and is about 0.15 volt. When capacitor 132 is sufficiently charged so that the voltage at terminal 134 exceeds the voltage at terminal 138, amplifier 136 triggers one shot circuit 148 which generates an output pulse of forty microsecond duration on output line 156. That output pulse is applied through resistor 158 to driver amplifier 160 that includes transistors 162 and 164 and the amplified output pulse is coupled by capacitor 176 to output terminal 178 as a flame present pulse. The amplified pulse is also coupled through resistor 180 and diode 182 to switch clamp transistor 184 into conduction, thus discharging capacitor 132 and resetting the filter 128.

A slow filter 190 includes resistor 192 and capacitor 194 and has a time constant of about 1½ seconds. The output of filter 190 is applied to input terminal 196 of comparator 198 whose reference terminal 200 which is connected to the voltage divider network of resistors 140, 142 via resistors 202 and 204. A second connection to reference terminal 200 is from the feedback network from the output of comparator 198 via diode 206 and resistor 208. The comparator output is also applied via resistor 210 and diode 212 to switch clamp transistor 184 into conduction. Should the output of filter 190 fall below 0.15 volt (the reference voltage at terminal 200), the output of comparator switches positive and applies a voltage through diode 206 to increase the reference voltage at terminal 200 to about 0.5 volt (thus raising the comparator threshold about 2½ times) and at the same time clamps capacitor 132 in discharged condition (via transistor 184) thus preventing the production of flame present pulse signals at terminal 178.

Thus, when the flame signal from the band pass amplifier 80 drops, in response to a low flame or no flame condition, comparator 198 switches its output signal, terminating the generation of output pulses at terminal 178 and also increasing the threshold of comparator 198. A larger flame signal (0.5 volt) is required to switch comparator 198 to remove the clamp from the flame pulse producing channel so that flame pulses will be again produced at output terminal 178 and when such flame signal is produced by filter 190, comparator 198 is switched back to the lower threshold value.

In operation, the burner 16A in proper operation provides a flame condition with fluctuating components in zone 22A. The sensor circuit 70 senses that fluctuating component and steady state components in zone 24 of flame 20 as well as in background radiation and produces an AC signal which coupled by capacitor 76 to the band pass amplifier 80 which amplifies that AC signal. As long as that AC signal above a minimum threshold is present, filter 128 periodically causes comparator 136 to trigger one shot 148 to produce a forty microsecond pulse at output terminal 178. Those output pulses are compatible with operating circuitry designed to respond to an ultraviolet flame sensor, for example. Should the magnitude of the output signal from the band pass amplifier fall sufficiently to switch comparator 198, however, the pulse generating circuit is clamped off and the threshold level is shifted by the feedback loop of comparator 198 to require a substantially greater magnitude of flame signal at terminal 62' to reinitiate the generation of output pulses at terminal 178 than was required to maintain application of those pulses at that terminal.

Values and types of components employed in the embodiment shown in FIG. 4 are set out in the following table:

| Reference No. | Component Value or Type |
|---|---|
| 52' | N5556T |
| 54' | CLM8500 |
| 60' | 1M |
| 64' | 3.2K |
| 74 | 100pf |
| 76 | 0.01uf |
| 78 | 100K |
| 82 | N5558T |
| 84 | N5558T |
| 86 | 220pf |
| 88 | 1M |
| 90 | 1M |
| 92 | 3.3K |
| 94 | 0.47uf |
| 96 | 0.022uf |
| 98 | 0.022uf |
| 100 | 39K |
| 102 | 39K |
| 104 | 33K |
| 106 | 10K |
| 108 | 10K |
| 124A | 1N4448 |
| 124B | 1N4448 |
| 126A | 3.3K |
| 126B | 3.3K |
| 130 | 33K |
| 132 | 1.8uf |
| 136 | N5558T |
| 140 | 10K |
| 142 | 100 |
| 144 | 33K |
| 146 | 4.7K |
| 148 | NE555T |
| 150 | 0.01uf |
| 152 | 0.001uf |
| 154 | 33K |
| 158 | 10K |
| 162 | 2N2222 |
| 164 | 2N3073 |
| 166 | 100K |
| 168 | 1K |
| 170 | 10K |
| 172 | 100 |
| 174 | 220 |
| 176 | 0.47uf |
| 180 | 1K |
| 182 | 1N4448 |
| 184 | 2N2222 |
| 192 | 33K |
| 194 | 56uf |

-continued

| Reference No. | Component Value or Type |
|---|---|
| 198 | N5558T |
| 202 | 3.3K |
| 204 | 33K |
| 206 | 1N4448 |
| 208 | 100K |
| 210 | 10K |

While a particular embodiment of the invention has been shown and described, various modifications thereof will be apparent to those skilled in the art and therefore it is not intended that the invention be limited to the disclosed embodiment or to details thereof and departures may be made therefrom within the spirit and scope of the invention as defined in the claims.

What is claimed is:

1. A flame monitoring system comprising

a flame sensor producing an electrical output signal having both higher frequency and lower frequency components derived from a monitored flame environment,

and signal processing circuitry connected to said flame sensor and responsive to both said higher frequency and said lower frequency components of said output signal, said signal processing circuitry including an amplifier and a feedback network with a variable impedance and being arranged so that said higher frequency components are amplified and the amplifier gain is decreased in response to an increase in said lower frequency components such that the resulting output of said signal processing circuitry provides discrimination between the flame monitored by said sensor and other conditions in the supervised environment.

2. The system as claimed in claim 1 wherein said flame sensor is a photosensor that has a high speed response characteristic.

3. The system as claimed in claim 1 wherein said signal processing circuit has a transfer function of the form

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $E_{O(AC)}$ is the output signal of said signal processing circuitry, $I_{D(AC)}$ is a higher frequency component of said flame signals, $I_{D(DC)}$ is a lower frequency component of said flame signal, and $n$ is in the range of 0.6–0.8.

4. The system as claimed in claim 2 wherein said signal processing circuitry further includes a radiation source connected to the output of said amplifier, and said feedback network includes a radiation responsive impedance element that is optically coupled to said radiation source and that has a response speed that is much slower than the response speed of said photosensor.

5. The system as claimed in claim 4 and further including selective attenuation circuitry coupled to said signal processing circuitry for attenuating components of said signal processing circuitry output.

6. The system as claimed in claim 5 wherein said selective attenuation circuitry includes band pass amplifier circuitry that has a band corresponding to the frequency range of said higher frequency components.

7. A flame monitoring system comprising:

a flame sensor for producing a flame signal as a function of flame conditions in a monitored environment,

flame signal enhancing circuitry coupled to said flame sensor, said flame signal enhancing circuitry having an amplifier and a feedback network with a variable impedance and being arranged so that a first characteristic of said flame signal is amplified and the amplifier gain is decreased in response to an increase in a second characteristic of said flame signal to provide an enhanced flame signal representative of the monitored flame as an output signal.

8. The system as claimed in claim 7 wherein said first characteristic is a higher frequency component of said flame signal and said second characteristic is a lower frequency component of said flame signal.

9. The system as claimed in claim 8 wherein said flame signal enhancing circuitry has a transfer function of the form

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $E_{O(AC)}$ is said enhanced flame signal, $I_{D(AC)}$ is said first characteristic of said flame signal, $I_{D(DC)}$ is said second characteristic of said flame signal, and $n$ is in the range of 0.6–0.8.

10. The system as claimed in claim 7 and further including selective attenuation circuitry coupled to said flame signal enhancing circuitry for attenuating components of said output signal corresponding to the frequency range of said second characteristic of said flame signal.

11. The system as claimed in claim 10 wherein said selective attenuation circuitry has a low frequency cutoff that excludes all signals in the range of said second characteristic.

12. The system as claimed in claim 11 wherein said low frequency cutoff is about 200 Hertz.

13. The system as claimed in claim 12 wherein said selective attenuation circuitry includes a band pass amplifier that has a center frequency of about 400 Hertz and a pass band of about 400 Hertz.

14. The system as claimed in claim 12 and further including gain adjustment means for varying the magnitude of said enhanced flame signal.

15. The system as claimed in claim 7 wherein said flame sensor is a photosensor.

16. The system as claimed in claim 15 wherein said photosensor is a solid state device that has a photosensitive junction region.

17. The system as claimed in claim 16 wherein said solid state device is a silicon photodiode device.

18. The system as claimed in claim 7 wherein said flame signal enhancing circuitry has a transfer function of the form

$$E_{O(AC)} = \frac{KI_{D(AC)}}{I_{D(DC)}{}^{n}}$$

where $E_{O(AC)}$ is said enhanced flame signal, $I_{D(AC)}$ is said first characterstic of said flame signal, $I_{D(DC)}$ is said second characteristic of said flame signal, and $n$ is in the range of 0.6–0.8.

19. The system as claimed in claim 18 wherein said feedback network includes an impedance element that has a damped response to said flame signal.

20. The system as claimed in claim 19 and further including a radiation source coupled to be energized by the output of said amplifier and a slow speed photoresistor connected in said feedback network and optically coupled to said radiation source.

21. The system as claimed in claim 20 and further including gain adjustment means for varying the magnitude of said enhanced flame signal.

22. The system as claimed in claim 21 and further including selective attenuation circuitry coupled to said flame signal enhancing circuitry for attenuating components of said enhanced flame signal corresponding to



the frequency range of said second characteristic of said flame signal.

23. The system as claimed in claim 22 wherein said sensor is a solid state silicon device that has a photosensitive junction region.

24. The system as claimed in claim 23 wherein said first characteristic is a higher frequency component of said flame signal and said second characteristic is a lower frequency component of said flame signal and said selective attenuation circuitry has a low frequency cutoff of about 200 Hertz.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 4,039,844

DATED : August 2, 1977

INVENTOR(S) : Malcolm F. MacDonald

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 36, delete "the";

Column 4, line 6, after "1", insert --microampere--;

Column 4, line 13, change "rear" to --near--;

Column 4, line 15, change "second" to --sensed--;

Column 7, line 49, change "signals" to --signal--;

Column 7, line 66, after "a", insert --pass--.

**Signed and Sealed this**

*Twenty-eighth* **Day of** *March 1978*

[SEAL]

*Attest:*

RUTH C. MASON
*Attesting Officer*

LUTRELLE F. PARKER
*Acting Commissioner of Patents and Trademarks*

# Reference 4

Reference 4

# United States Patent [19]

**Kompelien**

[11] **Patent Number:** **5,073,769**

[45] **Date of Patent:** **Dec. 17, 1991**


[54] **FLAME DETECTOR USING A DISCRETE FOURIER TRANSFORM TO PROCESS AMPLITUDE SAMPLES FROM A FLAME SIGNAL**


[75] Inventor: **Arlon D. Kompelien**, Crosslake, Minn.

[73] Assignee: **Honeywell Inc.**, Minneapolis, Minn.



[21] Appl. No.: **608,054**

[22] Filed: **Oct. 31, 1990**

[51] **Int. Cl.**[5] .......... **G08B 17/12**

[52] **U.S. Cl.** .......... **340/578**; 250/554; 364/576

[58] **Field of Search** .......... 340/578; 250/554; 364/576, 550



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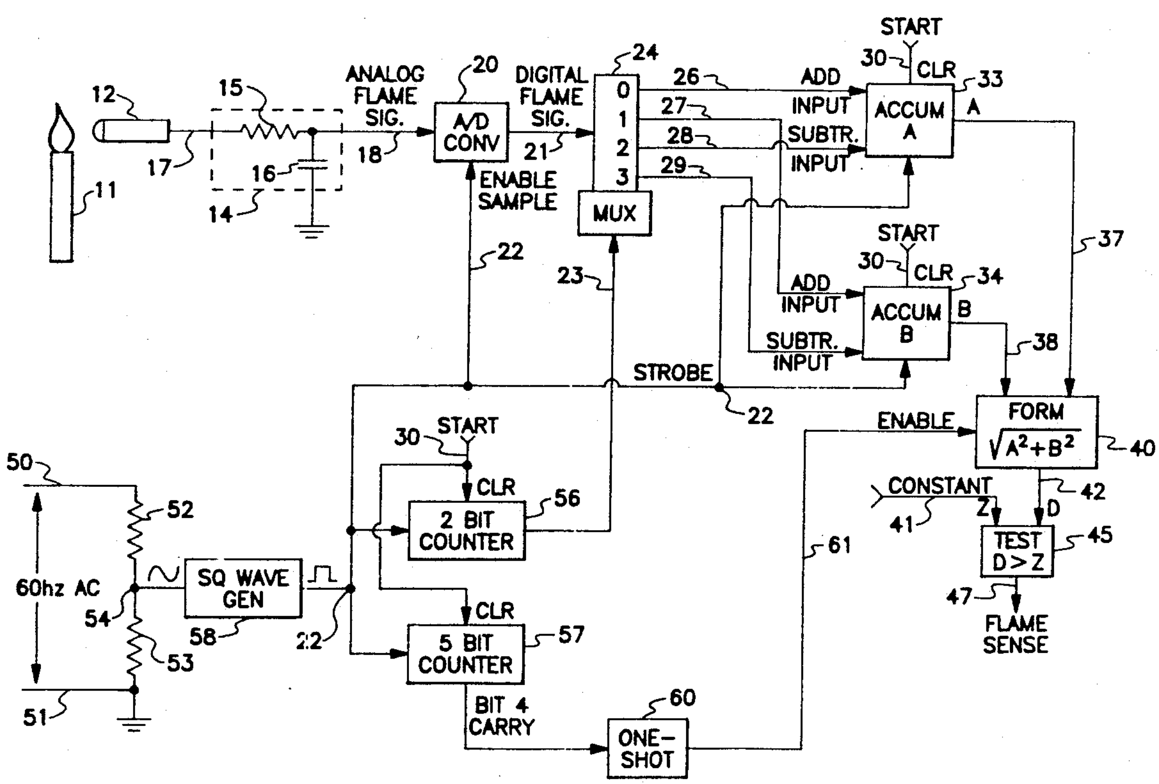
*Primary Examiner*—Jin F. Ng
*Assistant Examiner*—C. Oda
*Attorney, Agent, or Firm*—Edward Schwarz

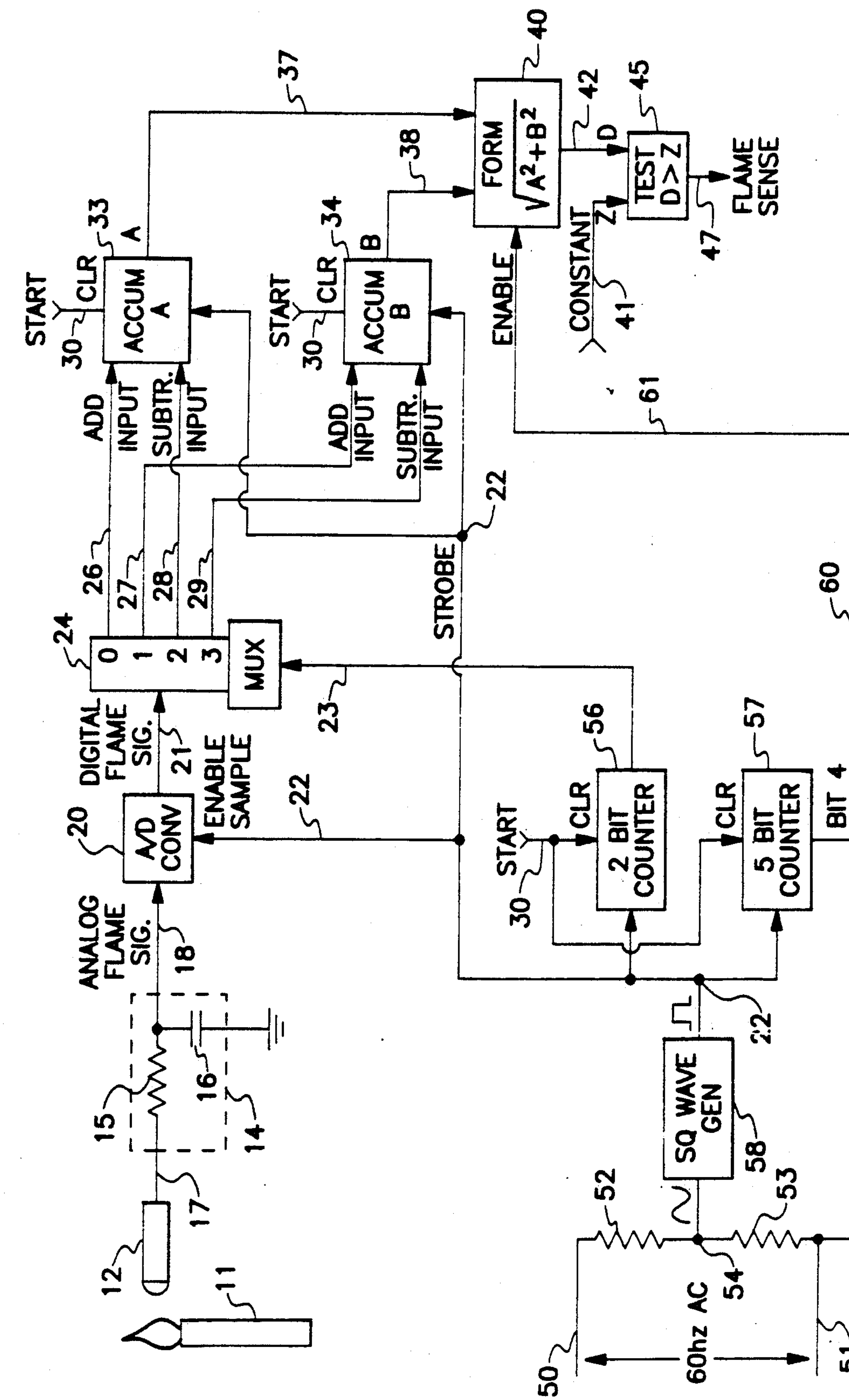


[57] **ABSTRACT**

A circuit for detecting presence of a flame receives a flame signal from a standard photocell positioned to receive radiation from the flame and digitally processes the amplitude variations in the photocell's output to sense for the presence of frequencies near a frequency which is characteristic of a flame. The frequencies substantially higher than the characteristic frequency are filtered from the signal, and the remaining signal is sampled at a frequency which is preferably four times the characteristic frequency. The samples are converted to digital values and processed using a discrete Fourier transform. If the value resulting from the transform operation exceeds a preselected value, presence of a flame is essentially certain. Such digital processing allows use of a dedicated microcircuit or a microprocessor for the flame sensing function and avoids the need for many large discrete components.


**7 Claims, 4 Drawing Sheets**





ANALOG FLAME SIG.
A/D CONV
ENABLE SAMPLE
DIGITAL FLAME SIG.
MUX
0 1 2 3
ADD INPUT
SUBTR. INPUT
START
CLR
ACCUM A
ACCUM B
A
B
STROBE
FORM $\sqrt{A^2+B^2}$
D
Z
TEST D>Z
FLAME SENSE
CONSTANT
ENABLE
ONE-SHOT
2 BIT COUNTER
5 BIT COUNTER
BIT 4 CARRY
SQ WAVE GEN
60hz AC
11
12
14
15
16
17
18
20
21
22
23
24
26
27
28
29
30
33
34
37
38
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41
42
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47
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51
52
53
54
56
57
58
60
61


Fig. 1

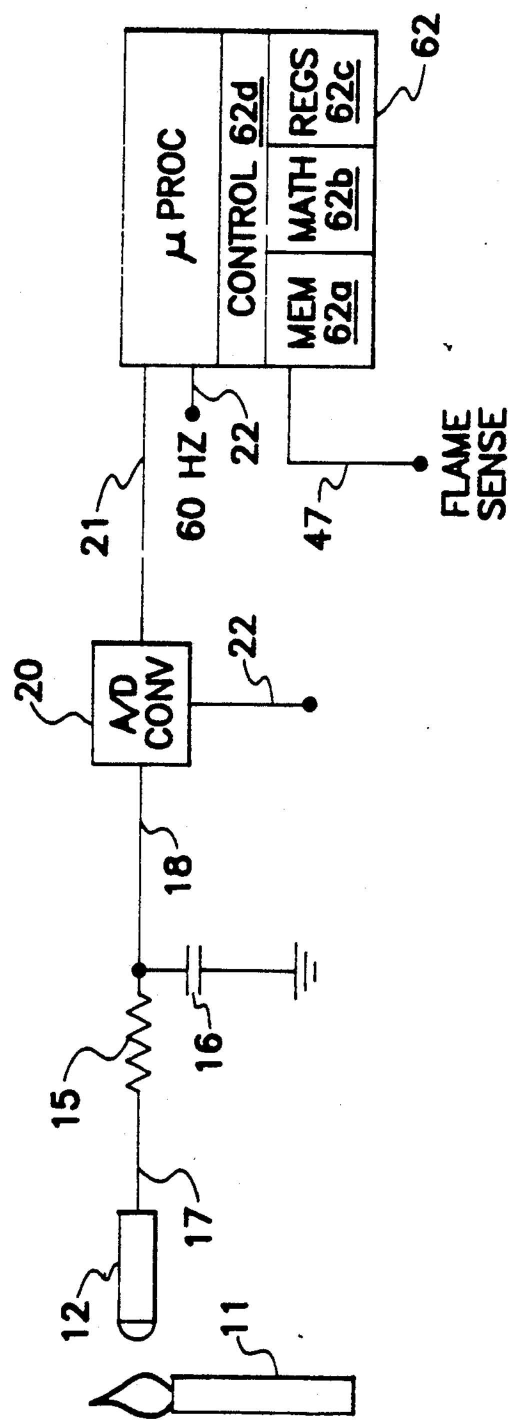

μ PROC
CONTROL 62d
MEM 62a
MATH 62b
REGS 62c
62
60 HZ
22
21
47
FLAME SENSE
A/D CONV
20
22
18
15
16
17
12
11

*Fig. 2*

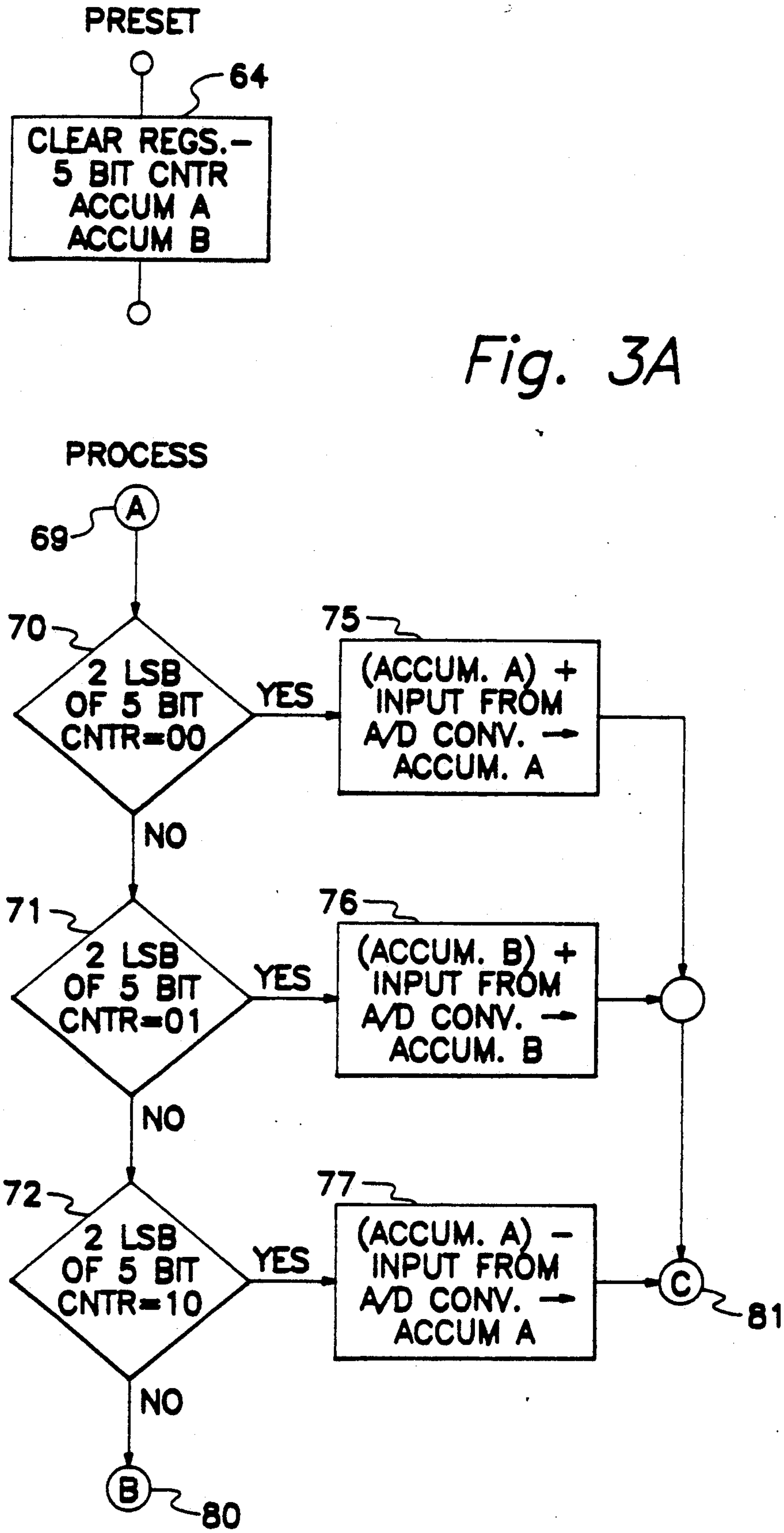

PRESET
64
CLEAR REGS.–
5 BIT CNTR
ACCUM A
ACCUM B
PROCESS
A
69
70
2 LSB
OF 5 BIT
CNTR=00
YES
NO
75
(ACCUM. A) +
INPUT FROM
A/D CONV. →
ACCUM. A
71
2 LSB
OF 5 BIT
CNTR=01
YES
NO
76
(ACCUM. B) +
INPUT FROM
A/D CONV. →
ACCUM. B
72
2 LSB
OF 5 BIT
CNTR=10
YES
NO
77
(ACCUM. A) –
INPUT FROM
A/D CONV. →
ACCUM A
C
81
B
80

*Fig. 3A*

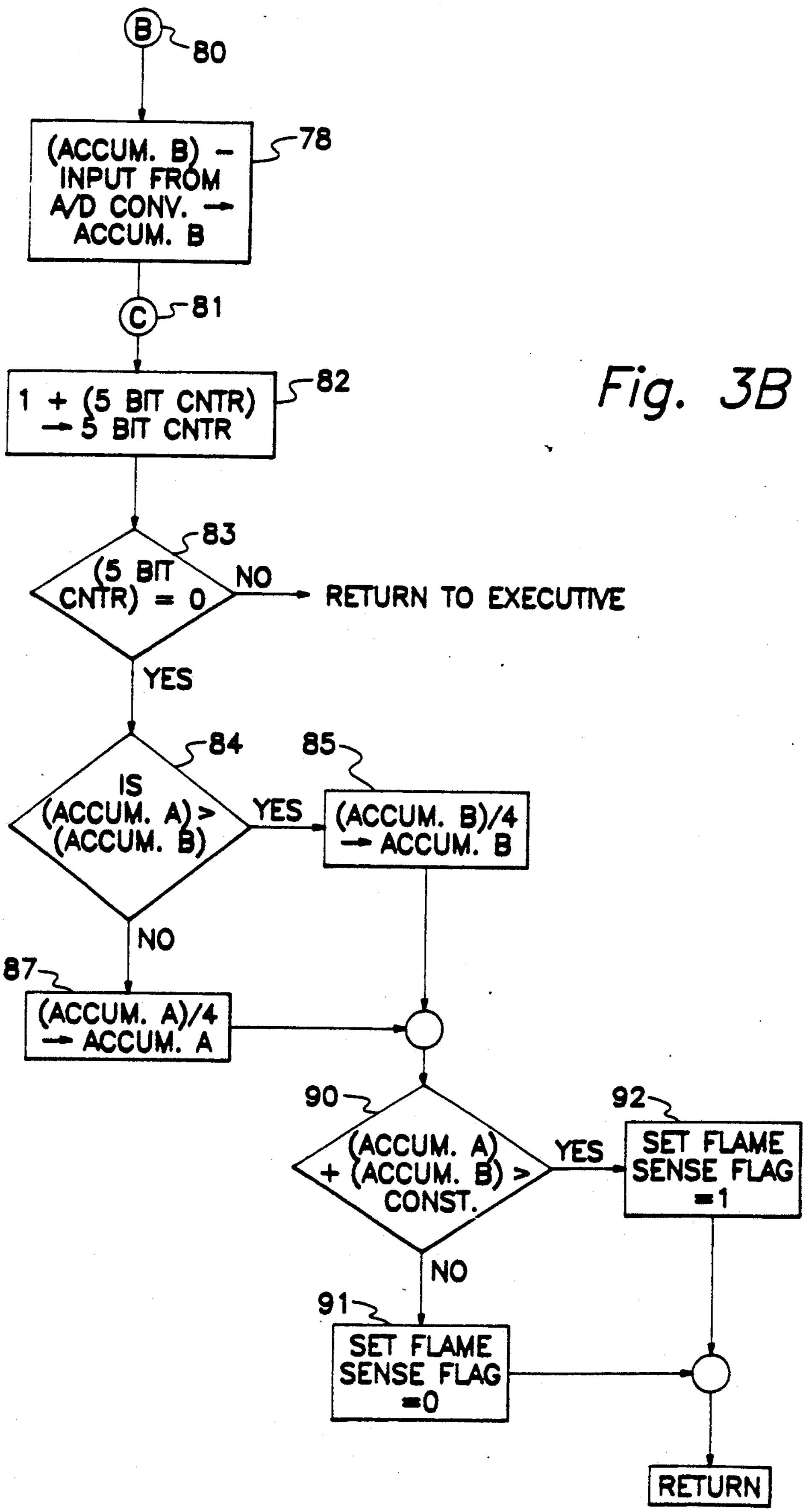

B
80
(ACCUM. B) – INPUT FROM A/D CONV. → ACCUM. B
78
C
81
1 + (5 BIT CNTR) → 5 BIT CNTR
82
(5 BIT CNTR) = 0
83
NO
RETURN TO EXECUTIVE
YES
IS (ACCUM. A) > (ACCUM. B)
84
YES
85
(ACCUM. B)/4 → ACCUM. B
NO
87
(ACCUM. A)/4 → ACCUM. A
90
(ACCUM. A) + (ACCUM. B) > CONST.
YES
92
SET FLAME SENSE FLAG =1
NO
91
SET FLAME SENSE FLAG =0
RETURN

Fig. 3B

# FLAME DETECTOR USING A DISCRETE FOURIER TRANSFORM TO PROCESS AMPLITUDE SAMPLES FROM A FLAME SIGNAL

## BACKGROUND OF THE INVENTION

In fuel burners such as furnaces where the main burner is lit by a pilot burner, it is necessary for obvious reasons to assure that the pilot burner is lit before the main burner fuel valve is opened. This is true whether a standing pilot or intermittent pilot is involved. While there are many different types of sensing operations which can reliably detect presence of a pilot flame, one which is preferred senses the flicker frequency of typical pilot flames. This flicker is a periodic variation of the intensity or amplitude of the infrared, visible, or ultraviolet radiation produced by the burning of the fuel sustaining the pilot flame. The flicker frequency of this radiation in most cases has a component in the range of 13–17 hz. This characteristic is fairly independent of the fuel and the size of the pilot flame.

In the past an analog circuit has been used to sense for presence of this flicker in the intensity of the radiation emanating from the location of the pilot flame. However, the relatively large size of components for an analog-based flame sensing system for the low frequencies involved here, cannot be easily included on a single circuit board with the smaller digital and logic-based circuits which are now more and more often being used to implement other functions of typical fuel burners. This necessitates a separate flame sensor board or a larger single board with a larger power supply, resulting in turn in undesirable expense and inconvenience.

## BRIEF DESCRIPTION OF THE INVENTION

The so-called fast Fourier transform (FFT) is a mathematical algorithm which has been used for signal frequency analysis for some time. When one desires to sense the presence of frequencies in a neighborhood of a particular single frequency, one can use a variation of the FFT called the discrete Fourier transform (DFT). A circuit for detecting presence of a radiation source such as a pilot flame having a significant flicker in its energy within a predetermined frequency range may use a particular variation of the DFT for the purpose of pilot flame detection. Such a circuit receives from a photocell a flame signal instantaneously representative of the intensity of the energy emanating from the flame. A simple analog low pass filter receives the flame signal and providing a filtered flame signal from which a substantial percentage of the amplitude of frequencies above the predetermined frequency range has been removed. This prevents the higher frequencies from simulating the flicker frequency of interest, a condition known as "aliasing", which is possible when using a DFT.

A clock circuit provides a clock signal having individual pulses at four times the frequency of the mid-point of the predetermined frequency range. For a common flicker frequency of 15 hz., it is convenient to use the normal 60 hz. power as the source of the clock signal. An analog to digital converter receives the filtered flame signal and the clock signal, samples the filtered flame signal responsive to each clock signal pulse, and provides a digital flame signal having a plurality of successive discrete, ordinally designated, digital values each encoding the amplitude of the filtered flame signal at successive sampling instants over a predetermined sampling interval. A first accumulator register receives the digital flame signal and forms from the plurality of digital values comprising the flame signal, the sum of the difference of successive pairs of even numbered ordinal digital values and provides at the end of each sampling interval a first intermediate digital transform signal encoding the current contents of the first accumulator register. A second accumulator register receives the digital flame signal and forms the sum of the difference of successive pairs of odd numbered ordinal digital values for the predetermined sampling interval, and provides at the end of each sampling interval a second intermediate digital transform signal encoding the current contents of the second accumulator register.

A calculator means receives the first and second intermediate digital transform signals from their respective accumulator registers and provides a transform signal digitally encoding a value at least approximately equal to the square root of the sum of the square of the digital values encoded in each of the first and second intermediate digital transform signals. That is, the actual computed value encoded in the transform signal to be used in the next phase of the operation of this apparatus should have at least the accuracy of an approximation of the precise value. A comparator means receives the transform signal from the calculator means and compares the value encoded in the transform signal with a predetermined transform constant value, and if greater than the transform constant value, issues a flame sense signal signifying presence of flame.

All of these elements except for the photocell analog low pass filter, and clock means can be formed by the proper programming of a microprocessor, and in fact this is the preferred embodiment for the invention.

Accordingly, one purpose of the invention is to reduce the size and power requirements of the flame sensing system in a burner control system.

A second purpose of the invention is to allow the flame sensing system to be included in the micro electronics package containing the control circuitry for the burner.

Yet another purpose of the invention is to allow changes in the sensitivity and response of the flame detector by software means only.

A further purpose is to increase the accuracy and reliability in detecting presence of a flame in a burner.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of electrical circuit employing discrete components to implement the invention.

FIG. 2 is a block diagram of a system implementing the invention using a microprocessor to perform the functions of the digital and logical blocks of FIG. 1.

FIGS. 3A and 3B flow diagram of instructions which may be loaded into the microprocessor of FIG. 2 to implement the invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention is for detecting a flame which has in its energy output intensity a flicker whose frequency is within a predetermined frequency range. The detection process used involves the so-called discrete Fourier transform (DFT) calculation to sense the presence of a component of the flicker frequency in the flame. In FIG. 1, a conventional burner 11, which may be a pilot burner such as is used in a conventional furnace or heater, produces a flame sensed by a photocell **12**. The photocell **12** provides a flame signal on path **17** which is instantaneously representative of the intensity of the energy emanating from the flame. For the typical pilot flame, there a frequency component in this flame signal within the 13-17 hz. range whose presence is a sufficient condition for the presence of a pilot flame, even though there are invariably many other frequencies present in the composite signal as well. This frequency component arises from the flow velocity, pressure, and combustion characteristics of the gaseous fuel supplying the typical pilot burner **11**, and is independent of the size or design of the pilot burner itself. However, the overall signal energy of this frequency component is substantially less than the signal energy of other frequencies present These other frequencies typically are radiated by the hot surfaces of the furnace interior after the pilot flame goes out, and thus of course provide no indication of the presence of any pilot flame. Accordingly, it is necessary to carefully tune a detector intended to sense presence of this frequency component, to detect frequencies within this 13-17 hz. range.

The flame signal on path **17** is filtered by a low pass filter **14** which comprises a series resistor **15** and a shunt capacitor **16** as shown. Preferably filter **14** has a cutoff frequency of approximately 20 hz., so that the amplitude of frequencies above 20 hz. is substantially attenuated. The output of filter **14** is a filtered flame signal on path **18** which is supplied to an analog to digital (A/D) converter **20**. In response to an enable sample signal on path **22**, A/D converter **20** provides a digital flame signal on path **21** which digitally encodes the digital value of the amplitude of the filtered flame signal at the instant that the enable sample signal on path **22** occurred. The range of converter **20** must be great enough to assure that there is no clipping of the input voltage level of the filtered flame signal reflected in the digital output. The enable sample signal is provided at fixed intervals by other circuitry of FIG. **1**, and it is strongly preferred that the enable sample signal occur at four times the rat of the flame signal frequency to be detected. Other sampling rates are possible, but any other rate involves substantially more complicated calculations to determine the DFT value of interest. When the invention is implemented within a simple and low powered microprocessor, complicated calculations are not easy to make, and such an implementation is the most likely. For the remainder of this description, the sampling rate of four times the DFT frequency will be assumed.

One can consider the output of A/D converter **20** as comprising a series of successive discrete, ordinally designated, digital values each encoding the magnitude of the filtered flame signal on path **18** at successive sampling instants occurring at the fixed enable sample rate. If a specific digital value is chosen as the first for a detection calculation, then it and the succeeding values may also be ordinally designated as well, as $x_0$, $x_1$, etc., with the subscripts forming the successive ordinal designations of the digital sample values.

The elements of FIG. **1** which will now be discussed will typically form parts of a microprocessor which is programmed to at the appropriate instants of time, perform the functions which the elements involved provide. In fact, many such microprocessors also include an A/D converter **20** as part of the package containing the microprocessor.

The digital flame signal on path **21** is supplied to the input of an output multiplexer **24**. Such a multiplexer has a number of output paths **26–29**, each of which has a unique address. The multiplexer **24** provides the binary digits encoded on its digital data input path **21** to the one of the output paths **26–29** whose address is specified by the address encoded in the signal on an address path **23**. All of the output paths **26–29** except for the one designated by the two bit address path **23** carry a digital value of zero. That is, the digital data on the input path **21** is carried by the output path **26**, **27**, **28** or **29** of multiplexer **24** accordingly as the input on the two bit address path **23** encodes a zero, one, two, or three. Output paths **26–29** which are not designated by the two bit address on path **23** encode a digital value of zero.

To understand the processing which is performed using the digital flame signal provided on path **21** it is useful to examine the mathematical expression of the discrete Fourier transform (DFT) which is employed here. A flicker signal generated when flame is present will almost always have a detectable frequency component at 15 hz. using the system being described, and will essentially never have such a component when no flame is present. As mentioned earlier, one can consider the A/D converter **20** as providing a plurality of successive discrete, ordinally designated, digital values each encoding the magnitude of the filtered flame signal on path **18** at successive sampling instants. The general theory for calculating a DFT for a waveform can be considerably simplified when the values of the waveform are sampled at a rate four times that of the DFT target frequency. In this simplified case, calculating the DFT involves forming two related summations to be explained shortly. For the purpose of reliably detecting presence of a pilot flame, it has been found to be sufficient to continue the summation over eight successive cycles of the 15 hz. frequency component. In the first summation, the sum of the difference of successive pairs o digital values having even ordinal designations must be formed. For the second summation, the sum of the difference of successive pairs of digital values having odd ordinal designations must be formed. If the first series value is designated A, and the ordinal designation of the successive digital values is represented by a subscript of from 0 to 31, then $A=x_0-x_2+x_4-x_6+\ldots+x_{28}-x_{30}$. (Equation 1) Similarly, the equation for the second series summation of the digital values can be written as $B=x_1-x_3+x_5-x_7+\ldots+x_{29}-x_{31}$. (Equation 2) The DFT for this wave form as sampled by converter **22** at these precise intervals is then given by $D=(A^2+B^2)^{1/2}$. (equation 3) It is possible to use other than precisely **32** samples for a single calculation, but I have found **32** to be adequate for accurate and reliable flame detection without excessive calculations or time required. At any rate, with this detection algorithm, the number of samples involved in a single evaluation should be a multiple of four.

To allow sampling to occur at exactly four times the rate of the target frequency of 15 hz., the enable sample signal must occur at 60 times per second. It is extremely convenient to use the standard 60 hz. power wave form as the clock which generates the enable sample signal on path **22** which controls the sampling of the filtered flame signal on path **18**. Accordingly, a 60 hz. AC signal on paths **50** and **51** is placed across a voltage divider comprising resistors **52** and **53**. The common point **54** of these resistors provides a low voltage 60 hz. sine wave input to a square wave generator **58** which produces a 60 hz. square wave output on path **22**. As mentioned earlier of course, the individual square wave pulses on path **22** enable successive samples of the filtered flame signal on path **18**. The square wave signal on path **22** is also provided to a two bit counter **56** and a five bit counter **57** to increment the contents of each of these counters by one each time a pulse is provided to the input on path **22**. It can be seen that two bit counter **56** counts from 0 to 3 decimal (0 to 11 binary) and then returns to 0 and continues cycling in that manner. Similarly, five bit counter **57** advances by one in response to each pulse on path **22** and after reaching **31** (11111 binary) returns to 0 and continues to advance with each additional pulse. It may well be more convenient to use the two least significant bits of five bit counter **57** as two bit counter **56**, and this is completely acceptable.

For sequencing purposes, it is necessary to employ a start signal provided by some external controller on path **30**. With respect to counters **56** and **57**, this signal is applied to clear (CLR) inputs which cause the counter **56** or **57** to be reset to 0. In addition, counter **57** provides a carry from its high order bit, bit 4 (the low order bit being bit 0), to indicate that 32 pulses have been applied to it since the counter **57** was last cleared. This bit 4 carry signal is applied to a one shot **60** which provides an output pulse whose duration is set by the internal characteristics of one shot **60**.

Multiplexer **24** along with an A accumulator **33** and a B accumulator **34** are the circuit elements directly involved with forming the two series summations of equations 1 and 2. While these two accumulators are shown here as discrete hardware elements, it is very likely that in a preferred embodiment using a microprocessor, these accumulators will be individual registers within the microprocessor memory. In such a case, the arithmetic unit of the microprocessor alternately cooperating with each of the registers to function as a part of one or the other of the accumulators. Each accumulator **33** or **34** has an add input and a subtract input, as the labeling indicates. Data on add input path **26** or **28** is added to the value stored in an accumulator **33** or **34** respectively responsive to a strobe signal on path **22**. Similarly, the data on subtract path **27** or **29** is subtracted from the value in the respective accumulator **33** or **34** responsive to a strobe signal on path **22**. It can thus be seen that individual digital values comprising the digital flame signal on path **21** are gated to one of the four output paths **26–29** of multiplexer **24** according to the value contained in two bit counter **56**, and each is then added to or subtracted from the respective accumulator contents. The start signal on path **30** clears the accumulators **33** and **34** prior to forming these two series. It can be seen that as two bit counter **56** continuously increments from 0 through 3, resets back to 0 and counts up again through **3**, each digital value from A/D converter **20** which is presented on path **21** when the two bit counter **56** is 0 is provided on path **26** to accumulator A **33** to be added to its contents. When the contents of two bit counter **56** equals 1 the digital valuc on path **21** is provided to accumulator B **34** to be added to its contents. When the contents of two bit counter **56** equals 2 then the digital value on path **21** is provided on path **28** to be subtracted from the contents of accumulator A **33**. And lastly when the contents of two bit counter **56** eequals 3 then the digital value on path **21** is gated to path **29** or subtraction from the contents of accumulator B **34**.

This sequence of cycling incrementally through two bit counter **56** occurs precisely eight times at which time five bit counter **57** crosses from a decimal value of 31 to 0 and a carry is provided on the bit four carry output of counter **57**. In this way exactly 32 sequential digital values are made available to compute the A and B summation series. The bit four carry signal is used to set one shot **60** which provides an enable signal on path **61** to a first arithmetic element **40** which receives the series summations in the A accumulator **33** and the B accumulator **34** on path A **37** and path B **38** respectively. Arithmetic module **40** computes the value $(A^2+B^2)^{\frac{1}{2}}$ and provides a digital representation D of this value encoded in a signal on path **42**. It is possible to employ an approximation for computing the value of D, and one possible formula for an acceptable approximation is explained in connection with the software implementation of FIGS. 3A and 3B. Thus, it may be said that if D is calculated by such an approximation, it is at least approximately equal to the precise value of D, and such precision is typically acceptable.

The value D is the actual DFT value for the flame signal on path **17** at 15 hz. To determine whether the 15 hz. frequency amplitude component in the flame signal on path **17** is sufficiently strong to indicate the presence of a flame, the value D is tested to be greater than a constant value Z provided on path **41**, and this test is performed by a digital comparator shown as test element **45**. As with the accumulators **33** and **34**, this test element will usually comprise circuitry within a microprocessor. If the inequality is true then a flame sense signal is provided on path **47**. This flame sense signal may be used for example as a precondition for opening the main valve of a burner, since this inequality assures that a pilot flame is present. The value Z should normally be equal to approximately four to five times the peak voltage of the filtered flame signal applied to the input of the A/D converter **20**, taking into account any scale factor which the A/D converter uses in determining the individual digital values indicative of the instantaneous flame signal voltage.

While FIG. **1** is a block diagram of a dedicated discrete component system for performing the operations of this invention, FIG. **2** shows a system having identical functions but implemented with a microprocessor **62** which performs all of the functions shown in FIG. **1** except for the square wave generation and initial signal acquisition and filtering. Such a microprocessor is currently available on the market with input channels such as shown connected to input paths **21** and **22** and a memory ***62a*** in Which instructions for accomplishing the computations of a DFT may be stored. Such a microprocessor **62** also includes computational and arithmetic capabilities in circuitry ***62b***, data storage in registers ***62c*** which typically comprise a random access memory, and overall control and decision making capabilities in the circuitry shown generally as ***62d***. In particular, the instructions stored in memory ***62a*** are selected so as to cause microprocessor **62** to function as the individual elements shown in FIG. **1** as directed by the instructions in memory ***62a***.

FIGS. 3A and 3B together form a flow chart of instructions which will direct microprocessor **62** to function as the individual elements shown in FIG. **1**. In FIGS. 3A and 3B, rectangular boxes are activity elements which denote instructions performing arithmetic and data transfer operations. Diamond-shaped boxes denote decision making elements. Within individual activity elements, a horizontal arrow denotes transfer of data identified o the left side of the arrow to the location specified on the right side of the arrow. Parentheses conventionally indicate the numeric or logical contents or value of whatever register or element is contained within the parentheses. It should be understood that microprocessor **62** will typically have many other functions to perform besides those related to this invention. In particular, there will typically be a control or executive software module which directs individual operating modules of the software to execute their functions as appropriate. Typically, some signal will be provided within microprocessor **62** which will eventually culminate in what is shown in FIG. **1** as the start signal encoded in the signal on path **30**.

It is desirable to test for flame at many times during a complete burner operating sequence, and each of these individual test times will typically be selected by microprocessor **6** operations. Each time that such a test time occurs, a short preset routine comprising instructions forming activity element **64** are executed. These presetting instructions clear five bit counter which may be a register forming one of the registers **62***c*, and also clear the A and B accumulators which will typically comprise two other registers of the registers **62***c*. The internal signals of microprocessor **62** which initiate this presetting operation correspond to the start signal carried on path **30** of the circuit of FIG. **1**.

The 60 hz. square wave signal is applied to an input **22** of microprocessor **62** which causes an internal interrupt within microprocessor **62** transferring execution of instructions to the A connector element **69** shown in FIG. **3A**, meaning that instructions commencing with decision element **70** and those following will be executed. The execution of instructions by microprocessor **62** is so fast compared with the 60 hz. sampling rate of A/D converter **20** that in every case the entire calculation plus whatever other functions which it may be necessary for microprocessor **62** to perform, have occurred before the next interrupt to connector element **69** occurs. The internal interrupt signal is simply one form of the enable sample signal on path **22** of FIG. **1**. As shown in FIGS. **1** and **2**, the signal on path **22** is also provided to an A/D converter **20** which provides a digital flame signal on path **21** to an input channel of microprocessor **62**.

The flow chart elements starting with connector **69** perform the actual update on a digital value to a digital value basis for computing the A and B summation series discussed earlier. After the last of the **32** values for a single DFT computation has been received and processed, the actual DFT value D is computed and compared with the constant shown on path **41** in FIG. **1**, to determine presence of a flame. In this embodiment, it is likely that this constant is internally stored by microprocessor **62**. Decision elements **70-72** and activity elements **75-78** compute the actual values of the A and B summation series. It is convenient to use the two least significant bits (LSB) of the five bit counter which counts the total number of digital data values provided by the A/D converter **20** to determine the position in the ordinal designation of each digital value and hence what series and what sign is required when the value is summed with the accumulator A or B value.

As indicated by decision element **70**, if the two least significant bits (LSB) of the five bit counter equal 00 (binary) then execution passes to the instructions represented by activity element **75**. These instructions read up the input from A/D converter **20** currently available on the associated input channel and read up the contents of the register functioning as accumulator A, add these two values together and store the value back into the register functioning as accumulator A.

If the two least significant bits of the five bit counter equal 01 binary, then the instructions of decision element **71** cause the instructions of activity element **76** to be executed. These instructions represented by element **76** take the input from the A/D converter **20**, add that digital value to the contents of the register functioning as accumulator B, and stores this sum back into accumulator B.

If the two least significant bits of the five bit counter are unequal to 01, then execution of instructions instead passe to the instructions represented by decision element **72**. If the instructions of decision element **72** find the two least significant bits of the five bit digital value counter to be equal to 10 (binary), then execution passes to the instructions represented by activity element **77**. Instructions of this element **77** cause the contents of the register serving as accumulator A to be read up, and then the input from the A/D converter **20** to be read up and subtracted from the contents of accumulator A. This difference is then stored back into accumulator A.

If the two least significant bits of the five bit counter are unequal to 00, 01, and 10 as sensed by the instructions of decision elements **70-72**, then control is transferred to the instructions comprising activity element **78** as symbolized by the B connector **80**. The instructions of element **78** cause the contents of the register functioning as accumulator B to be read up and from this value the input from the A/D converter **20** is subtracted. This difference value is then stored back into the register serving as accumulator B. It can be seen that the instructions symbolized by the activity and decision elements discussed above for computing the values in accumulators A and B in essence cause the microprocessor **62** to momentarily comprise multiplexer **24** and the A and B accumulators **33** and **34** of FIG. **1**.

After one of the instruction groups for elements **75**, **76**, **77**, or **78** have been executed during a pass through the program and the digital flame signal value has been added to or subtracted from the appropriate accumulator, control then passes to C element connector **81** and the instructions symbolized by activity element **82**. The instructions of this element **82** simply increment the contents of the five bit counter by **1** and store that value back into the five bit counter. Then the contents of the five bit counter are tested, and if equal to 0 this implies that the contents of the counter has advanced to 32 (decimal) on the previous pass through this sequence of instructions because this last increment by the instructions of element **82** changed the value from 31 to 0. If the counter value is unequal to 0 then control is returned to the executive portion of the software module for further processing of other functions of the burner control system. If however, the five bit counter is equal to 0 then the A and B summation series of equations 1 and 2 has been computed, and the value $D=(A^2+B^2)^{\frac{1}{2}}$ can be computed.

Because the small microprocessors likely to be used in these applications typically perform multiplications and extract square roots very slowly, it is frequently preferable to use an approximation so as to save instruction execution time for other functions. An appropriate approximation here is given by $(A^2+B^w)^{\frac{1}{2}} \sim A\ +B/4$, where A>B. The division by 4 can be accomplished easily with a right shift of the value of B two binary places. This approximation is accurate to within 5% for the values which will typically occur for A and B, and 5% is more than adequate accuracy. Of course, the reader understands that where B>A, that B +A/4 must be calculated.

To implement this approximation algorithm, the instructions represented by decision element **84** compares the magnitude A of the contents of accumulator A with the magnitude B of the contents of the register containing accumulator B, and if A>B, then the instructions represented by activity element **85** are executed. These instructions cause the contents of accumulator B to be right shifted two places, which is the same as a divide by **4** without rounding, and then store this right shifted value back into the register functioning as accumulator B. If B>A, then the result of activity element **87** is that value A is divided by 4 by a right shift of two and this result stored back into the register functioning a accumulator A. Then regardless of whether the instructions of activity elements **85** or **87** were executed, instruction execution proceeds with those represented by decision element **90**. The sum of the contents of the registers functioning as accumulators A and B are compared with a constant value and if the sum is greater than the constant value then the instructions represented by activity element **92** are executed. These instructions set a flame sense flag equal to 1, which symbolizes that flame has been detected. The flame sense flag value may be made available externally on path **47** if desired, or may be used as the criteria for further operations in a burner operation sequence If the sum of the contents of the registers functioning as accumulators A and B is equal to or less than the constant value, then the flame sense flag is cleared by the instructions which activity element **91** represents. In either case, then operation returns to the executive portion of the program for further operation in the burner control sequence.

The preceding describes my invention.

What I wish to claim by letters patent is:

**1**. A flame sensing system for providing a flame sense signal responsive to receiving a flame signal from a photocell receiving radiative energy from a flame having in its energy output intensity a flicker whose frequency is within a predetermined frequency range, said flame signal instantaneously representative of the intensity of the energy emanating from the flame, the system comprising

a) a low pass filter receiving the flame signal and providing a filtered flame signal from which a substantial percentage of the amplitude of frequencies above the predetermined frequency range has been removed;

b) a clock circuit providing a clock signal having individual pulses at four times the frequency of the midpoint of the predetermined frequency range;

c) an analog to digital converter receiving the filtered flame signal and the clock signal, sampling he filtered flame signal responsive to each clock signal pulse, and providing a digital flame signal having a plurality of successive discrete, ordinary designated, digital values each encoding the amplitude of the filtered flame signal at successive sampling instants;

d) a fist accumulator register receiving the digital flame signal and forming from the plurality of digital values in the flame signal, the sum of the difference of successive pairs of digital values having even oridinal designations, and providing after a sampling instant a first intermediate digital transform signal ascending he current contents o the fist accumulator register;

e) a second accumulator register receiving the digital flame signal and forming from the plurality of digital values in the flame signal, the sum of he difference of successive pairs of digital values having odd ordinal designations, and providing after a sampling instant a second intermediate digital transform signal encoding the current contents of the second accumulator register;

f) a calculator means receiving the first ad second intermediate digital transform signals, and providing a transform signal at lest approximately equal o the square root of the sum of the squares of the digital value encoded in each of the fist and second intermediate digital transform signals; and

g) a comparator means receiving he transom signal for comparing the digital value encoded in the transform signal with a predetermined transform constant value, and if generator than the transform constant value, issuing a flame sense signal signifying presence of flame.

**2**. The sensing system of claim **1** adapted for detecting a flame having a flicker frequency range of approximately 13 to 17 hz., where the clock circuit has a pluse rate of 60 hz. and wherein the low pass filter has a cutoff frequency of approximately 20 hz.

**3**. The sensing system of claim **1** wherein the clock circuit comprises a signal generator receiving a 60 hz. AC signal input and providing a 60 hz. square wave logic level signal whose frequency is that of the AC signal input.

**4**. The sensor of claim **1** wherein the calculator means comprises means for comparing the digital value encoded in the first intermediate digital transform signal with that encoded in the second intermediate digital transform signal, selecting the larger of the two intermediate digital transform signals, and forming the sum of the larger of the digital values encoded in the intermediate digital transform signals and one fourth of the smaller of the digital values encoded in the intermediate digital transform signals, and encoding this value in the transform signal.

**5**. A flame sensing system for providing a flame sense signal responsive to receiving a flame signal from a photocell receiving radiative energy from a flame having a flicker in its energy intensity whose frequency is within a predetermined frequency range, said flame signal instantaneously representative of the intensity of the energy emanating from the flame, the system comprising

a) a low pass filter receiving the flame signal and providing a filtered flame signal from which a substantial percentage of the amplitude of frequencies above the predetermined frequency range has been removed;

b) a clock circuit providing a clock signal having individual pulses at four times the frequency of the midpoint of the predetermined frequency range;

c) an analog to digital converter receiving the filtered flame signal and the clock signal, sampling the filtered flame signal responsive to each clock signal pulse, and providing a digital flame signal having a plurality of successive discrete, ordinally designated, digital values each encoding the amplitude of the filtered flame signal at successive sampling instants; and

d) a microprocessor for executing instructions and including data registers, an instruction memory containing a plurality of instructions, and a digital input channel, said microprocessor instruction memory including instructions for causing the microprocessor to function as:

i) a first accumulator register receiving through the input channel the digital flame signal from the analog to digital converter and forming from the plurality of digital values in the flame signal, the sum of the difference of successive pairs o f digital values having even ordinal designations, and providing at the end of each sampling interval a first intermediate digital transform signal encoding the current contents of the first accumulator register;

ii) a second accumulator register receiving through the input channel the digital flame signal from the analog to digital converter and forming from the plurality of digital values in the flame signal, the sum of the difference of successive pairs of digital values having odd ordinal designations, and providing at the end of each sampling interval a second intermediate digital transform signal encoding the current contents of the second accumulator register;

iii) a calculator means receiving the first and second intermediate digital transform signals and providing a transform signal approximating the square root of sum of the squares of the digital values encoded in each of the first and second intermediate digital transform signals; and

iv) a comparator means receiving the transform signal for comparing the digital value encoded in the transform signal with a predetermined transform constant value, and if greater than the transform constant value, issuing a flame sense signal signifying presence of flame.

**6**. The flame sensing system of claim **5** adapted for detecting a flame having a flicker frequency range of approximately 13 to 17 hz., where the clock circuit has a pulse rate of 60 hz. and wherein the low pass filter has a cutoff frequency of approximately 20 hz.

**7**. The sensor of claim **5** wherein the calculator means comprises means for comparing the digital value encoded in the first intermediate digital transform signal with that encoded in the second intermediate digital transform signal, selecting the larger of the two intermediate digital transform signals, and forming the sum of the larger of the digital values encoded in the intermediate digital transform signals and one fourth of the smaller of the digital values encoded in the intermediate digital transform signals, and encoding this value in the transform signal.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 5,073,769

DATED : December 17, 1991

INVENTOR(S) : Arlon D. Kompelien

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 9, line 59, cancel "he" and substitute --the--.
Column 9, line 62, cancel "ordinary" and substitute --ordinally--.
Column 10, line 2, cancel "oridinal" and substitute --ordinal--.
Column 10, line 4, cancel "ascending he" and substitute --encoding the--
Column 10, line 8, cancel "he" and substitute --the--.
Column 10, line 14, cancel "ad" and substitute --and--.
Column 10, line 16, cancel "o" and substitute --to--.
Column 10, line 18, cancel "fist" and substitute --first--.
Column 10, line 20, cancel "he transom" and substitute --the transform--.
Column 10, line 23, cancel "generator" and substitute --greater--.

**Signed and Sealed this**

**Thirtieth Day of March, 1993**

*Attest:*

STEPHEN G. KUNIN

*Attesting Officer*

*Acting Commissioner of Patents and Trademarks*

# Reference 5

Reference 5

**IEEE Std 315-1975 (Reaffirmed 1993)**
**ANSI Y32.2-1975 (Reaffirmed 1989)**
**CSA Z99-1975**
(Revision of IEEE Std 315-1971
ANSI Y32.1-1972
CSA Z99-1972)

# IEEE Standard
# American National Standard
# Canadian Standard

# Graphic Symbols for Electrical and Electronics Diagrams

## (Including Reference Designation Letters)

Sponsor
**IEEE Standards Coordinating Committee 11, Graphic Symbols**

Secretariat for American National Standards Committee Y32

**American Society of Mechanical Engineers**
**Institute of Electrical and Electronics Engineers**

Approved September 4, 1975
Reaffirmed October 20, 1988
Reaffirmed December 2, 1993
**IEEE Standards Board**

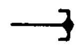
Approved October 31, 1975
Reaffirmed January 16, 1989
**American National Standards Institute**

Approved October 9, 1975
**Canadian Standards Association**

Approved Adopted for Mandatory Use October 31, 1975
**Department of Defense, United States of America**

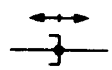
**3.8.2** Short circuit (short). Not a fault.

NOTE — 3.8.2A: Use of the dot is optional.

IEC 

See Note 3.8.2A

**3.8.3** Application: movable short circuit



See Note 3.8.2A

## 3.9 Circuit Return

**3.9.1** Ground, general symbol

NOTE — 3.9.1A: Supplementary information may be added to define the status or purpose of the earth if this is not readily apparent.

1) A direct conducting connection to the earth or body of water that is a part thereof.
2) A conducting connection to a structure that serves a function similar to that of an earth ground (that is, a structure such as a frame of an air, space, or land vehicle that is not conductively connected to earth).

IEC 

**3.9.1.1** Low-noise ground (IEC) noiseless, clean earth)

IEC 

**3.9.1.2** Safety or protective ground

NOTE — 3.9.1.2A: This symbol may be used in place of symbol 3.9.1 to indicate a ground connection having a specified protective function (e.g., for protection against electrical shock in case of a fault).

IEC 

**3.9.2** Chassis or frame connection; equivalent chassis connection (of printed-wiring boards)

A conducting connection to a chassis or frame, or equivalent chassis connection of a printed-wiring board. The chassis or frame (or equivalent chassis connection of a printed-wiring board) may be at substantial potential with respect to the earth or structure in which this chassis or frame (or printed-wiring board) is mounted.

# Reference 6

Reference 6

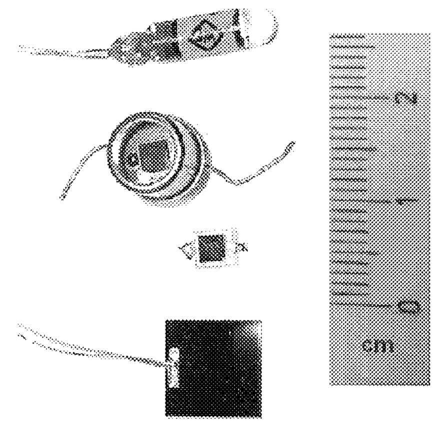
# Photodiode

From Wikipedia, the free encyclopedia

A **photodiode** is a semiconductor device that converts light into current. The current is generated when photons are absorbed in the photodiode. A small amount of current is also produced when no light is present. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. Photodiodes usually have a slower response time as their surface area increases. The common, traditional solar cell used to generate electric solar power is a large area photodiode.

Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p–n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.[1]

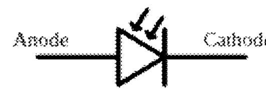
**Photodiode**




Three Si and one Ge (top) photodiodes.

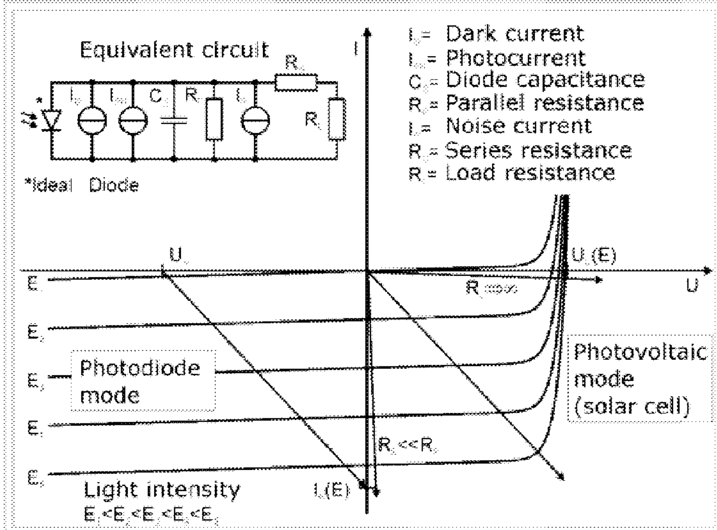
| | |
|---|---|
| **Type** | Passive |
| **Working principle** | Converts light into current |
| **Pin configuration** | anode and cathode |

**Electronic symbol**




## Contents






I-V characteristic of a photodiode. The linear load lines represent the response of the external circuit: I=(Applied bias voltage-Diode voltage)/Total resistance. The points of intersection with the curves represent the actual current and voltage for a given bias, resistance and illumination.

## Principle of operation

A photodiode is a p–n junction or PIN structure. When a photon of sufficient energy strikes the diode, it creates an electron-hole pair. This mechanism is also known as the inner photoelectric

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effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device.[2]

### Photovoltaic mode

When used in zero bias or ***photovoltaic mode***, the flow of photocurrent out of the device is restricted and a voltage builds up. This mode exploits the photovoltaic effect, which is the basis for solar cells – a traditional solar cell is just a large area photodiode.

### Photoconductive mode

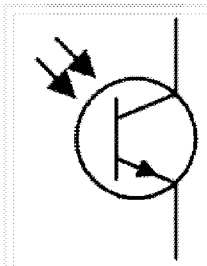
In this mode the diode is often reverse biased (with the cathode driven positive with respect to the anode). This reduces the response time because the additional reverse bias increases the width of the depletion layer, which decreases the junction's capacitance. The reverse bias also increases the dark current without much change in the photocurrent. For a given spectral distribution, the photocurrent is linearly proportional to the illuminance (and to the irradiance).[3]

Although this mode is faster, the photoconductive mode tends to exhibit more electronic noise.[4] The leakage current of a good PIN diode is so low (<1 nA) that the Johnson–Nyquist noise of the load resistance in a typical circuit often dominates.

### Other modes of operation

**Avalanche photodiodes** are photodiodes with structure optimized for operating with high reverse bias, approaching the reverse breakdown voltage. This allows each *photo-generated* carrier to be multiplied by avalanche breakdown, resulting in internal gain within the photodiode, which increases the effective *responsivity* of the device.

A **phototransistor** is a light-sensitive transistor. A common type of phototransistor, called a photobipolar transistor, is in essence a bipolar transistor encased in a transparent case so that light can reach the *base–collector junction*. It was invented by Dr. John N. Shive (more famous for his wave machine) at Bell Labs in 1948,[5]:205 but it was not announced until 1950.[6] The electrons that are generated by photons in the base–collector junction are injected into the base, and this photodiode current is amplified by the transistor's current gain $\beta$ (or $h_{fe}$). If the base and collector leads are used and the emitter is left unconnected, the phototransistor becomes a photodiode. While phototransistors have a higher responsivity for light they are not able to detect low levels of light any better than photodiodes. Phototransistors also have significantly longer response times. Field-effect phototransistors, also known as photoFETs, are light-sensitive field-effect transistors. Unlike photobipolar transistors, photoFETs control drain-source current by creating a gate voltage.



Electronic symbol for a phototransistor

## Materials

The material used to make a photodiode is critical to defining its properties, because only photons with sufficient

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energy to excite electrons across the material's bandgap will produce significant photocurrents.

Materials commonly used to produce photodiodes include:[7]

| Material | Electromagnetic spectrum wavelength range (nm) |
|---|---|
| Silicon | 190–1100 |
| Germanium | 400–1700 |
| Indium gallium arsenide | 800–2600 |
| Lead(II) sulfide | <1000–3500 |
| Mercury cadmium telluride | 400–14000 |

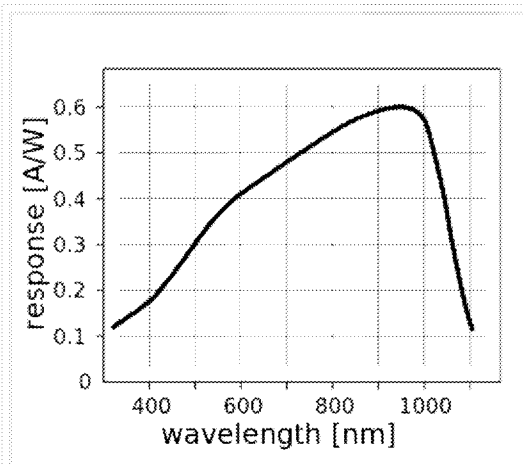
Because of their greater bandgap, silicon-based photodiodes generate less noise than germanium-based photodiodes.

## Unwanted photodiode effects

Any p–n junction, if illuminated, is potentially a photodiode. Semiconductor devices such as transistors and ICs contain p–n junctions, and will not function correctly if they are illuminated by unwanted electromagnetic radiation (light) of wavelength suitable to produce a photocurrent;[8][9] this is avoided by encapsulating devices in opaque housings. If these housings are not completely opaque to high-energy radiation (ultraviolet, X-rays, gamma rays), transistors and ICs can malfunction[10] due to induced photo-currents. Background radiation from the packaging is also significant.[11] Radiation hardening mitigates these effects.

# Features

Critical performance parameters of a photodiode include:



Response of a silicon photo diode vs wavelength of the incident light

**Responsivity**
: The Spectral responsivity is a ratio of the generated photocurrent to incident light power, expressed in A/W when used in photoconductive mode. The wavelength-dependence may also be expressed as a *Quantum efficiency*, or the ratio of the number of photogenerated carriers to incident photons, a unitless quantity.

**Dark current**
: The current through the photodiode in the absence of light, when it is operated in photoconductive mode. The dark current includes photocurrent generated by background radiation and the saturation current of the semiconductor junction. Dark current must be accounted for by calibration if a photodiode is used to make an accurate optical power measurement, and it is also a source of noise when a photodiode is used in an optical communication system.

**Response time**
: A photon absorbed by the semiconducting material will generate an electron-hole pair which will in turn

start moving in the material under the effect of the electric field and thus generate a current. The finite duration of this current is known as the transit-time spread and can be evaluated by using Ramo's theorem. One can also show with this theorem that the total charge generated in the external circuit is well e and not 2e as might seem by the presence of the two carriers. Indeed, the integral of the current due to both electron and hole over time must be equal to e. The resistance and capacitance of the photodiode and the external circuitry give rise to another response time known as RC time constant $\tau = RC$. This combination of R and C integrates the photoresponse over time and thus lengthens the impulse response of the photodiode. When used in an optical communication system, the response time determines the bandwidth available for signal modulation and thus data transmission.

**Noise-equivalent power**

(NEP) The minimum input optical power to generate photocurrent, equal to the rms noise current in a 1 hertz bandwidth. NEP is essentially the minimum detectable power. The related characteristic detectivity ($D$) is the inverse of NEP, 1/NEP. There is also the specific detectivity ($D^\star$) which is the detectivity multiplied by the square root of the area ($A$) of the photodetector, ($D^\star = D\sqrt{A}$) for a 1 Hz bandwidth. The specific detectivity allows different systems to be compared independent of sensor area and system bandwidth; a higher detectivity value indicates a low-noise device or system.[12] Although it is traditional to give ($D^\star$) in many catalogues as a measure of the diode's quality, in practice, it is hardly ever the key parameter.

When a photodiode is used in an optical communication system, all these parameters contribute to the *sensitivity* of the optical receiver, which is the minimum input power required for the receiver to achieve a specified *bit error rate*.

# Applications

P–n photodiodes are used in similar applications to other photodetectors, such as photoconductors, charge-coupled devices, and photomultiplier tubes. They may be used to generate an output which is dependent upon the illumination (analog; for measurement and the like), or to change the state of circuitry (digital; either for control and switching, or digital signal processing).

Photodiodes are used in consumer electronics devices such as compact disc players, smoke detectors, and the receivers for infrared remote control devices used to control equipment from televisions to air conditioners. For many applications either photodiodes or photoconductors may be used. Either type of photosensor may be used for light measurement, as in camera light meters, or to respond to light levels, as in switching on street lighting after dark.

Photosensors of all types may be used to respond to incident light, or to a source of light which is part of the same circuit or system. A photodiode is often combined into a single component with an emitter of light, usually a light-emitting diode (LED), either to detect the presence of a mechanical obstruction to the beam (slotted optical switch), or to couple two digital or analog circuits while maintaining extremely high electrical isolation between them, often for safety (optocoupler). The combination of LED and photodiode is also used in many sensor systems to characterize different types of products based on their optical absorbance.

Photodiodes are often used for accurate measurement of light intensity in science and industry. They generally have a more linear response than photoconductors.

They are also widely used in various medical applications, such as detectors for computed tomography (coupled with scintillators), instruments to analyze samples (immunoassay), and pulse oximeters.

PIN diodes are much faster and more sensitive than p–n junction diodes, and hence are often used for optical communications and in lighting regulation.

P–n photodiodes are not used to measure extremely low light intensities. Instead, if high sensitivity is needed, avalanche photodiodes, intensified charge-coupled devices or photomultiplier tubes are used for applications such as astronomy, spectroscopy, night vision equipment and laser rangefinding.

Pinned photodiode is not a PIN photodiode, it has p+/n/p regions in it. It has a shallow P+ implant in N type diffusion layer over a P-type epitaxial substrate layer. It is used in CMOS Active pixel sensor.[13]

### Comparison with photomultipliers

Advantages compared to photomultipliers:[14]

1. Excellent linearity of output current as a function of incident light
2. Spectral response from 190 nm to 1100 nm (silicon), longer wavelengths with other semiconductor materials
3. Low noise
4. Ruggedized to mechanical stress
5. Low cost
6. Compact and light weight
7. Long lifetime
8. High quantum efficiency, typically 60–80% [15]
9. No high voltage required

Disadvantages compared to photomultipliers:

1. Small area
2. No internal gain (except avalanche photodiodes, but their gain is typically $10^2$–$10^3$ compared to $10^5$-$10^8$ for the photomultiplier)
3. Much lower overall sensitivity
4. Photon counting only possible with specially designed, usually cooled photodiodes, with special electronic circuits
5. Response time for many designs is slower
6. latent effect

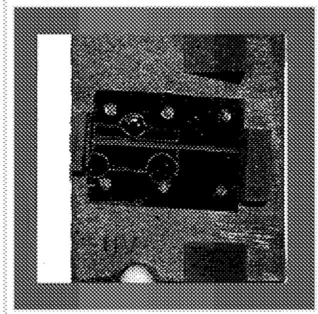
## Photodiode array

A one-dimensional array of hundreds or thousands of photodiodes can be used as a position sensor, for example as part of an angle sensor.[16] One advantage of photodiode arrays (PDAs) is that they allow for high speed parallel read out since the driving electronics may not be built in like a traditional CMOS or CCD sensor.

## See also

- Electronics
- Band gap
- Infrared
- Optoelectronics
- Optical interconnect
- Light Peak
- Interconnect bottleneck
- Optical fiber cable
- Optical communication
- Parallel optical interface
- Opto-isolator
- Semiconductor device
- Solar cell
- Avalanche photodiode
- Transducer

- LEDs as Photodiode Light Sensors
- Light meter
- Image sensor
- Transimpedance amplifier


A 2 x 2 cm photodiode array chip with more than 200 diodes

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This article incorporates public domain material from the General Services Administration document "Federal Standard 1037C" (http://www.its.bldrdoc.gov/fs-1037/fs-1037c.htm).

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16. Gao, Wei (2010). *Precision Nanometrology: Sensors and Measuring Systems for Nanomanufacturing*. Springer. pp. 15–16. ISBN 978-1-84996-253-7.

# External links

- Hamamatsu Application Note (http://www.hamamatsu.com/resources/pdf/ssd/e02_handbook_si_photodiode.pdf)
- Using the Photodiode to convert the PC to a Light Intensity Logger (http://www.emant.com/324003.page)
- Design Fundamentals for Phototransistor Circuits (http://www.fairchildsemi.com/an/AN/AN-3005.pdf)
- Working principles of photodiodes (http://ece-www.colorado.edu/~bart/book/book/chapter4/ch4_7.htm)

Wikimedia Commons has media related to ***Photodiodes***.

- Excelitas Application Notes on Pacer Website (http://www.pacer.co.uk/Assets/Pacer/User/Photodiodes.pdf)

Retrieved from "https://en.wikipedia.org/w/index.php?title=Photodiode&oldid=759051160"

Categories: Optical devices | Optoelectronics | Optical diodes | Photodetectors | Photonics

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# Reference 7

Reference 7

# Phase-locked loop

From Wikipedia, the free encyclopedia

A **phase-locked loop** or **phase lock loop (PLL)** is a control system that generates an output signal whose phase is related to the phase of an input signal. While there are several differing types, it is easy to initially visualize as an electronic circuit consisting of a variable frequency oscillator and a phase detector. The oscillator generates a periodic signal, and the phase detector compares the phase of that signal with the phase of the input periodic signal, adjusting the oscillator to keep the phases matched. Bringing the output signal back toward the input signal for comparison is called a feedback loop since the output is "fed back" toward the input forming a loop.

Keeping the input and output phase in lock step also implies keeping the input and output frequencies the same. Consequently, in addition to synchronizing signals, a phase-locked loop can track an input frequency, or it can generate a frequency that is a multiple of the input frequency. These properties are used for computer clock synchronization, demodulation, and frequency synthesis.

Phase-locked loops are widely employed in radio, telecommunications, computers and other electronic applications. They can be used to demodulate a signal, recover a signal from a noisy communication channel, generate a stable frequency at multiples of an input frequency (frequency synthesis), or distribute precisely timed clock pulses in digital logic circuits such as microprocessors. Since a single integrated circuit can provide a complete phase-locked-loop building block, the technique is widely used in modern electronic devices, with output frequencies from a fraction of a hertz up to many gigahertz.

## Contents



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# Practical analogies

## Automobile race analogy

For a practical idea of what is going on, consider an auto race. There are many cars, and the driver of each of them wants to go around the track as fast as possible. Each lap corresponds to a complete cycle, and each car will complete dozens of laps per hour. The number of laps per hour (a speed) corresponds to an angular velocity (i.e. a frequency), but the number of laps (a distance) corresponds to a phase (and the conversion factor is the distance around the track loop).

During most of the race, each car is on its own and the driver of the car is trying to beat the driver of every other car on the course, and the phase of each car varies freely.

However, if there is an accident, a pace car comes out to set a safe speed. None of the race cars are permitted to pass the pace car (or the race cars in front of them), but each of the race cars wants to stay as close to the pace car as it can. While it is on the track, the pace car is a reference, and the race cars become phase-locked loops. Each driver will measure the phase difference (a distance in laps) between him and the pace car. If the driver is far away, he will increase his engine speed to close the gap. If he's too close to the pace car, he will slow down. The result is all the race cars lock on to the phase of the pace car. The cars travel around the track in a tight group that is a small fraction of a lap.

## Clock analogy

Phase can be proportional to time,[1] so a phase difference can be a time difference. Clocks are, with varying degrees of accuracy, phase-locked (time-locked) to a master clock.

Left on its own, each clock will mark time at slightly different rates. A wall clock, for example, might be fast by a few seconds per hour compared to the reference clock at NIST. Over time, that time difference would become substantial.

To keep the wall clock in sync with the reference clock, each week the owner compares the time on his wall clock to a more accurate clock (a phase comparison), and he resets his clock. Left alone, the wall clock will continue to diverge from the reference clock at the same few seconds per hour rate.

Some clocks have a timing adjustment (a fast-slow control). When the owner compared his wall clock's time to the reference time, he noticed that his clock was too fast. Consequently, he could turn the timing adjust a small amount to make the clock run a little slower (frequency). If things work out right, his clock will be more accurate than before. Over a series of weekly adjustments, the wall clock's notion of a second would agree with the reference time (locked both in frequency and phase within the wall clock's stability).

An early electromechanical version of a phase-locked loop was used in 1921 in the Shortt-Synchronome clock.

# History

Spontaneous synchronization of weakly coupled pendulum clocks was noted by the Dutch physicist Christiaan Huygens as early as 1673.[2] Around the turn of the 19th century, Lord Rayleigh observed synchronization of weakly coupled organ pipes and tuning forks.[3] In 1919, W. H. Eccles and J. H. Vincent found that two electronic oscillators that had been tuned to oscillate at slightly different frequencies but that were coupled to a resonant circuit would soon oscillate at the same frequency.[4] Automatic synchronization of electronic oscillators was described in 1923 by Edward Victor Appleton.[5]

Earliest research towards what was later named the phase-locked loop goes back to 1932, when British researchers developed an alternative to Edwin Armstrong's superheterodyne receiver, the Homodyne or direct-conversion receiver. In the homodyne or synchrodyne system, a local oscillator was tuned to the desired input frequency and multiplied with the input signal. The resulting output signal included the original modulation information. The intent was to develop an alternative receiver circuit that required fewer tuned circuits than the superheterodyne receiver. Since the local oscillator would rapidly drift in frequency, an automatic correction signal was applied to the oscillator, maintaining it in the same phase and frequency of the desired signal. The technique was described in 1932, in a paper by Henri de Bellescize, in the French journal *L'Onde Électrique*.[6][7][8]

In analog television receivers since at least the late 1930s, phase-locked-loop horizontal and vertical sweep circuits are locked to synchronization pulses in the broadcast signal.[9]

When Signetics introduced a line of monolithic integrated circuits like the NE565 that were complete phase-locked loop systems on a chip in 1969,[10] applications for the technique multiplied. A few years later RCA introduced the "CD4046" CMOS Micropower Phase-Locked Loop, which became a popular integrated circuit.

# Structure and function

Phase-locked loop mechanisms may be implemented as either analog or digital circuits. Both implementations use the same basic structure. Both analog and digital PLL circuits include four basic elements:

- Phase detector,
- Low-pass filter,
- Variable-frequency oscillator, and
- feedback path (which may include a frequency divider).

## Variations

There are several variations of PLLs. Some terms that are used are analog phase-locked loop (APLL) also referred to as a linear phase-locked loop (LPLL), digital phase-locked loop (DPLL), all digital phase-locked loop (ADPLL), and software phase-locked loop (SPLL).[11]

**Analog or linear PLL (APLL)**

Phase detector is an analog multiplier. Loop filter is active or passive. Uses a Voltage-controlled oscillator (VCO).

**Digital PLL (DPLL)**

An analog PLL with a digital phase detector (such as XOR, edge-trigger JK, phase frequency detector).

May have digital divider in the loop.

**All digital PLL (ADPLL)**
Phase detector, filter and oscillator are digital. Uses a numerically controlled oscillator (NCO).

**Software PLL (SPLL)**
Functional blocks are implemented by software rather than specialized hardware.

**Neuronal PLL (NPLL)**
Phase detector, filter and oscillator are neurons or small neuronal pools. Uses a rate controlled oscillator (RCO). Used for tracking and decoding low frequency modulations (< 1 kHz), such as those occurring during mammalian-like active sensing.

## Performance parameters

- Type and order
- Hold-in range
- Pull-in range (capture range, acquisition range)
- Lock-in range
- Loop bandwidth: Defining the speed of the control loop.
- Transient response: Like overshoot and settling time to a certain accuracy (like 50ppm).
- Steady-state errors: Like remaining phase or timing error.
- Output spectrum purity: Like sidebands generated from a certain VCO tuning voltage ripple.
- Phase-noise: Defined by noise energy in a certain frequency band (like 10 kHz offset from carrier). Highly dependent on VCO phase-noise, PLL bandwidth, etc.
- General parameters: Such as power consumption, supply voltage range, output amplitude, etc.

# Applications

Phase-locked loops are widely used for synchronization purposes; in space communications for coherent demodulation and threshold extension, bit synchronization, and symbol synchronization. Phase-locked loops can also be used to demodulate frequency-modulated signals. In radio transmitters, a PLL is used to synthesize new frequencies which are a multiple of a reference frequency, with the same stability as the reference frequency.

Other applications include:

- Demodulation of both FM and AM signals
- Recovery of small signals that otherwise would be lost in noise (lock-in amplifier to track the reference frequency)
- Recovery of clock timing information from a data stream such as from a disk drive
- Clock multipliers in microprocessors that allow internal processor elements to run faster than external connections, while maintaining precise timing relationships
- DTMF decoders, modems, and other tone decoders, for remote control and telecommunications
- DSP of video signals; Phase-locked loops are also used to synchronize phase and frequency to the input analog video signal so it can be sampled and digitally processed
- Atomic force microscopy in tapping mode, to detect changes of the cantilever resonance frequency due to tip–surface interactions
- DC motor drive

## Clock recovery

Some data streams, especially high-speed serial data streams (such as the raw stream of data from the magnetic head of a disk drive), are sent without an accompanying clock. The receiver generates a clock from an approximate frequency reference, and then phase-aligns to the transitions in the data stream with a PLL. This process is referred to as clock recovery. In order for this scheme to work, the data stream must have a transition frequently enough to correct any drift in the PLL's oscillator. Typically, some sort of line code, such as 8b/10b encoding, is used to put a hard upper bound on the maximum time between transitions.

## Deskewing

If a clock is sent in parallel with data, that clock can be used to sample the data. Because the clock must be received and amplified before it can drive the flip-flops which sample the data, there will be a finite, and process-, temperature-, and voltage-dependent delay between the detected clock edge and the received data window. This delay limits the frequency at which data can be sent. One way of eliminating this delay is to include a deskew PLL on the receive side, so that the clock at each data flip-flop is phase-matched to the received clock. In that type of application, a special form of a PLL called a delay-locked loop (DLL) is frequently used.[12]

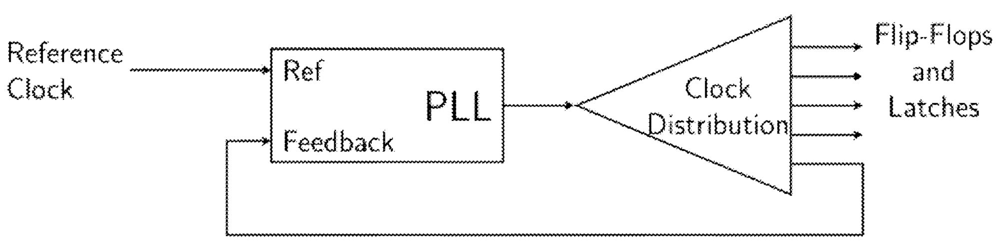
## Clock generation

Many electronic systems include processors of various sorts that operate at hundreds of megahertz. Typically, the clocks supplied to these processors come from clock generator PLLs, which multiply a lower-frequency reference clock (usually 50 or 100 MHz) up to the operating frequency of the processor. The multiplication factor can be quite large in cases where the operating frequency is multiple gigahertz and the reference crystal is just tens or hundreds of megahertz.

## Spread spectrum

All electronic systems emit some unwanted radio frequency energy. Various regulatory agencies (such as the FCC in the United States) put limits on the emitted energy and any interference caused by it. The emitted noise generally appears at sharp spectral peaks (usually at the operating frequency of the device, and a few harmonics). A system designer can use a spread-spectrum PLL to reduce interference with high-Q receivers by spreading the energy over a larger portion of the spectrum. For example, by changing the operating frequency up and down by a small amount (about 1%), a device running at hundreds of megahertz can spread its interference evenly over a few megahertz of spectrum, which drastically reduces the amount of noise seen on broadcast FM radio channels, which have a bandwidth of several tens of kilohertz.

## Clock distribution




Typically, the reference clock enters the chip and drives a phase locked loop (**PLL**), which then drives the system's clock distribution. The clock distribution is usually balanced so that the clock arrives at every endpoint simultaneously. One of those endpoints is the PLL's feedback input. The function of the PLL is to compare the distributed clock to the incoming reference clock, and vary the phase and frequency of its output until the reference and feedback clocks are phase and frequency matched.

PLLs are ubiquitous—they tune clocks in systems several feet across, as well as clocks in small portions of individual chips. Sometimes the reference clock may not actually be a pure clock at all, but rather a data stream with enough transitions that the PLL is able to recover a regular clock from that stream. Sometimes the reference clock is the same frequency as the clock driven through the clock distribution, other times the distributed clock may be some rational multiple of the reference.

### Jitter and noise reduction

One desirable property of all PLLs is that the reference and feedback clock edges be brought into very close alignment. The average difference in time between the phases of the two signals when the PLL has achieved lock is called the **static phase offset** (also called the **steady-state phase error**). The variance between these phases is called **tracking jitter**. Ideally, the static phase offset should be zero, and the tracking jitter should be as low as possible.

Phase noise is another type of jitter observed in PLLs, and is caused by the oscillator itself and by elements used in the oscillator's frequency control circuit. Some technologies are known to perform better than others in this regard. The best digital PLLs are constructed with emitter-coupled logic (ECL) elements, at the expense of high power consumption. To keep phase noise low in PLL circuits, it is best to avoid saturating logic families such as transistor-transistor logic (TTL) or CMOS.

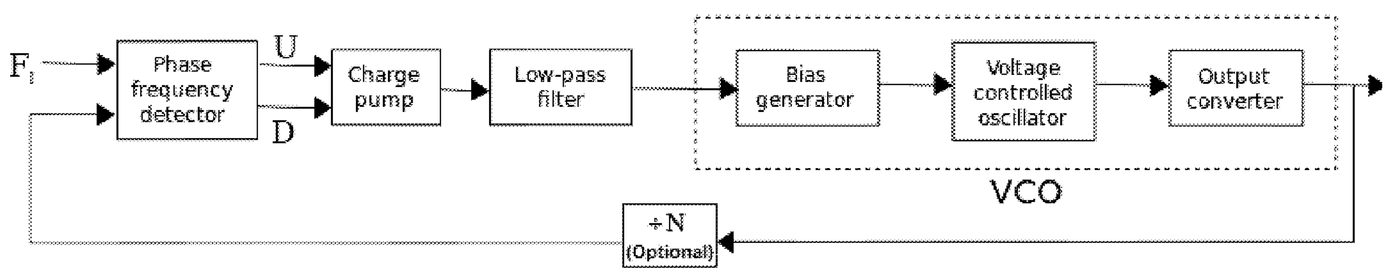
Another desirable property of all PLLs is that the phase and frequency of the generated clock be unaffected by rapid changes in the voltages of the power and ground supply lines, as well as the voltage of the substrate on which the PLL circuits are fabricated. This is called substrate and supply noise rejection. The higher the noise rejection, the better.

To further improve the phase noise of the output, an injection locked oscillator can be employed following the VCO in the PLL.

### Frequency synthesis

In digital wireless communication systems (GSM, CDMA etc.), PLLs are used to provide the local oscillator up-conversion during transmission and down-conversion during reception. In most cellular handsets this function has been largely integrated into a single integrated circuit to reduce the cost and size of the handset. However, due to the high performance required of base station terminals, the transmission and reception circuits are built with discrete components to achieve the levels of performance required. GSM local oscillator modules are typically built with a frequency synthesizer integrated circuit and discrete resonator VCOs.

## Block diagram




Block diagram of a phase-locked loop

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A phase detector compares two input signals and produces an error signal which is proportional to their phase difference. The error signal is then low-pass filtered and used to drive a VCO which creates an output phase. The output is fed through an optional divider back to the input of the system, producing a negative feedback loop. If the output phase drifts, the error signal will increase, driving the VCO phase in the opposite direction so as to reduce the error. Thus the output phase is locked to the phase at the other input. This input is called the reference.

Analog phase locked loops are generally built with an analog phase detector, low pass filter and VCO placed in a negative feedback configuration. A digital phase locked loop uses a digital phase detector; it may also have a divider in the feedback path or in the reference path, or both, in order to make the PLL's output signal frequency a rational multiple of the reference frequency. A non-integer multiple of the reference frequency can also be created by replacing the simple divide-by-*N* counter in the feedback path with a programmable pulse swallowing counter. This technique is usually referred to as a fractional-N synthesizer or fractional-N PLL.

The oscillator generates a periodic output signal. Assume that initially the oscillator is at nearly the same frequency as the reference signal. If the phase from the oscillator falls behind that of the reference, the phase detector changes the control voltage of the oscillator so that it speeds up. Likewise, if the phase creeps ahead of the reference, the phase detector changes the control voltage to slow down the oscillator. Since initially the oscillator may be far from the reference frequency, practical phase detectors may also respond to frequency differences, so as to increase the lock-in range of allowable inputs.

Depending on the application, either the output of the controlled oscillator, or the control signal to the oscillator, provides the useful output of the PLL system.

# Elements

## Phase detector

A phase detector (PD) generates a voltage, which represents the phase difference between two signals. In a PLL, the two inputs of the phase detector are the reference input and the feedback from the VCO. The PD output voltage is used to control the VCO such that the phase difference between the two inputs is held constant, making it a negative feedback system. There are several types of phase detectors in the two main categories of analog and digital.

Different types of phase detectors have different performance characteristics.

For instance, the frequency mixer produces harmonics that adds complexity in applications where spectral purity of the VCO signal is important. The resulting unwanted (spurious) sidebands, also called "reference spurs" can dominate the filter requirements and reduce the capture range well below and/or increase the lock time beyond the requirements. In these applications the more complex digital phase detectors are used which do not have as severe a reference spur component on their output. Also, when in lock, the steady-state phase difference at the inputs using this type of phase detector is near 90 degrees. The actual difference is determined by the DC loop gain.

A **bang-bang** charge pump phase detector must always have a **dead band** where the phases of inputs are close enough that the detector detects no phase error. For this reason, bang-bang phase detectors are associated with significant minimum peak-to-peak jitter, because of drift within the dead band. However these types, having outputs consisting of very narrow pulses at lock, are very useful for applications requiring very low VCO spurious outputs. The narrow pulses contain very little energy and are easy to filter out of the VCO control voltage. This results in low VCO control line ripple and therefore low FM sidebands on the VCO.

In PLL applications it is frequently required to know when the loop is out of lock. The more complex digital phase-frequency detectors usually have an output that allows a reliable indication of an out of lock condition.

## Filter

The block commonly called the PLL loop filter (usually a low pass filter) generally has two distinct functions.

The primary function is to determine loop dynamics, also called stability. This is how the loop responds to disturbances, such as changes in the reference frequency, changes of the feedback divider, or at startup. Common considerations are the range over which the loop can achieve lock (pull-in range, lock range or capture range), how fast the loop achieves lock (lock time, lock-up time or settling time) and damping behavior. Depending on the application, this may require one or more of the following: a simple proportion (gain or attenuation), an integral (low pass filter) and/or derivative (high pass filter). Loop parameters commonly examined for this are the loop's gain margin and phase margin. Common concepts in control theory including the PID controller are used to design this function.

The second common consideration is limiting the amount of reference frequency energy (ripple) appearing at the phase detector output that is then applied to the VCO control input. This frequency modulates the VCO and produces FM sidebands commonly called "reference spurs". The low pass characteristic of this block can be used to attenuate this energy, but at times a band reject "notch" may also be useful.

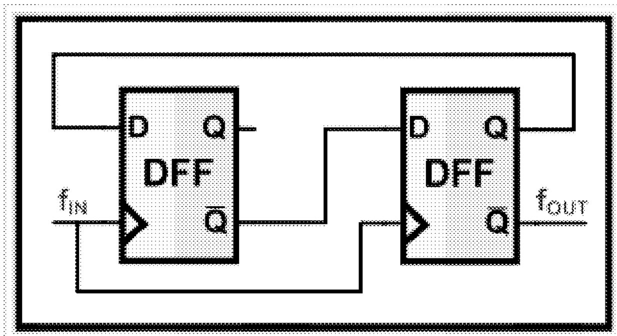
The design of this block can be dominated by either of these considerations, or can be a complex process juggling the interactions of the two. Typical trade-offs are: increasing the bandwidth usually degrades the stability or too much damping for better stability will reduce the speed and increase settling time. Often also the phase-noise is affected.

## Oscillator

All phase-locked loops employ an oscillator element with variable frequency capability. This can be an analog VCO either driven by analog circuitry in the case of an APLL or driven digitally through the use of a digital-to-analog converter as is the case for some DPLL designs. Pure digital oscillators such as a numerically controlled oscillator are used in ADPLLs.

## Feedback path and optional divider

PLLs may include a divider between the oscillator and the feedback input to the phase detector to produce a frequency synthesizer. A programmable divider is particularly useful in radio transmitter applications, since a large number of transmit frequencies can be produced from a single stable, accurate, but expensive, quartz crystal–controlled reference oscillator.



An example digital divider (by 4) for use in the feedback path of a multiplying PLL

Some PLLs also include a divider between the reference clock and the reference input to the phase detector. If the divider in the feedback path divides by $N$ and the reference input divider divides by $M$, it allows the PLL to multiply the reference frequency by $N/M$. It might seem simpler to just feed the PLL a lower frequency, but in some cases the reference frequency may be constrained by other issues, and then the reference divider is useful.

Frequency multiplication can also be attained by locking the VCO output to the *N*th harmonic of the reference signal. Instead of a simple phase detector, the design uses a harmonic mixer (sampling mixer). The harmonic mixer turns the reference signal into an impulse train that is rich in harmonics.[13] The VCO output is coarse tuned to be close to one of those harmonics. Consequently, the desired harmonic mixer output (representing the difference between the *N* harmonic and the VCO output) falls within the loop filter passband.

It should also be noted that the feedback is not limited to a frequency divider. This element can be other elements such as a frequency multiplier, or a mixer. The multiplier will make the VCO output a sub-multiple (rather than a multiple) of the reference frequency. A mixer can translate the VCO frequency by a fixed offset. It may also be a combination of these. An example being a divider following a mixer; this allows the divider to operate at a much lower frequency than the VCO without a loss in loop gain.

# Modeling

## Time domain model

The equations governing a phase-locked loop with an analog multiplier as the phase detector and linear filter may be derived as follows. Let the input to the phase detector be $f_1(\theta_1(t))$ and the output of the VCO is $f_2(\theta_2(t))$ with phases $\theta_1(t)$ and $\theta_2(t)$. The functions $f_1(\theta)$ and $f_2(\theta)$ describe waveforms of signals. Then the output of the phase detector $\phi(t)$ is given by

$$\phi(t) = f_1(\theta_1(t)) f_2(\theta_2(t))$$

The VCO frequency is usually taken as a function of the VCO input $g(t)$ as

$$\dot{\theta}_2(t) = \omega_2(t) = \omega_{free} + g_v g(t)$$

where $g_v$ is the *sensitivity* of the VCO and is expressed in Hz / V; $\omega_{free}$ is a free-running frequency of VCO.

The loop filter can be described by a system of linear differential equations

$$\begin{array}{rcl} \dot{x} & = & Ax + b\phi(t), \\ g(t) & = & c^* x, \end{array} \quad x(0) = x_0,$$

where $\phi(t)$ is an input of the filter, $g(t)$ is an output of the filter, $A$ is $n$-by-$n$ matrix, $x \in \mathbb{C}^n, \quad b \in \mathbb{R}^n, \quad c \in \mathbb{C}^n, \quad . x_0 \in \mathbb{C}^n$ represents an initial state of the filter. The star symbol is a conjugate transpose.

Hence the following system describes PLL

$$\begin{array}{rcl} \dot{x} & = & Ax + bf_1(\theta_1(t)) f_2(\theta_2(t)), \\ \dot{\theta}_2 & = & \omega_{free} + g_v(c^* x) \end{array} \quad x(0) = x_0, \quad \theta_2(0) = \theta_0.$$

where $\theta_0$ is an initial phase shift.

## Phase domain model

Consider the input of PLL $f_1(\theta_1(t))$ and VCO output $f_2(\theta_2(t))$ are high frequency signals. Then for any

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piecewise differentiable $2\pi$-periodic functions $f_1(\theta)$ and $f_2(\theta)$ there is a function $\varphi(\theta)$ such that the output $G(t)$ of Filter

$$\begin{array}{rcl}\dot{x} & = & Ax + b\varphi(\theta_1(t) - \theta_2(t)),\\ G(t) & = & c^* x,\end{array} \quad x(0) = x_0,$$

in phase domain is asymptotically equal ( the difference $G(t) - g(t)$ is small with respect to the frequencies) to the output of the Filter in time domain model. [14] [15] Here function $\varphi(\theta)$ is a phase detector characteristic.

Denote by $\theta_\Delta(t)$ the phase difference

$$\theta_\Delta = \theta_1(t) - \theta_2(t).$$

Then the following dynamical system describes PLL behavior

$$\begin{array}{rcl}\dot{x} & = & Ax + b\varphi(\theta_\Delta),\\ \dot{\theta}_\Delta & = & \omega_\Delta - g_v(c^* x).\end{array} \quad x(0) = x_0, \quad \theta_\Delta(0) = \theta_1(0) - \theta_2(0).$$

Here $\omega_\Delta = \omega_1 - \omega_{free}$; $\omega_1$ is the frequency of a reference oscillator (we assume that $\omega_{free}$ is constant).

**Example**

Consider sinusoidal signals

$$f_1(\theta_1(t)) = A_1 \sin(\theta_1(t)), \quad f_2(\theta_2(t)) = A_2 \cos(\theta_2(t))$$

and a simple one-pole RC circuit as a filter. The time-domain model takes the form

$$\dot{x} = -\frac{1}{RC}x + \frac{1}{RC}A_1 A_2 \sin(\theta_1(t)) \cos(\theta_2(t)),$$

$$\dot{\theta}_2 = \omega_{free} + g_v(c^* x)$$

PD characteristics for this signals is equal[16] to

$$\varphi(\theta_1 - \theta_2) = \frac{A_1 A_2}{2} \sin(\theta_1 - \theta_2)$$

Hence the phase domain model takes the form

$$\dot{x} = -\frac{1}{RC}x + \frac{1}{RC}\frac{A_1 A_2}{2} \sin(\theta_\Delta),$$

$$\dot{\theta}_\Delta = \omega_\Delta - g_v(c^* x).$$

This system of equations is equivalent to the equation of mathematical pendulum

$$x = \frac{\dot{\theta}_2 - \omega_2}{g_v c^*} = \frac{\omega_1 - \dot{\theta}_\Delta - \omega_2}{g_v c^*},$$

$$\dot{x} = \frac{\ddot{\theta}_2}{g_v c^*},$$

$$\theta_1 = \omega_1 t + \Psi,$$

$$\theta_\Delta = \theta_1 - \theta_2,$$

$$\dot{\theta}_\Delta = \dot{\theta}_1 - \dot{\theta}_2 = \omega_1 - \dot{\theta}_2,$$

$$\frac{1}{g_v c^*}\ddot{\theta}_\Delta - \frac{1}{g_v c^* RC}\dot{\theta}_\Delta - \frac{A_1 A_2}{2RC}\sin\theta_\Delta = \frac{\omega_2 - \omega_1}{g_v c^* RC}.$$

## Linearized phase domain model

Phase locked loops can also be analyzed as control systems by applying the Laplace transform. The loop response can be written as:

$$\frac{\theta_o}{\theta_i} = \frac{K_p K_v F(s)}{s + K_p K_v F(s)}$$

Where

- $\theta_o$ is the output phase in radians
- $\theta_i$ is the input phase in radians
- $K_p$ is the phase detector gain in volts per radian
- $K_v$ is the VCO gain in radians per volt-second
- $F(s)$ is the loop filter transfer function (dimensionless)

The loop characteristics can be controlled by inserting different types of loop filters. The simplest filter is a one-pole RC circuit. The loop transfer function in this case is:

$$F(s) = \frac{1}{1 + sRC}$$

The loop response becomes:

$$\frac{\theta_o}{\theta_i} = \frac{\frac{K_p K_v}{RC}}{s^2 + \frac{s}{RC} + \frac{K_p K_v}{RC}}$$

This is the form of a classic harmonic oscillator. The denominator can be related to that of a second order system:

$$s^2 + 2s\zeta\omega_n + \omega_n^2$$

Where

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- $\zeta$ is the damping factor
- $\omega_n$ is the natural frequency of the loop

For the one-pole RC filter,

$$\omega_n = \sqrt{\frac{K_p K_v}{RC}}$$
$$\zeta = \frac{1}{2\sqrt{K_p K_v RC}}$$

The loop natural frequency is a measure of the response time of the loop, and the damping factor is a measure of the overshoot and ringing. Ideally, the natural frequency should be high and the damping factor should be near 0.707 (critical damping). With a single pole filter, it is not possible to control the loop frequency and damping factor independently. For the case of critical damping,

$$RC = \frac{1}{2K_p K_v}$$
$$\omega_c = K_p K_v \sqrt{2}$$

A slightly more effective filter, the lag-lead filter includes one pole and one zero. This can be realized with two resistors and one capacitor. The transfer function for this filter is

$$F(s) = \frac{1 + sCR_2}{1 + sC(R_1 + R_2)}$$

This filter has two time constants

$$\tau_1 = C(R_1 + R_2)$$
$$\tau_2 = CR_2$$

Substituting above yields the following natural frequency and damping factor

$$\omega_n = \sqrt{\frac{K_p K_v}{\tau_1}}$$
$$\zeta = \frac{1}{2\omega_n \tau_1} + \frac{\omega_n \tau_2}{2}$$

The loop filter components can be calculated independently for a given natural frequency and damping factor

$$\tau_1 = \frac{K_p K_v}{\omega_n^2}$$
$$\tau_2 = \frac{2\zeta}{\omega_n} - \frac{1}{K_p K_v}$$

Real world loop filter design can be much more complex e.g. using higher order filters to reduce various types or source of phase noise. (See the D Banerjee ref below)

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## Implementing a digital phase-locked loop in software

Digital phase locked loops can be implemented in hardware, using integrated circuits such as a CMOS 4046. However, with microcontrollers becoming faster, it may make sense to implement a phase locked loop in software for applications that do not require locking onto signals in the MHz range or faster, such as precisely controlling motor speeds. Software implementation has several advantages including easy customization of the feedback loop including changing the multiplication or division ratio between the signal being tracked and the output oscillator. Furthermore, a software implementation is useful to understand and experiment with. As an example of a phase-locked loop implemented using a phase frequency detector is presented in MATLAB, as this type of phase detector is robust and easy to implement. This example uses integer arithmetic rather than floating point, as such an example is likely more useful in practice.

```
% This example is written in MatLab

% Initialize variables
vcofreq = zeros(1, numiterations);
ervec = zeros(1, numiterations);
% keep track of last states of reference, signal, and error signal
qsig = 0; qref = 0; lref = 0; lsig = 0; lersig = 0;
phs = 0;
freq = 0;

% Loop filter constants (proportional and derivative)
% Currently powers of two to facilitate multiplication by shifts
prop = 1/128;
deriv = 64;

for it=1:numiterations
    % Simulate a local oscillator using a 16 bit counter
    phs = mod(phs + floor(freq/2^16), 2^16);
    ref = phs < 32768;
    % Get the next digital value (0 or 1) of the signal to track
    sig = tracksig(it);
    % Implement the phase-frequency detector
    rst = ~(qsig & qref);  % Reset the "flip flop" of the phase frequency
                           % detector when both signal and reference are high
    qsig = (qsig | (sig & ~lsig)) & rst;    % Trigger signal flip-flop and leading edge of signal
    qref = (qref | (ref & ~lref)) & rst;    % Trigger reference flip-flop on leading edge of reference
    lref = ref; lsig = sig; % Store these values for next iteration (for edge detection)
    ersig = qref   qsig;    % Compute the error signal (whether frequency should increase or decrease)
                            % Error signal is given by one or the other flip flop signal
    % Implement a pole-zero filter by proportional and derivative input to frequency
    filtered_ersig = ersig + (ersig - lersig) * deriv;
    % Keep error signal for proportional output
    lersig = ersig;
    % Integrate VCO frequency using the error signal
    freq = freq   2^16 * filtered_ersig * prop;
    % Frequency is tracked as a fixed-point binary fraction
    % Store the current VCO frequency
    vcofreq(1, it) = freq / 2^16;
    % Store the error signal to show whether signal or reference is higher frequency
    ervec(1, it) = ersig;
end
```

In this example, an array `tracksig` is assumed to contain a reference signal to be tracked. The oscillator is implemented by a counter, with the most significant bit of the counter indicating the on/off status of the oscillator. This code simulates the two D-type flip-flops that comprise a phase-frequency comparator. When either the reference or signal has a positive edge, the corresponding flip-flop switches high. Once both reference and signal is high, both flip-flops are reset. Which flip-flop is high determines at that instant whether the reference or signal leads the other. The error signal is the difference between these two flip-flop values. The pole-zero filter is implemented by adding the error signal and its derivative to the filtered error signal. This in turn is integrated to find the oscillator frequency.

In practice, one would likely insert other operations into the feedback of this phase-locked loop. For example, if the phase locked loop were to implement a frequency multiplier, the oscillator signal could be divided in frequency before it is compared to the reference signal.

# See also

- Direct-digital synthesis
- Costas loop
- Kalman filter
- Direct conversion receiver
- Circle map – a simple mathematical model of the phase-locked loop showing both mode-locking and chaotic behavior.
- Carrier recovery
- Delay-locked loop (DLL)
- PLL multibit
- Shortt–Synchronome clock – slave pendulum phase-locked to master (ca 1921).

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Categories: Oscillators | Communication circuits | Electronic design | Radio electronics

# Reference 8

Reference 8

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# Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques

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# *Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques*

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## FIGURES

## ABSTRACT

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Statistical parameters of the phase-error behavior of a phase-locked loop tracking a constant frequency signal in the presence of additive, stationary, Gaussian noise are obtained by treating the problem as a continuous random walk with a sinusoidal restoring force. The Fokker-Planck or diffusion equation is obtained for a general loop. An exact expression for the steady-state phase-error distribution is available only for the first-order loop, but approximate and asymptotic expressions are derived for the second-order loop. Results are obtained also for the expected time to loss of lock and for the frequency of skipping cycles. Threshold criteria for the phase-locked loop are discussed, and thresholds of approximate models which have been widely accepted are obtained by comparison with the exact results available for the first-order loop.

## I. INTRODUCTION

The phase-locked loop is a communication receiver which operates as a coherent detector by continuously correcting its local oscillator frequency according to a measurement of the phase error. A block diagram of the device is shown in Fig. 1 with the pertinent input and output signals indicated. The output of the voltage-controlled oscillator (VCO) is a sinusoid whose frequency is controlled by the input voltage $e(t)$; that is,

$$\dot{\theta}_2(t) = \frac{d\theta_2}{dt} = K_2\, e(t) \qquad (1)$$

so that when $e(t) = 0$, the oscillator frequency is $\omega_0$. The received signal is a sinusoid of power $A^2$ w, of arbitrary

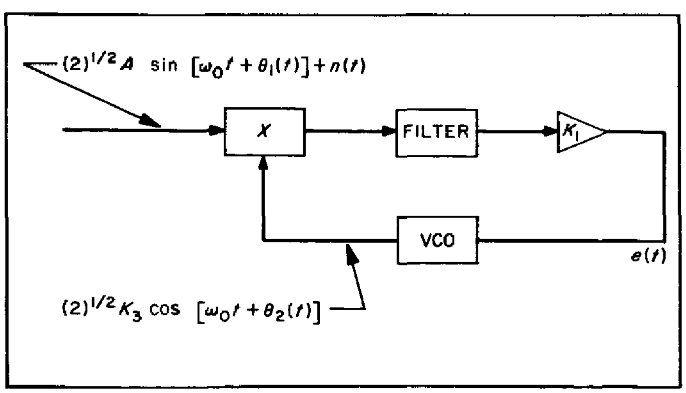


**Fig. 1. Phase-locked loop**

frequency $\omega$, and of phase $\theta$. Thus, it is represented by the expression

$$(2)^{1/2} A \sin[\omega t + \theta] = (2)^{1/2} A \sin[\omega_0 t + \theta_1(t)]$$

where

$$\theta_1(t) = (\omega - \omega_0)t + \theta \tag{2}$$

The noise is assumed to be stationary, Gaussian, and white of one-sided spectral density $N_0$ w/cps. The noise process over an arbitrary period of duration $T$ can be expanded in a Fourier series whose coefficients become independent Gaussian variables in the limit as $T$ approaches infinity (Ref. 1). By collecting the sine and cosine terms of the series, we can represent the noise process of infinite duration by the expression

$$n(t) = (2)^{1/2} n_1(t) \sin(\omega t + \theta) + (2)^{1/2} n_2(t) \cos(\omega t + \theta)$$

where $n_1(t)$ and $n_2(t)$ are both stationary, white, Gaussian processes of one-sided spectral density $N_0$ w/cps and are statistically independent of one another.

Thus the product of input and reference signals is

$$\begin{aligned}
&2\{A\sin[\omega_0 t + \theta_1(t)] + n_1(t)\sin(\omega t + \theta) \\
&\quad + n_2(t)\cos(\omega t + \theta)\}\{K_3 \cos[\omega_0 t + \theta_2(t)]\} \\
&= AK_3 \sin[\theta_1(t) - \theta_2(t)] \\
&\quad + K_3 n_1(t) \sin[(\omega - \omega_0)t + \theta - \theta_2(t)] \\
&\quad + K_3 n_2(t) \cos[(\omega - \omega_0)t + \theta - \theta_2(t)] \\
&\quad + \text{double frequency terms} \\
&= AK_3 \sin[\theta_1(t) - \theta_2(t)] \\
&\quad + K_3 n_1(t) \sin[\theta_1(t) - \theta_2(t)] \\
&\quad + K_3 n_2(t) \cos[\theta_1(t) - \theta_2(t)] \\
&\quad + \text{double frequency terms}
\end{aligned}$$

where $\theta_1(t)$ is given by Eq. (2). The double frequency terms may be neglected since neither the filter nor the VCO will respond significantly to these for reasonably large $\omega_0$. Then from Fig. 1 we see that

$$\begin{aligned}
e(t) = K_1 F(s)\{&AK_3 \sin[\theta_1(t) - \theta_2(t)] \\
&+ K_3 n_1(t) \sin[\theta_1(t) - \theta_2(t)] \\
&+ K_3 n_2(t) \cos[\theta_1(t) - \theta_2(t)]\}
\end{aligned} \tag{3}$$

where $F(s)$ is a rational function which represents in operational notation the effect of the linear filter in the loop. If we let $\phi(t) = \theta_1(t) - \theta_2(t)$ and $K = K_1 K_2 K_3$ and use Eq. (1), we obtain

$$\dot{\phi}(t) = \dot{\theta}_1(t) - K_2 e(t)$$

Then from Eq. (2) and (3) we have

$$\begin{aligned}
\dot{\phi}(t) = (\omega - \omega_0) - KF(s)[&A\sin\phi(t) \\
&+ n_1(t)\sin\phi(t) + n_2(t)\cos\phi(t)]
\end{aligned} \tag{4}$$

The instantaneous phase error or difference between the received signal and the reference signal at the output of the VCO is $\phi(t)$. Equation (4) is the exact expression for the operation of the phase-locked loop in the presence of noise. Several authors beginning with Gruen (Ref. 2) have obtained solutions of this equation in the absence of noise for a number of filter transfer functions and also for the case of linearly time-varying input frequency. The most complete treatment of the noise-free performance is contained in Ref. 3. The general case in which additive noise is present has been treated by a variety of approximations. Jaffe and Rechtin (Ref. 4) assumed $\phi(t)$ to be at all times small enough that $\cos\phi \simeq 1$ and $\sin\phi \simeq \phi << 1$ so that the expression in brackets in Eq. (4) becomes $A\phi(t) + n_2(t)$. This produces a linear time-invariant model of the system. Recently Van Trees (Ref. 5) refined this analysis by linearizing about the equilibrium point $\phi_0$, making the assumption

$$\sin(\phi - \phi_0) \simeq \phi - \phi_0$$

and

$$\cos(\phi - \phi_0) \simeq 1$$

This generates a linear time-varying model. Develet (Ref. 6) applied Booton's quasi-linearization technique (Ref. 7), replacing the sinusoidal nonlinearity by its average gain. Both Van Trees' and Devlet's methods obtain estimates of the noise threshold of the device. Margolis (Ref. 8) obtained a series representation for the moments of the phase error, but the method was too involved to give useful results.

Unlike these analyses, continuous random walk or Fokker-Planck techniques yield exact expressions for the statistics of the random process $\phi(t)$. Unfortunately, expressions in closed form can be obtained only for the first-order loop (i.e., when the filter is omitted). For the general case, a partial differential equation in $\phi$ and its time derivatives is derived, but solutions cannot be obtained in general.

These techniques were first applied to this problem in the Soviet literature by Tikhonov (Ref. 9, 10), who obtained the steady-state probability distribution of $\phi$

for the first-order loop enclosed form and an approximate expression for the distribution when the loop contains a one-stage RC filter. Tikhonov's result on the steady-state distribution for the first-order loop is contained in Part III of this Report. The variance and cumulative distribution are also obtained. In Part IV, we derive the Fokker-Planck equation for the general loop filter which produces zero mean error. In Part V, this equation is specialized to the second-order loop, and the form of the solution for the steady-state probability distribution of $\phi$ is obtained. Part VI presents results on the mean time to loss of lock and the frequency of skipping cycles for the first-order loop, which is a random walk problem with absorbing boundaries. Finally, in Part VIII, the results are compared with those of the above mentioned approximate models in an attempt to determine validity thresholds for the models and a performance threshold for the device.

First of all, in the next Part, a simple mechanical analog of the phase-locked loop is presented which provides a qualitative description of the operation of the device and an understanding of the nature of the statistical parameters required for its quantitative description.

## II. THE FIRST-ORDER LOOP AND ITS MECHANICAL ANALOG

If the filter is omitted, we let $F(s) = 1$ in Eq. (4) and obtain the first-order differential equation

$$\dot{\phi}(t) = (\omega - \omega_0) - K[A \sin \phi(t) + n_1(t) \sin \phi(t) + n_2(t) \cos \phi(t)] \qquad (5)$$

Hence the term "first-order" loop. Since $n_1(t)$ and $n_2(t)$ are both white, the instantaneous change in $\phi$ represented by its derivative depends only on the present value of $\phi$ and the present value of the noise. Hence $\phi(t)$ is a continuous Markov process, permitting us to use random walk techniques to determine its probability distribution. A mechanical analog is useful in understanding the mechanism of this "random walk." Consider the pendulum of Fig. 2 consisting of a weightless ball attached by an infinitesimally thin, weightless rod to a fixed point, and let the apparatus be horizontal on a table top which is being randomly agitated. The pendulum is free to turn a full revolution about the point. Let the rod be initially at an angle $\phi$ with respect to the vertical axis. Let an external force (such as a constant wind) be exerted on the ball in the vertical direction. Let the surface of the table be rough so that it produces a frictional force opposing motion of magnitude $f\dot{\phi}$. In addition, let the ball be equipped with an internal engine which exerts a constant force $F$ along the axis of motion. The random agitation of the table produces a force on the ball which may be represented by the two stationary, white, Gaussian processes of zero means $n_1(t)$ in the vertical direction, and $n_2(t)$ in the horizontal direction. Then by equating forces along the instantaneous axis of motion, we obtain:

$$f\dot{\phi} + G \sin \phi = F - n_1(t) \sin \phi - n_2(t) \cos \phi \qquad (6)$$

If we divide by $f$ and identify $F/f$ with $(\omega - \omega_0)$, $G/f$ with $AK$, and $1/f$ with $K$, we see that Eq. (6) is the same as Eq. (5).

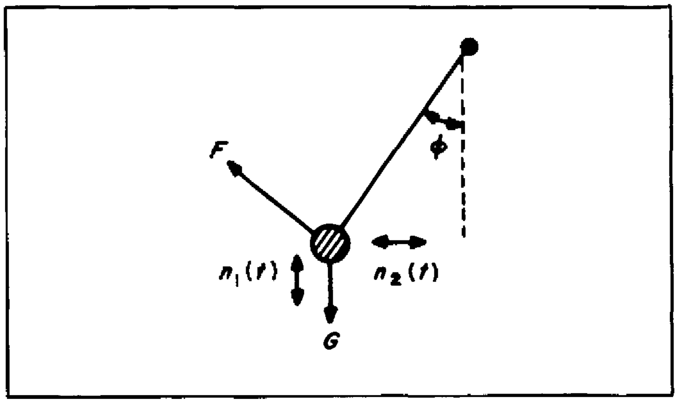


**Fig. 2. Mechanical analog of the first-order loop**

It is clear that in the absence of the random forces, the pendulum approaches the equilibrium position

$$\phi_0 = \sin^{-1}(F/G) = \sin^{-1}(\omega - \omega_0)/(AK) \qquad (7)$$

at which point the velocity is zero. Because this is a first-order system, there can be no overshoot. If $F > G$ or $(\omega - \omega_0) > AK$, there can be no equilibrium position, and the pendulum continues to revolve indefinitely which corresponds to a loop which can not achieve lock. When the random or noise forces are applied as well as the constant ones, the motion becomes a random walk, but when the noise variance is small, there is a strong tendency for the angle $\phi$ to approach and remain about this equilibrium position.

The complete statistical description of the random walk of the angle $\phi$ is given by its probability density as a function of time, $p(\phi, t)$. To understand qualitatively the behavior of this function, let us assume that the constant force $F = 0$ and that initially (at $t = 0$) the pendulum is at rest in the vertical position. Thus, $p(\phi, 0) = \delta(\phi)$. With the passage of time, the effect of the random forces will be felt in the movement of the pendulum from the equilibrium position. The qualitative behavior of the probability density function is sketched in Fig. 3. Of course, the condition

$$\int_{-\infty}^{\infty} p(\phi, t)\, d\phi = 1$$

must always be met. After a sufficient amount of time, the random forces will push the pendulum around by more than half a revolution so that it will tend to return to the equilibrium position after a full cycle of rotation in either direction. This corresponds to the reference signal of the phase-locked loop advancing or retreating one cycle relative to the received signal. The average time for this occurrence depends on the signal-to-noise ratio. Thus after a sufficiently long period, the probability density will appear as a multimodal function, each mode being centered about equilibrium positions spaced $2\pi$ rad apart, the central mode being the largest with each successive maximum progressively smaller. After an even longer period equal to several times the average time between revolutions, the central mode of the probability density will have diminished, the modes to either side will have become almost as large, and more modes of significant magnitude will have appeared. The central mode will remain the largest since the pendulum may have revolved in either direction with equal probability. Finally, in the steady state an arbitrary number of revolutions will have occurred. Then the probability density will be a periodic function (as will be proved in Part III). However, because the integral of the function must equal one at all times, the magnitude must be everywhere zero.

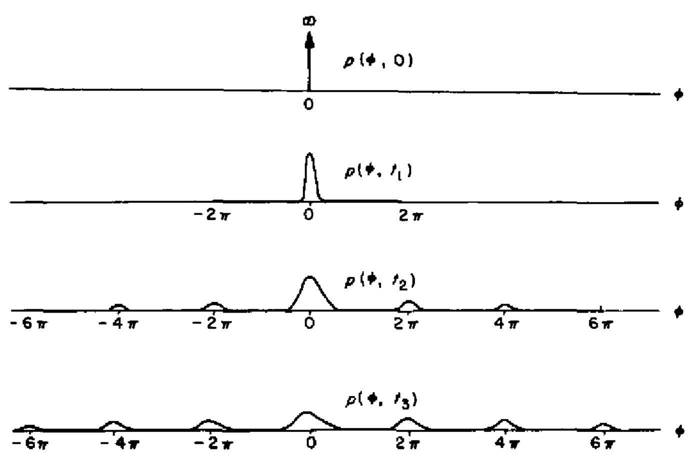


**Fig. 3. Qualitative behavior of the probability density function for the first-order loop, $\omega = \omega_0$**

In the case for which $F$ is not zero, or equivalently $\omega \neq \omega_0$, then clearly the pendulum will have a greater tendency to swing around in the sense corresponding to the direction of the force. Hence, the density function $p(\phi, t)$ will not be symmetrical. In either case, we are lead to realize that the significant parameter, at least in the steady state, is the angle (or phase error) $\phi$ modulo $2\pi$, since the number of revolutions of the pendulum which have occurred does not affect the present state of the system. In fact, although $p(\phi, t)$ yields a complete description of the statistical behavior, it would appear that a combination of the steady-state distribution of $\phi$ modulo $2\pi$ and the frequency or average time between revolutions would yield a simpler and equally valid representation. In the following Parts of this Report, these parameters will be obtained quantitatively.

## III. THE STEADY-STATE PHASE-ERROR PROBABILITY DENSITY FOR THE FIRST-ORDER LOOP

A continuous random walk which is a Markov process is described by the statistical parameters of the incremental change of position as a function of the present position. Thus from Eq. (5), in the infinitesimal increment of time $\Delta t$, the phase will change by an amount[1]

$$\Delta\dot{\phi} = \int_t^{t+\Delta t} \phi(t)\,dt = (\omega - \omega_0)\,\Delta t - (AK\sin\phi)\,\Delta t - K\left[\sin\phi\int_t^{t+\Delta t} n_1(u)\,du + \cos\phi\int_t^{t+\Delta t} n_2(u)\,du\right]$$

Thus, since $n_1(t)$ and $n_2(t)$ are white, Gaussian processes with

$$\overline{n_1(u)} = \overline{n_2(u)} = 0$$

and

$$\overline{n_1(u)\,n_1(v)} = \overline{n_2(u)\,n_2(v)} = (N_0/2)\,\delta(u-v)$$

it follows that for a given position $\phi$, $\Delta\phi$ is a Gaussian variable with mean

$$\overline{\Delta\phi} = [(\omega - \omega_0) - AK\sin\phi]\,\Delta t \tag{8}$$

and variance

$$\begin{aligned}\sigma^2_{\Delta\phi} &= \overline{(\Delta\phi)^2} - (\overline{\Delta\phi})^2 \\ &= K^2\left[\sin^2\phi\int_t^{t+\Delta t}\int_t^{t+\Delta t}\overline{n_1(u)\,n_1(v)}\,du\,dv + \cos^2\phi\int_t^{t+\Delta t}\int_t^{t+\Delta t}\overline{n_2(u)\,n_2(v)}\,du\,dv\right] \\ &= K^2(N_0/2)\,\Delta t\end{aligned} \tag{9}$$

It is worth noting in passing that for the determination of $p(\phi;t)$, Eq. (9) shows that the two noise terms could be replaced by a single noise $n'(t)$ of the same spectral density so that Eq. (5) could be rewritten

$$\dot{\phi}(t) = (\omega - \omega_0) - AK\sin\phi(t) - K\,n'(t) \tag{10}$$

which is conveniently represented by the block diagram of Fig. 4. The model can be shown trivially also to hold

[1]This assumes that $\phi(t)$ is a continuous process, which is justified by physical considerations.

for a higher order loop in which the filter is included after the amplifier. The VCO of Fig. 1 is replaced by an integrator and the multiplier by an adder and sinusoidal nonlinearity. This differs from the linearized model of Ref. 4 only in the inclusion of the sinusoidal nonlinearity.

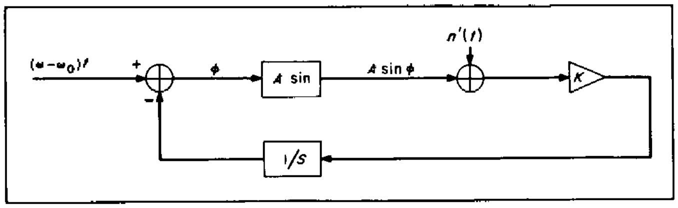


**Fig. 4. Model of first-order loop**

With the knowledge of the statistical parameters of the increment $\Delta\phi$, we may proceed to obtain $p(\phi,t)$. It was shown by Uhlenbeck and Ornstein (Ref. 11) and Wang and Uhlenbeck (Ref. 12) that for a continuous Markov process, the instantaneous probability density $p(\phi,t)$ must satisfy the partial differential equation

$$\frac{\partial p(\phi,t)}{\partial t} = -\frac{\partial}{\partial\phi}[A(\phi)\,p(\phi,t)] + \frac{1}{2}\frac{\partial^2}{\partial\phi^2}[B(\phi)\,p(\phi,t)] \tag{11}$$

with the initial condition

$$p(\phi,0) = \delta(\phi - \phi_0)$$

where $\phi_0$ is the initial value of $\phi$, and where $A(\phi)$ and $B(\phi)$ are normalized moments of the infinitesimal increment given by the following expressions:

$$A(\phi) = \lim_{\Delta t\to 0}(1/\Delta t)\,\overline{\Delta\phi}$$

$$B(\phi) = \lim_{\Delta t\to 0}(1/\Delta t)\,\sigma^2_{\Delta\phi}$$

Equation (11) is known as the Fokker-Planck equation or the diffusion equation because it is essentially the same as the equation for heat diffusion. From Eq. (8) and (9) we obtain

$$A(\phi) = (\omega - \omega_0) - AK\sin\phi$$

$$B(\phi) = K^2N_0/2$$

so that Eq. (11) becomes

$$\frac{\partial p}{\partial t} = \frac{\partial}{\partial\phi}[(AK\sin\phi + \omega_0 - \omega)\,p] + \frac{1}{4}K^2N_0\frac{\partial^2 p}{\partial\phi^2} \tag{12}$$

Although the equation is linear in $p$, the complete solution for $p(\phi,t)$ is somewhat complicated by the nonlinear behavior of the variable coefficients.

However, the result of greatest interest is the steady-state distribution

$$p(\phi) = \lim_{t\to\infty} p(\phi,t) \tag{13}$$

By definition, the steady-state distribution does not vary with time. Therefore,

$$\frac{\partial p(\phi)}{\partial t} = \lim_{t\to\infty}\frac{\partial p(\phi,t)}{\partial t} = 0 \tag{14}$$

Thus in the steady state, the partial differential Eq. (12) reduces to an ordinary differential equation in $p(\phi)$. Letting

$$\alpha = (4A)/(KN_0)$$

and

$$\beta = [4(\omega - \omega_0)]/(K^2N_0) \tag{15}$$

we obtain from Eq. (12)

$$0 = \frac{d}{d\phi}\left[(\alpha\sin\phi - \beta)\,p(\phi) + \frac{dp(\phi)}{d\phi}\right] \tag{16}$$

If we integrate once with respect to $\phi$, we obtain a first-order linear differential equation which is readily solved as[2]

$$p(\phi) = C\exp(\alpha\cos\phi + \beta\phi)$$
$$\times\left[1 + D\int_{-\pi}^{\phi}\exp - (\alpha\cos x + \beta x)\,dx\right]$$
$$-\pi \leq \phi \leq \pi \tag{17}$$

To evaluate the constants, we must utilize boundary conditions. First of all, as was pointed out in Part II, in the steady state we are interested in the distribution of $\phi$ modulo $2\pi$. Thus, one condition is:

$$p(\pi) = p(-\pi) \tag{18}$$

Secondly, since $\phi$ must lie between $-\pi$ and $\pi$ and $p(\phi)$ is a probability density, it follows that

[2]The results of Eq. (17) through (21) were first obtained by V. I. Tikhonov (Ref. 9). Actually, these are a special case of an expression derived by Andronov, Pontryagin and Witt (Ref. 13) for a random walk problem with arbitrary nonlinear restoring forces.

$$\int_{-\pi}^{\pi} p(\phi)\, d\phi = 1 \tag{19}$$

Using Eq. (18), we obtain

$$D = \frac{\exp(-2\beta\pi) - 1}{\int_{-\pi}^{\pi} \exp - (\alpha \cos x + \beta x)\, dx} \tag{20}$$

Then by means of Eq. (19), the constant $C$ can be evaluated.

In the special case $\beta = 0$ (which requires $\omega = \omega_0$; i.e., when the VCO quiescent frequency is exactly at the frequency of the incoming signal), from Eq. (20) we see that $D = 0$ and that when $\omega = \omega_0$, the probability density becomes

$$p(\phi) = \frac{\exp(\alpha \cos\phi)}{2\pi I_0(\alpha)} \qquad -\pi \leqq \phi \leqq \pi \tag{21}$$

since

$$C = \frac{1}{\int_{-\pi}^{\pi} \exp(\alpha \cos\phi)\, d\phi} = \frac{1}{2\pi I_0(\alpha)}$$

The parameter $\alpha$ plays a very important role. From Eq. (15) we have

$$\alpha = \frac{(4A)}{(KN_0)} = \frac{(A^2)}{[N_0(AK/4)]} \tag{22}$$

But $A^2$ is the received signal power, while $AK/4$ is an important parameter defined for the linearized model of the loop (Ref. 4). If we replace the sinusoidal nonlinearity in the model of Fig. 4 by its gain $A$ about $\phi = 0$, we obtain the linearized model. Then the variance of $\phi$ is obtained by using Parseval's theorem as:

$$\sigma_\phi^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{N_0}{2} \frac{K^2/\omega^2}{1 + (A^2K^2/\omega^2)}\, d\omega = N_0(AK/4)$$

The variance of $\phi$ is the same as the noise power at the output of an ideal low-pass filter of bandwidth $AK/4$ when the input is white noise of one-sided spectral density $N_0$. Hence, for the first-order filter, the loop bandwidth is defined as

$$B_L = AK/4 \tag{23}$$

so that Eq. (22) becomes

$$\alpha = (A^2)/(N_0 B_L) \tag{24}$$

which is the signal-to-noise ratio in the bandwidth of the loop.

Equation (21) is plotted in Fig. 5 for several values of $\alpha$. It resembles a Gaussian distribution for large signal-to-noise ratios, $\alpha$, and becomes flat as $\alpha$ approaches zero. The asymptotic behavior of Eq. (21) for large $\alpha$ is of interest. Since for large $\alpha$

$$I_0(\alpha) \sim (\exp\alpha)/(2\pi\alpha)^{1/2}$$

$$p(\phi) = \frac{[\exp(\alpha\cos\phi)]}{[2\pi I_0(\alpha)]} \sim \frac{\{\exp[\alpha(\cos\phi - 1)]\}}{(2\pi/\alpha)^{1/2}}$$

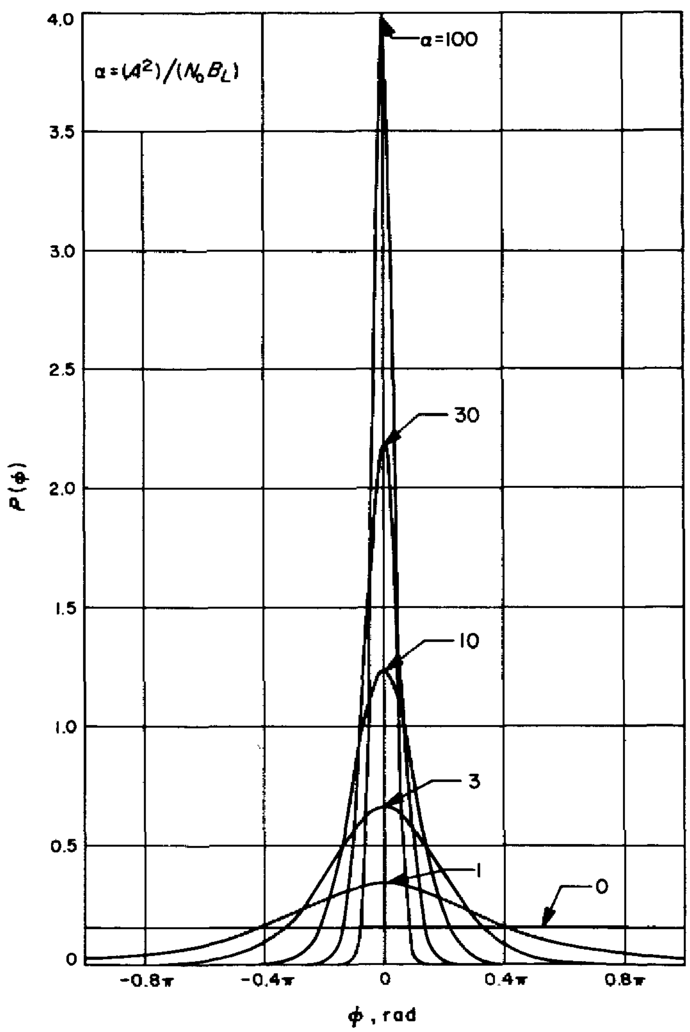


**Fig. 5. First-order loop, steady-state probability densities for $\omega = \omega_0$**

Expanding cos $\phi$ in a Taylor series, we obtain

$$p(\phi) \sim \frac{\exp\left[\frac{-\alpha\phi^2}{2}\left(1 - \frac{2\phi^4}{4!} + \frac{2\phi^6}{6!} \cdots\right)\right]}{(2\pi/\alpha)^{1/2}} \qquad (25)$$

$$-\pi \leqq \phi \leqq \pi$$

When $\alpha$ is large, $p(\phi)$ decays rapidly so that the function is very small for all but very small values of $\phi$. Thus the higher order terms of the series representation of cos $\phi$ have very little effect for moderate values of $p(\phi)$. Hence the graph of $p(\phi)$ will appear to be nearly Gaussian for large $\alpha$, and in this case, the results of the linear model are quite accurate.

The cumulative steady-state probability distribution

$$P(|\phi| < \phi_0) = \int_{-\phi_0}^{\phi_0} p(\phi)\, d\phi \qquad 0 < \phi_0 < \pi$$

is also of interest since it indicates the percentage of time during which the absolute value of the loop phase error $\phi$ is less than a given magnitude $\phi_0$. This may be calculated when $\omega = \omega_0$ in the following manner. Expanding $p(\phi)$ of Eq. (21) in a Fourier series, we have

$$p(\phi) = \frac{\exp(\alpha\cos\phi)}{2\pi I_0(\alpha)}$$

$$= \frac{1}{2\pi I_0(\alpha)}\left[I_0(\alpha) + 2\sum_{n=1}^{\infty} I_n(\alpha)\cos n\phi\right]$$

Then

$$P(|\phi| < \phi_0) = 2\int_0^{\phi_0} p(\phi)\, d(\phi)$$

$$= \frac{\phi_0}{\pi} + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{I_n(\alpha)\sin n\phi_0}{nI_0(\alpha)}$$

$$0 < \phi_0 < \pi \quad \text{for } \omega = \omega_0 \qquad (26)$$

This series converges rapidly so that Eq. (26) could be calculated for several values of $\alpha$ without the use of a large-scale digital computer. The results are shown in Fig. 6.

The variance of $\phi$ can be similarly obtained.

$$\sigma_\phi^2 = \int_{-\pi}^{\pi} \phi^2 \exp(\alpha\cos\phi)\, d\phi$$

$$= \frac{1}{2\pi I_0(\alpha)}\int_{-\pi}^{\pi}\phi^2\left[I_0(\alpha) + 2\sum_{n=1}^{\infty} I_n(\alpha)\cos n\phi\right] d\phi$$

$$= \frac{\pi^2}{3} + 4\sum_{n=1}^{\infty}\frac{(-1)^n I_n(\alpha)}{n^2 I_0(\alpha)} \qquad (27)$$

This series converges even more rapidly than that of Eq. (26). It was computed manually and is plotted in Fig. 7 as a function of $1/\alpha$. Note that as the SNR $\alpha$ approaches zero, the variance approaches $\pi^2/3$ which is the variance of a random variable that is uniformly distributed from $-\pi$ to $+\pi$.

For the general case ($\omega \neq \omega_0$), Eq. (17), (19), and (20) yield the entire distribution. However, analog or digital computation is required to evaluate the pertinent integrals. The case for which $(\beta/\alpha) = (\omega - \omega_0)/(AK) = \sin(\pi/4)$ is shown in Fig. 8. The constants as well as the distribution were obtained by means of the analog computer.

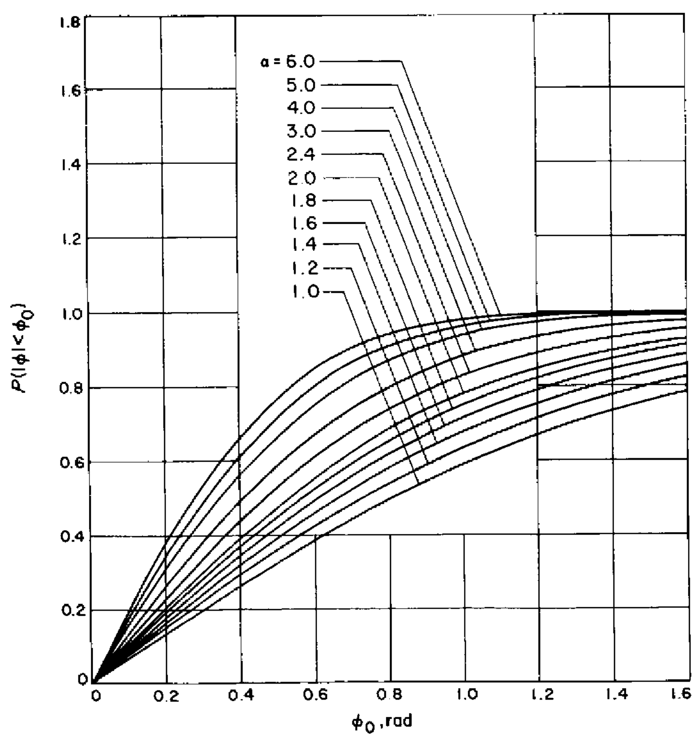


**Fig. 6. Steady-state, cumulative probability distribution of first-order loop for $\omega = \omega_0$**

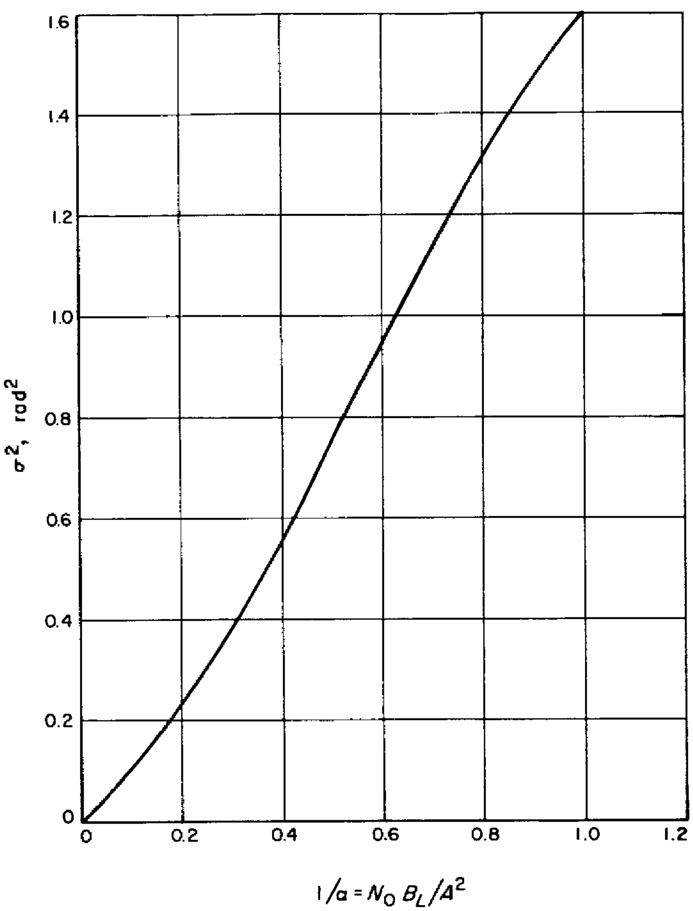


**Fig. 7. Variance of phase-error for first-order loop where $\omega = \omega_0$**

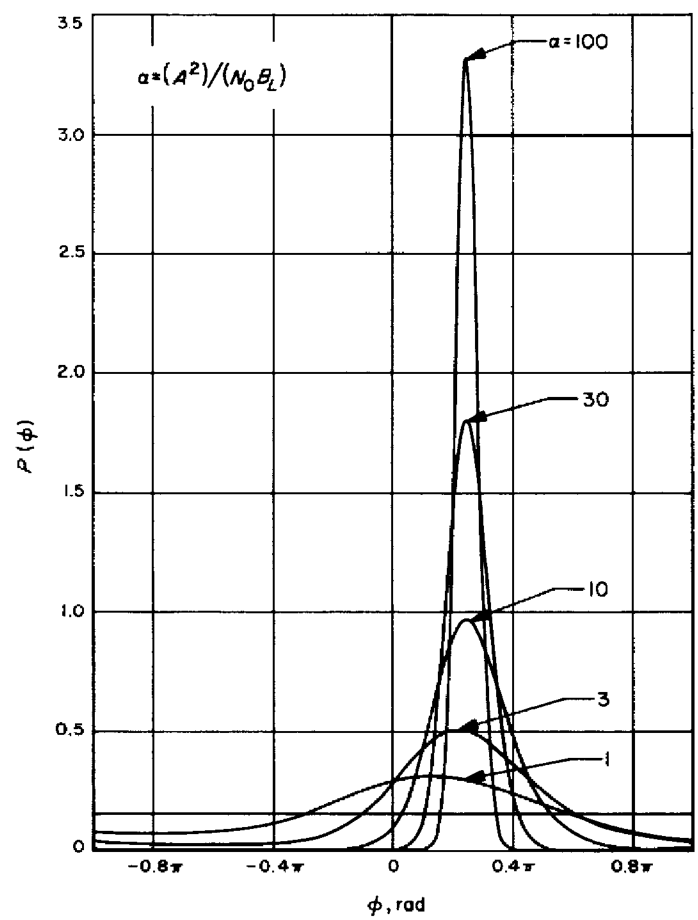


**Fig. 8. First-order loop, steady-state probability densities for $(\omega = \omega_0)/(A\,K) = \sin(\pi/4)$**

## IV. THE FOKKER-PLANCK EQUATION FOR HIGHER-ORDER LOOPS

Consider the phase-locked loop whose filter has the rational transfer function

$$F(s) = G(s)/H(s)$$

where $G(s)$ and $H(s)$ are polynomials such that $G(0) = 1$, $H(0) = 0$

$$\deg G(s) \leqq \deg H(s) = n - 1$$

then

$$G(s) = \sum_{k=0}^{n-1} a_k s^k \qquad a_0 \neq 0$$
$$H(s) = \sum_{k=1}^{n-1} b_k s^k \qquad b_{n-1} \neq 0 \tag{28}$$

This will be referred to as an $n$th-order loop. In this case, Eq. (4) which describes the operation of the loop becomes

$$sH(s)\,\phi = -KG(s)\,[(A + n_1)\sin\phi + n_2\cos\phi] \tag{29}$$

since

$$s^k(\omega - \omega_0) = \frac{dk}{dt}(\omega - \omega_0) = 0 \qquad \text{for } k \geqq 1$$

The reason for the pole at the origin of $F(s)$ is now clear. It eliminates the constant $(\omega - \omega_0)$ which causes the steady-state phase error in the first-order loop. Now let us define the random variable $\varepsilon$ by the relation[3]

$$\phi = G(s)\,\varepsilon \tag{30}$$

Inserting this in Eq. (29), we obtain

$$sH(s)\,\varepsilon = -K\{[A + n_1]\sin[G(s)\,\varepsilon] + n_2\cos[G(s)\,\varepsilon]\} \tag{31}$$

which is an $n$th-order differential equation. Now let us define the $n$ random variables $x_0, x_1, \cdots, x_{n-1}$ as

$$x_k = \frac{d^k\varepsilon}{dt^k} \qquad k = 0, 1, \cdots, n-1 \tag{32}$$

Inserting these for the derivatives of $\varepsilon$ in Eq. (31) and by using Eq. (28), we obtain

$$b_{n-1}\dot{x}_{n-1} + \sum_{k=1}^{n-2} b_k x_{k+1} = -K\left[(A + n_1)\sin\left(\sum_{k=0}^{n-1} a_k x_k\right) + n_2\cos\left(\sum_{k=0}^{n-1} a_k x_k\right)\right]$$

Also, we have

$$x_k = \frac{d}{dt}\frac{d^{k-1}\varepsilon}{dt^{k-1}} = \dot{x}_{k-1}$$

so that we may express the derivatives $\dot{x}_k$ in terms of the variables $x_k$ by the $n$ differential equations

$$\dot{x}_{n-1} = -\sum_{k=1}^{n-2}\frac{b_k}{b_{n-1}}x_{k+1} - \frac{K}{b_{n-1}} \times \left[(A + n_1)\sin\left(\sum_{k=0}^{n-1} a_k x_k\right) + n_2\cos\left(\sum_{k=0}^{n-1} a_k x_k\right)\right]$$
$$\dot{x}_{n-2} = x_{n-1}$$
$$\vdots$$
$$\dot{x}_0 = x_1 \tag{33}$$

It follows also from Eq. (28), (30), and (32) that

$$\phi = \sum_{k=0}^{n-1} a_k s^k \tag{34}$$

The random vector $(x_0, \cdots, x_{n-1})$ is a Markov vector since an incremental change depends only on the present state of the vector.

Wang and Uhlenbeck (Ref. 12) have shown that for a vector Markov process $\mathbf{x} = (x_0, x_1, \cdots, x_{n-1})$, the Fokker-Planck equation is

$$\frac{\partial P(x)}{\partial t} = -\sum_{k=0}^{n-1}\frac{\partial}{\partial x_k}[A_k(\mathbf{x})\,P(\mathbf{x})] + \frac{1}{2}\sum_{k=0}^{n-1}\sum_{l=0}^{n-1}\frac{\partial^2}{\partial x_k\,\partial x_l}[B_{kl}(\mathbf{x})\,P(\mathbf{x})]$$

where

$$A_k(\mathbf{x}) = \lim_{\Delta t \to 0}\frac{1}{\Delta t}(\overline{\Delta x_k})$$

and

$$B_{kl}(\mathbf{x}) = \lim_{\Delta t \to 0}\frac{1}{\Delta t}(\overline{\Delta x_k)(\Delta x_l}) \tag{35}$$

[3]This substitution which leads to the representation of $\phi$ as the sum of the components of a Markov vector (Eq. 33) was suggested by J. N. Franklin.

with the initial condition

$$P(\mathbf{x},0) = \prod_{k=0}^{n-1} \delta(x_k - x_{k,0})$$

$$A_k(\mathbf{x}) = x_{k+1} \quad \text{for } k = 0, 1, \cdots, n-2$$

$$A_{n-1}(\mathbf{x}) = -\sum_{k=1}^{n-2} \frac{b_k}{b_{n-1}} x_{k+1} - \frac{KA}{b_{n-1}} \sin \sum_{k=0}^{n-1} a_k x_k$$

$$B_{n-1,n-1}(\mathbf{x}) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} \frac{K^2}{b_{n-1}^2} \times \left[ \sin^2\phi \int_t^{t+\Delta t} \int_t^{t+\Delta t} \overline{n_1(u)\, n_1(v)}\, du\, dv + \cos^2\phi \int_t^{t+\Delta t} \int_t^{t+\Delta t} \overline{n_2(u)\, n_2(v)}\, du\, dv \right] = \frac{K^2 N_0/2}{b_{n-1}^2}$$

$$B_{k,l}(\mathbf{x}) = 0 \quad \text{for all } k \neq n-1 \text{ and } l \neq n-1$$

Thus, the Fokker-Planck equation for the $n$th-order loop is

$$\frac{\partial P(x,t)}{\partial t} = -\sum_{k=0}^{n-2} x_{k+1} \frac{\partial P(x,t)}{\partial x_k} + \frac{1}{b_{n-1}} \frac{\partial}{\partial x_{n-1}} \times \left[ \left( \sum_{k=0}^{n-2} b_k x_{k+1} + KA \sin \sum_{k=0}^{n-1} a_k x_k \right) P(x,t) \right] + \frac{K^2 N_0}{4 b_{n-1}^2} \frac{\partial^2 P(x,t)}{\partial x_{n-1}^2} \tag{36}$$

where

$$\phi = \sum_{k=0}^{n-1} a_k x_k$$

Solution of this general case does not appear possible. However, in the next Section some results are obtained for the second-order loop.

## V. STEADY-STATE PROBABILITY DISTRIBUTION FOR THE SECOND-ORDER LOOP

The loop filter of greatest interest[4] is

$$F(s) = 1 + (a/s) = (s + a)/(s)$$

which requires a single integrator with gain $a$. In terms of the parameters of Eq. (28), $n = 2$, $a_0 = a$, $a_1 = 1$, $b_1 = 1$. Substituting these parameters in Eq. (33) and (36), we obtain the differential equations for the random variables

$$\dot{x}_1 = -K[(A + n_1)\sin(ax_0 + x_1)] - Kn_2\cos(ax_0 + x_1)$$
$$\dot{x}_0 = x_1 \qquad (37)$$

and the Fokker-Planck equation

$$\frac{\partial P}{\partial t} = -x_1\frac{\partial p}{\partial x_0} + \frac{\partial}{\partial x_1}[(AK\sin(ax_0 + x_1)P] + \frac{K^2N_0}{4}\frac{\partial^2 P}{\partial x_1^2} \qquad (38)$$

where

$$\phi = ax_0 + x_1$$

If we restrict our attention to the steady-state probability distribution

$$P(x_0, x_1) = \lim_{t\to\infty} P(x_0, x_1, t)$$

since

$$\lim_{t\to\infty}\frac{dP}{dt}(x_0, x_1, t) = 0$$

we obtain

$$x_1\frac{\partial P}{\partial x_0} = AK\frac{\partial}{\partial x_1}[\sin(ax_0 + x_1)P] + \frac{K^2N_0}{4}\frac{\partial^2 P}{\partial x_1^2} \qquad (39)$$

With the substitutions

$$\phi = ax_0 + x_1$$
$$z = ax_0 \qquad (40)$$

we obtain an equation in $P(\phi, z)$ (note that the Jacobian of the transformation is $a$)

$$a(\phi - z)\left(\frac{\partial P}{\partial \phi} + \frac{\partial P}{\partial z}\right) = AK\frac{\partial}{\partial \phi}(\sin\phi P) + \frac{K^2N_0}{4}\frac{\partial^2 P}{\partial \phi^2} \qquad (41)$$

Even this partial differential equation cannot be solved directly. However, since we are interested only in the distribution of $\phi$

$$p(\phi) = \int_{-\infty}^{\infty} P(\phi, z)\,dz$$

we may integrate both sides of Eq. (41) with respect to $z$ over the infinite line and obtain an ordinary differential equation in $p(\phi)$

$$a\left\{\frac{d(\phi p)}{d\phi} - \frac{d}{d\phi}\left[\int_{-\infty}^{\infty} zP(\phi, z)\,dz\right]\right\} = AK\frac{d}{d\phi}(\sin\phi\, p) + \frac{K^2N_0}{4}\frac{d^2p}{d\phi^2} \qquad (42)$$

But

$$\int_{-\infty}^{\infty} zP(\phi, z)dz = p(\phi)\int_{-\infty}^{\infty} zP(z|\phi)\,dz = p(\phi)E(z|\phi)$$

so that Eq. (42) becomes

$$0 = \frac{d}{d\phi}\left\{[AK\sin\phi - a\phi + aE(z|\phi)]\,p + \frac{K^2N_0}{4}\frac{dp}{d\phi}\right\} \qquad (43)$$

Unfortunately, it is not possible to determine exactly $E(z|\phi)$, which is a function of $\phi$, without knowing $P(z, \phi)$, which would require solution of Eq. (41). However, its general form can be obtained as follows: from Eq. (40) we have $z = \phi - x_1$ so that

$$E[z(t)|\phi(t)] = E[\phi(t) - x_1(t)|\phi(t)] \qquad (44)$$
$$= \phi(t) - E[x_1(t)|\phi(t)]$$

Integrating Eq. (37) using Eq. (40), we have

$$x_1(\infty) - x_1(t) = -AK\int_t^{\infty}\sin\phi(\xi)\,d\xi - K\int_t^{\infty} n_1(\xi)\sin\phi(\xi)\,d\xi - K\int_t^{\infty} n_2(\xi)\cos\phi(\xi)\,d\xi$$

[4]Tikhonov (Ref. 10) considered the RC low-pass filter whose transfer function is $1/(s + b)$. Its value is questionable, however, since it does not reduce the mean phase error to zero, as the perfect integrator does.

Since the noise is white, $n_1(t)$ and $n_2(t)$ are independent of $\phi(t)$ for all $t$ so that, since $\overline{n_1(t)} = \overline{n_2(t)} = 0$, the expectations of the noise terms are zero. Also

$$E[x_1(\infty)|\phi(t)] = E[x_1(\infty)] = 0$$

since it is clear that the mean of the process is zero. Therefore,

$$E[x_1(t)|\phi(t)] = AK\int_t^\infty E[\sin\phi(\xi)|\phi(t)]\,d\xi \tag{45}$$

This is the integral of the expectation of sin $\phi$ over the entire past history of the process given the present value of $\phi$. Combining Eq. (43), (44), and (45), and letting $\xi = t + \tau$, we obtain

$$0 = \frac{d}{d\phi}\left\{\frac{4A}{KN_0}\left(\sin\phi - a\int_0^\infty E[\sin\phi(t+\tau)|\phi(t)]d\tau\right) \times p(\phi) + \frac{dp(\phi)}{d\phi}\right\} \tag{46}$$

The magnitude of the expectation is always less than one and becomes negligible for values of $\tau$ several times the inverse bandwidth of the spectrum of $\phi(t)$. This bandwidth is proportional to $AK$, as we found for the first-order loop. Therefore, the order of magnitude of the integral is inversely proportional to $AK$, and if $a << AK$, the second term in the coefficient of $p(\phi)$ is much smaller than the first. Neglecting this second term reduces Eq. 46 to the steady-state Fokker-Planck equation for the first-order loop (Eq. 16) with $\omega = \omega_0$, whose solution is Eq. (21). Thus when the second integrator gain $a << AK$,

$$p(\phi) \simeq \frac{\exp(\alpha\cos\phi)}{2\pi I_0(\alpha)} \qquad -\pi \leq \phi \leq \pi \tag{47}$$

On the other hand, for any value of $a$ when the SNR is large enough, $\phi(t)$ will be small for all time so that $\sin\phi(t) \simeq \phi(t)$ and both $\phi(t)$ and $\sin\phi(t)$ will be nearly Gaussian processes. In this case, the expectation can be approximated by

$$\int_0^\infty E[\sin\phi(t+\tau)|\phi(t)]\,d\tau \simeq \left[\int_0^\infty \rho_\phi(\tau)\,d\tau\right]\sin\phi \tag{48}$$

where $\rho_\phi(\tau)$ is the normalized autocorrelation function of the stationary process $\phi(t)$. The integral can be obtained by using Parseval's theorem:

$$\int_0^\infty \rho_\phi(\tau) = \frac{1}{2\sigma^2}\int_{-\infty}^\infty R_\phi(\tau)\,d\tau = \frac{S_\phi(0)}{2\sigma^2}$$

where $R_\phi(\tau)$ is the unnormalized autocorrelation function, $\sigma^2$ the variance of $\phi$, and $S_\phi(\omega)$ the spectral density. Since we have approximated sin $\phi$ by $\phi$, we may use the linearized version of Fig. 4 with the loop filter $F(s) = [1 + (a/s)]$ inserted. Then

$$S_\phi(\omega) = \frac{N_0K^2}{2}\left|\frac{s+a}{s^2+AKs+aAK}\right|^2$$

so that $S_\phi(0) = (N_0)/(2A^2)$.

$$\sigma^2 = \frac{1}{2\pi}\int_{-\infty}^\infty S_\phi(\omega)\,d\omega = \frac{N_0}{4A^2}(AK+a)$$

and

$$\int_0^\infty \rho_\phi(\tau)\,d\tau = 1/(AK+a)$$

Inserting this integral in Eq. (48) and substituting in Eq. (46), we obtain

$$0 = \frac{d}{d\phi}\left\{\frac{4A}{KN_0}\left[\sin\phi\left(\frac{AK}{AK+a}\right)\right]p(\phi) + \frac{dp(\phi)}{d\phi}\right\}$$

whose solution with the boundary conditions of Eq. (18) and (19) is

$$p(\phi) \simeq \frac{\exp(\alpha'\cos\phi)}{2\pi I_0(\alpha')} \qquad \text{for large } \alpha' \tag{49}$$

where the effective SNR, $\alpha'$, is given by

$$\alpha' = (A^2)/[N_0(AK+a)/(4)]$$

If we let $B_L = (AK + a)/4$, this is the same expression as that for the first-order loop with $\omega = \omega_0$. As would be expected, this expression for loop bandwidth for the second-order loop is that obtained from the linear model of the loop.

# VI. MEAN TIME TO LOSS OF LOCK AND FREQUENCY OF SKIPPING CYCLES

Since we have obtained only solutions for steady-state probabilities, a valuable statistic is the expected time required for the absolute value of the phase error to exceed some value $\phi_l$ when it is initially zero. When this occurs, the loop will be said to have lost lock. Of particular interest is the case for which $\phi_l = \pm 2\pi$, which represents a loss or gain of a complete cycle, or for the mechanical analog, a complete revolution of the pendulum.

We only treat the case of the first-order loop for which the received frequency $\omega$ equals the VCO quiescent frequency $\omega_0$ so that $\phi = 0$ is the equilibrium position. This is also a good approximation to the steady-state behavior of the second-order loop with any value of $\omega - \omega_0$ but with very small integrator gain $a$, as will be discussed later in this Part. For the first-order loop, when $\omega \neq \omega_0$, the same approach can be used measuring phase error from the equilibrium position rather than from zero, but the results are in the form of integrals which require numerical calculation.

Returning to the mechanical analog of the pendulum of Part II, we treat the motion of the ball by the operational equation

$$\dot{\phi} = -AK \sin\phi - Kn_1 \sin\phi - Kn_2 \cos\phi$$

as long as $|\phi| < \phi_l$. But when the pendulum angle $\phi$ reaches $\pm\phi_l$, we assume that it is grasped by a demon and removed from operation forever after. We seek the average time for this event to occur when the pendulum is initially at rest at $\phi = 0$. As long as $|\phi| < \phi_l$, the probability density of $\phi$ is described in the same manner as before by the Fokker-Planck equation

$$\frac{\partial p}{\partial t} = \frac{\partial}{\partial\phi}(AK \sin\phi\, p) + \frac{N_0K^2}{4}\frac{\partial^2 p}{\partial\phi^2}$$

$$p(\phi, 0) = \delta(\phi) \quad \text{for } |\phi| < \phi_l \qquad (50)$$

However, as soon as $|\phi|$ reaches $\phi_l$ for the first time, the pendulum is removed from action so that

$$p(\phi, t) = 0 \quad \text{for all } |\phi| \geq \phi_l$$

Thus we have the boundary conditions[5]

$$p(\phi_l, t) = p(-\phi_l, t) = 0 \qquad (51)$$

Solution of Eq. (50) over the interval $-\phi_l < \phi < \phi_l$ with the boundary conditions of Eq. (51) would yield the probability density $p(\phi, t)$. Its integral over the interval

$$\psi(t) = \int_{-\phi_l}^{\phi_l} p(\phi, t)\, d\phi \qquad (52)$$

gives the probability that $\phi$ has not yet reached $\phi_l$ at time $t$. Then the probability density of the time when $|\phi|$ reaches $\phi_l$ is $-[\partial\psi(t)]/(\partial t)$. Thus the expected time to reach the out-of-lock position $\phi_l$ is

$$T = \int_0^\infty -t\frac{\partial\psi(t)}{\partial t} = -\Big[t\,\psi(t)\Big]_0^\infty + \int_0^\infty \psi(t)\, dt \qquad (53)$$

Since with probability 1, $|\phi|$ must reach $\phi_l$ before $t = \infty$, then $\psi(\infty) = 0$ so that the combination of Eq. (52) and (53) yields the mean time to lose lock

$$T = \int_0^\infty \int_{-\phi_l}^{\phi_l} p(\phi, t)\, d\phi dt \qquad (54)$$

Now if we integrate both sides of Eq. (50) with respect to $t$ over the infinite interval, we obtain

$$p(\phi, \infty) - p(\phi, 0) = \frac{\partial}{\partial\phi}(AK \sin\phi\, P) + \frac{N_0K^2}{4}\frac{\partial^2 P(\phi)}{\partial\phi^2} \qquad (55)$$

where

$$P(\phi) = \int_0^\infty p(\phi, t)\, dt$$

As we noted previously, $p(\phi, \infty) = 0$, and since $\phi$ is assumed initially at zero, $p(\phi, 0) = \delta(\phi)$. Therefore, we have

$$-\delta(\phi) = \frac{\partial}{\partial\phi}[AK \sin\phi\, P(\phi)] + \frac{N_0K^2}{4}\frac{\partial^2 P(\phi)}{\partial\phi^2} \qquad (56)$$

[5]The solution of the so-called first passage time problem by means of the Fokker-Planck equation with absorbing boundaries was first treated by Siegert (Ref. 14).

which may be solved using the boundary conditions

$$
\begin{aligned}
P(\phi_l) &= \int_0^\infty p(\phi_l, t)\,dt = 0 \\
P(-\phi_l) &= \int_0^\infty p(-\phi_l, t)\,dt = 0
\end{aligned}
\tag{57}
$$

The solution to Eq. (56) may then be integrated with respect to $\phi$ over the interval $-\phi_l, \phi_l$ to obtain $T$, the expected time to lose lock of Eq. (54). Taking the indefinite integral of both sides of Eq. (56), we obtain

$$
C - u(\phi) = AK \sin\phi\, P(\phi) + \frac{N_0 K^2}{4}\frac{\partial P(\phi)}{\partial \phi} \tag{58}
$$

where $C$ is a constant to be evaluated from the boundary conditions. The solution to the first-order differential equation is

$$
P(\phi) = D \exp(\alpha \cos\phi) + \exp(\alpha\cos\phi)\int_{-\phi_l}^{\phi} \frac{\exp(-\alpha\cos x)}{\gamma}[C - u(x)]\,dx \tag{59}
$$

where

$$
\alpha = \frac{A^2}{N_0 (AK/4)}
$$

and

$$
\gamma = \frac{N_0 K^2}{4} = \frac{AK}{\alpha} = \frac{4B_L}{\alpha}
$$

Applying the boundary conditions of Eq. (57) yields the values of the constants as $D = 0$ and $C = 1/2$.

Thus

$$
P(\phi) = \frac{\exp(\alpha\cos\phi)}{\gamma}\int_{-\phi_l}^{\phi}\exp(-\alpha\cos x)\left[\frac{1}{2} - u(x)\right]dx \tag{60}
$$

and integrating with respect to $\phi$ over the interval $[-\phi_l, \phi_l]$, we obtain an expression for the mean time to lose lock

$$
\begin{aligned}
T &= \int_{\phi_l}^{\phi_l} P(\phi)\,d\phi = \frac{1}{\gamma}\int_{-\phi_l}^{\phi_l} d\phi \\
&\quad \times \int_{-\phi_l}^{\phi} \exp\alpha(\cos\phi - \cos x)\left[\frac{1}{2} - u(x)\right]dx \\
&= \frac{1}{\gamma}\int_0^{\phi_l}\int_{\phi}^{\phi_l} \exp\alpha(\cos\phi - \cos x)\,dx\,d\phi
\end{aligned}
\tag{61}
$$

The domain of integration is the right isosceles triangle shown in Fig. 9. We can obtain a series representation of this double integral by expanding the integrands in Fourier series

$$
\begin{aligned}
\exp(\alpha\cos\phi) &= I_0(\alpha) + 2\sum_{m=1}^{\infty} I_m(\alpha)\cos m\phi \\
\exp(-\alpha\cos x) &= I_0(\alpha) + 2\sum_{n=1}^{\infty}(-1)^n I_n(\alpha)\cos nx
\end{aligned}
\tag{62}
$$

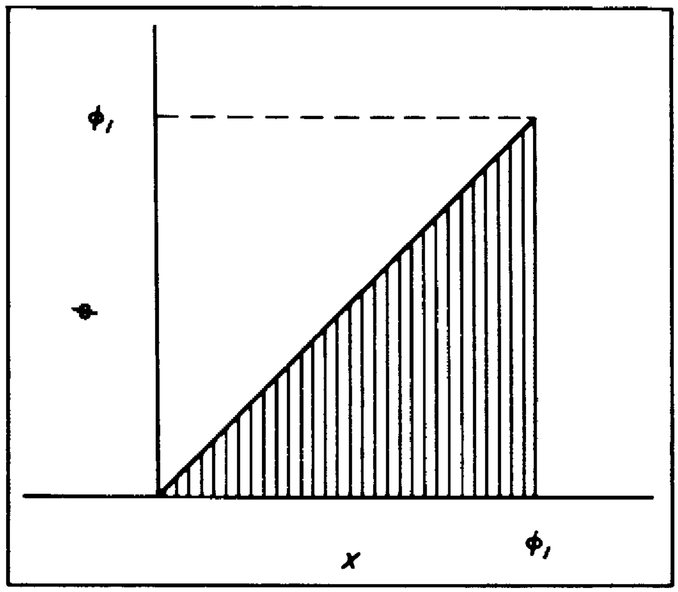


**Fig. 9. Domain of integral T**

Then

$$
\begin{aligned}
T &= \frac{1}{\gamma}\int_0^{\phi_l}\int_{\phi}^{\phi_l} \\
&\quad \times \left[\begin{aligned} &I_0^2(\alpha) + 4I_0(\alpha)\sum_{n=2,4,6,\cdots}^{\infty}(-1)^n I_n(\alpha)\cos n\phi \\ &+ 4\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} -(1)^n I_m(\alpha) I_n(\alpha)\cos m\phi\cos nx \end{aligned}\right] d\phi\,dx \\
&= \frac{1}{\gamma}\left[\frac{I_0^2(\alpha)\phi_l^2}{2} + 4I_0(\alpha)\sum_{n=1}^{\infty}\frac{I_{2n}(\alpha)}{2n}\sin 2n\phi_l \right. \\
&\quad + 4\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}(-1)^n I_m(\alpha) I_n(\alpha) \\
&\quad \left. \times \int_0^{\phi_l}\int_{\phi}^{\phi_l}\cos m\phi\cos nx\,dx\,d\phi\right]
\end{aligned}
$$

where

$$\int_0^{\phi_l}\int_{\phi}^{\phi_l}\cos m\phi\cos nx\,dx\,d\phi =$$

$$= \begin{cases} \cos(n-m)\phi_l\left[\dfrac{1}{nm}+\dfrac{1}{n(n-m)}\right] \\ -\dfrac{4\cos n\phi_l}{nm}-\dfrac{1}{(n-m)n} \end{cases} \text{when } n \neq m$$

$$= \left(\frac{1}{m^2}-\frac{\cos m\phi_l}{m^2}\right) \qquad \text{when } n = m \qquad (63)$$

This expression may be computed without the aid of a large-scale digital computer because the sequence $I_n(\alpha)$, and consequently the above series, converges quite rapidly.

However, the most important result which we seek can be obtained in closed form. This is the frequency of skipping cycles, or, in other words, the inverse of the expected time between skipping cycles, which is $T(\phi_l = 2\pi)$. It is clear from Eq. (63) that when $\phi_l = 2\pi$

$$T(2\pi) = \frac{2\pi^2}{\gamma} I_0^2(\alpha) = \frac{\pi^2 \alpha I_0^2(\alpha)}{2B_L} \qquad (64)$$

where we have used

$$\gamma = \frac{N_0K^2}{4} = \frac{AK}{\alpha} = \frac{4B_L}{\alpha}$$

so that

$$\text{frequency of skipping cycles} = (2B_L)/[\pi^2\alpha I_0^2(\alpha)] \qquad (65)$$

This parameter normalized by $B_L$ is shown as a function of $\alpha$ in Fig. 10.

For large SNR, $\alpha$,

$$I_0(\alpha) \sim (e^{\alpha})/(2\pi\alpha)^{1/2}$$

so that

$$\text{frequency of skipping cycles} \simeq [(4B_L)/\pi]\, e^{-2\alpha} \qquad (66)$$

for large $\alpha$.

Another parameter which is equally significant is the frequency of dropping or advancing half cycles ($\phi_l = \pi$).

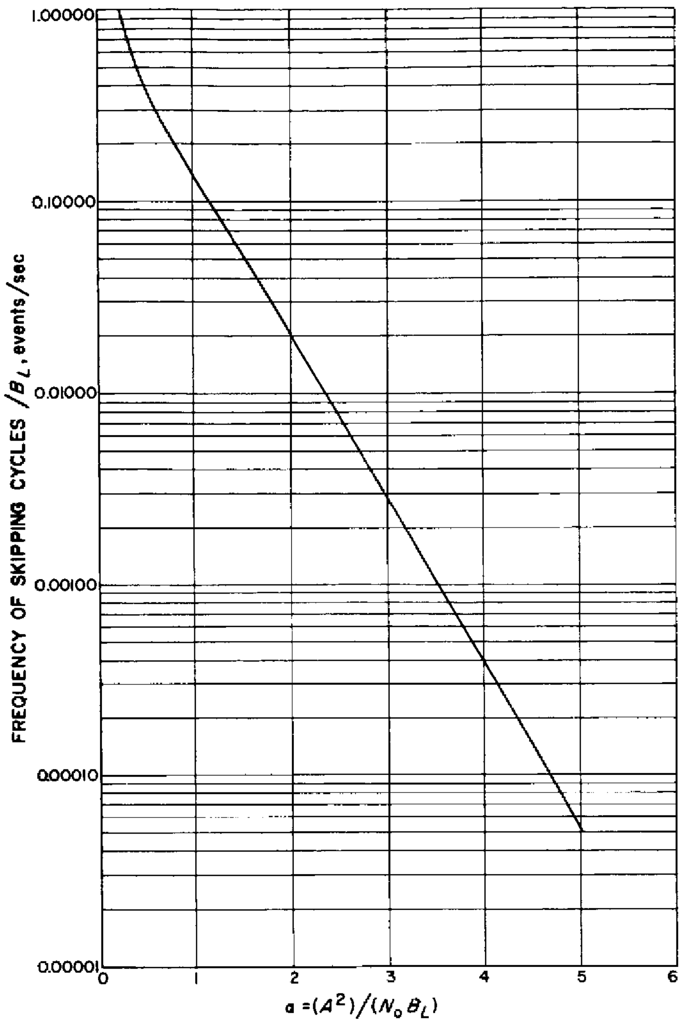


**Fig. 10. Frequency of skipping cycles normalized by loop bandwidth for first-order loop where $\omega = \omega_0$**

In the mechanical analog this corresponds to the pendulum arriving at the unstable equilibrium position and returning to the stable equilibrium position, either by the same route or by going around the full revolution. It is nearly intuitive that for a Markov process the frequency of this event is exactly double the frequency of skipping cycles. However, to show this rigorously, we note that the expected time for the pendulum to go from the equilibrium position $\phi = 0$ to $\phi = \pi$ and to return is $T(\pi) + T'(\pi)$, where $T(\pi)$ is the expected time to go from 0 to $\pm\pi$ and $T'(\pi)$ is the expected time to go from $\pi$ to either 0 or $2\pi$. $T(\pi)$ is given by Eq. (61) with $\phi_l = \pi$, while we can show that

$$T'(\pi) = \frac{1}{\gamma}\int_0^{\phi_l}\int_0^{\phi}\exp\alpha(\cos\phi - \cos x)\,dx\,d\phi$$

The integrand is the same as that for $T(\pi)$, but the domain of integration is its complement with respect to the square of side $\pi$ (Fig. 11). Therefore,

$$T(\pi) + T'(\pi) = \frac{1}{\gamma}\int_0^\pi \int_0^\pi \exp \alpha (\cos \phi - \cos x)\, dx\, d\phi$$
$$= (\pi^2/\gamma) I_0^2(\alpha) = [T(2\pi)/2] \qquad (67)$$

and

$$\text{frequency of skipping half-cycles} = (4B_L)/[\pi^2 \alpha I_0^2(\alpha)] \qquad (68)$$

We can show that these results are approximately correct also for the second-order loop when $\alpha$ is large or $a << 1$ by means of the arguments used in Part V to obtain Eq. (43) through (49).

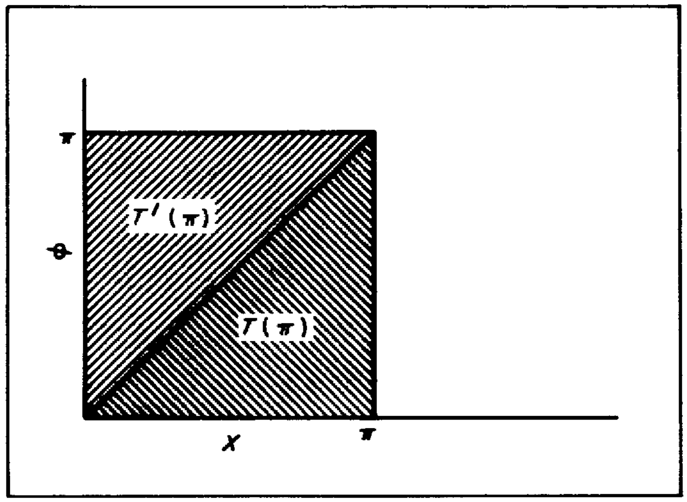


**Fig. 11. Domains of integration for $T(\pi)$ and $T'(\pi)$**

## VII. THRESHOLD CONSIDERATIONS AND CONCLUSIONS

By means of the approximate models discussed in Part I, Van Trees (Ref. 5) and Develet (Ref. 6) have attempted to determine the threshold of the phase-locked loop; the threshold, as they define it, is the value of SNR for which the variance of the phase error becomes unbounded. However, we have shown by an exact analysis that the variance of the steady-state error is always bounded by the variance of the rectangular distribution $p(\phi) = (1/2\pi)$ for $-\pi < \phi < \pi$, which equals $(\pi^2/3)$. This is due to the fact that phase is measured to the nearest cycle (i.e., modulo $2\pi$). On the other hand, if we count a change of a full cycle of phase as a phase error of $2\pi$, and consider the resulting distribution and its variance, we find that the variance is unbounded for all noise densities greater than zero, for with this premise, the steady-state probability density has been shown to be a periodic function, so that its variance is necessarily unbounded. In simple physical terms, for any nonzero noise power, if the noise has a Gaussian distribution with probability one the loop will gain or lose a cycle if enough time elapses. (For the first-order loop, the expected time was obtained exactly in Eq. 64). Therefore, in the steady state (i.e., after an infinite interval of time has elapsed), the number of cycles skipped has a flat probability distribution; hence the probability density function is periodic. Since the idea of infinite variance for all finite SNR is ridiculous, we have no alternative but to accept the concept that phase is meaningful only modulo $2\pi$, so that the variance is never unbounded. The mechanical analog of the simple pendulum discussed in Part II is useful in visualizing these conclusions.

If we redefine threshold to mean that value of SNR for which the linear model, or some other approximate model, becomes inadequate for the analysis, then our foregoing results can be utilized to determine the threshold of the model. It has been shown that, for a first-order loop with no frequency offset, the steady-state phase error has probability density

$$p(\phi) = \frac{\exp(\alpha \cos \phi)}{2\pi I_0(\alpha)} \qquad -\pi \leq \phi \leq \pi$$

where $\alpha = (A^2)/(N_0 B_L)$ and that this is approximately correct also for a second-order loop with small integrator gain. Also, we have shown that the variance of $\phi$ in this case is given by

$$\sigma_\phi^2 = \frac{\pi^2}{3} + 4 \sum_{n=1}^{\infty} \frac{(-1)^n I_n(\alpha)}{n^2 I_0(\alpha)} \tag{69}$$

This is shown in Fig. 12 as a function of $1/\alpha = N_0 B_L/A^2$, where it is compared with the variance obtained from the linear model which is simply

$$\sigma_\phi^2 = \frac{N_0 B_L}{A^2} = \frac{1}{\alpha} \qquad \text{(Linear)} \tag{70}$$

Also shown in Fig. 12 are the results using the approximate models of Van Trees and Develet. Van Trees (Ref. 5) shows that for the first-order loop with no frequency offset (in our terminology)

$$\sigma_\phi^2 = \frac{1}{\alpha - 1} \qquad \text{(Van Trees)} \tag{71}$$

so that the model yields an unbounded variance at $\alpha \leq 1$. Develet (Ref. 6) used the quasi-linearization technique of Booton (Ref. 7) which replaces the sinusoidal nonlinearity of Fig. 4 by its average gain, assuming that the input distribution is nearly Gaussian. The gain of a sinusoidal nonlinearity for an input of value $x$ is $A \cos x$. Therefore, the average gain when the input is Gaussian of mean zero and variance $\sigma^2$ is

$$\int_{-\infty}^{\infty} A \cos x \exp\left(\frac{x^2}{2\sigma^2}\right) dx = A \exp\left(-\frac{\sigma^2}{2}\right)$$

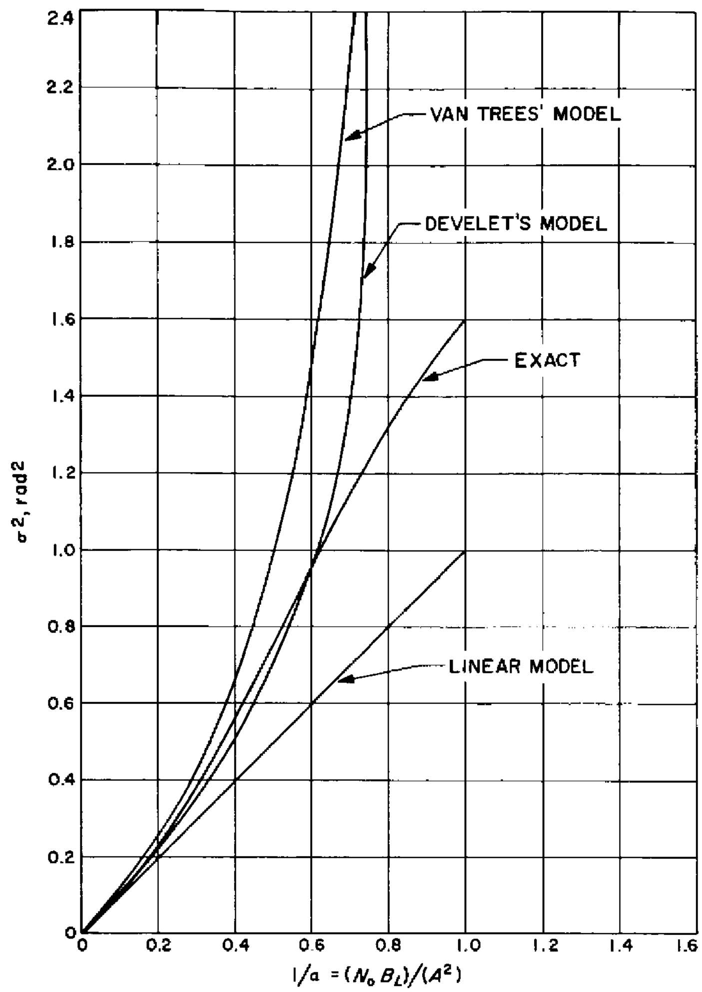


**Fig. 12. Comparison of variance for first-order loop with results of approximate models**

Replacing the nonlinear element of Fig. 4 by this gain, we obtain, by the usual linear analysis, the variance of the phase error for the first-order loop:

$$\sigma^2 = (1/\alpha) \exp(\sigma^2/2) \qquad \text{(Develet)} \tag{72}$$

The solution of this transcendental equation yields the value of the variance which is also shown in Fig. 12. The maximum of $\sigma^2 \exp - (\sigma^2/2)$ is $2/e$ so that there can be no solution for $\alpha < e/2$. This is the point of unbounded variance for Develet's model.

In Fig. 12 we see that for SNR $= \alpha > 1$, the linear model always yields an underestimate while Van Trees' result is always an overestimate of the variance of the phase error, as might be expected from the nature of the approximations. With the linear model the error in the approximation is less than 20% as long as $[(N_0 B_L)/A^2] < 1/4$, or $\alpha > 4$ which is a figure often quoted by experimenters as a threshold of the linear model. Develet's model yields by far the most accurate result. In fact, it differs from the exact result by less than 10% for $[(N_0 B_L)/A^2] < 0.65$, or $\alpha > 1.54$. Thus it would appear that if the exact solution cannot be obtained, as is the case for higher order loops, colored noise, or a modulated carrier, the Booton quasi-linearized model would yield quite accurate results when the SNR in the loop bandwidth is above 1.5.

The other significant result of this Report, which can be used to define threshold, is the frequency of skipping cycles. It was shown in Part VI that for a first-order loop with no frequency offset or a second-order loop with very small integrator gain, the

$$\text{frequency of skipping cycles} = (2B_L)/[\pi^2 \alpha I_0^2(\alpha)]$$

which is plotted in Fig. 10. Thus we might set the threshold of the system as the SNR below which the frequency of skipping cycles exceeds a given value. Thus, for example, let $B_L = 20$ cps and the maximum allowable frequency of skipping cycles be once every minute. Then we see from Fig. 10 that the threshold of the system is at $\alpha = 3.6$. Note, however, that when the system operates at $\alpha = 7.2$, 3 db above threshold, the frequency of skipping cycles drops to once every 20 hr reflecting the exponential behavior of this expression. This definition of threshold is most significant for coherent tracking applications wherein the doppler frequency is measured and integrated to obtain relative range information. Loss or gain of a cycle will yield incorrect results.

A third definition of threshold is the SNR for which the absolute value of the loop phase error $|\phi|$ exceeds a given value $\phi_0$ exactly half the time. For the first-order loop with $\omega = \omega_0$, this information is available from the cumulative probability distribution of Fig. 6. For example, if we set $\phi_0$ at $\pi/4$ rad, we find from Fig. 6 that the SNR at which $|\phi|$ exceeds this value exactly half the time is $\alpha = 1.1$. We see also that when the SNR is 3 db above this threshold level (i.e., $\alpha = 2.2$), then $|\phi|$ exceeds $\pi/4$ rad only about three-tenths of the time.

It is felt that the third definition of threshold has the least significance. The definition in terms of skipping cycles is most meaningful for ranging and tracking applications. However, the most useful result is the determination of the threshold of validity of the various models of the phase-locked loop. By comparing the variance of the phase error computed from each of the models with the actual variance for the first-order loop, which is the only case for which an exact solution in closed form is available, we have been able to determine these validity thresholds. The linear model underestimates the variance by less than 20%, for SNR $> 4$ (6 db). Van Trees' model overestimates $\sigma^2$ to within this accuracy for SNR $> 2.5$ (4 db), while Develet's model is accurate to within 10% for SNR $> 1.54$ (1.7 db). It does not necessarily follow that each model will yield equal accuracy for more complicated loops or signals, but these figures do represent lower bounds on the over-all validity. They also provide a ranking on the merits of the three models. It appears that the simpler the expression for variance, the less accurate is the result. If we wish merely to obtain bounds on performance, the results of Fig. 12 suggest that we use the linear model as an upper bound and Van Trees' model as a lower bound. On the other hand, if we are willing to solve a transcendental equation of the type of Eq. (69), it appears that Develet's model produces significantly greater accuracy over a much wider range of SNR.

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## ACKNOWLEDGMENT

The writer is indebted to Prof. J. N. Franklin and Dr. E. C. Posner for several valuable discussions during the preparation of this manuscript.

# Electronic Acknowledgement Receipt

| | |
|---|---|
| **EFS ID:** | 28266104 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 04-FEB-2017 |
| **Filing Date:** | 26-JUN-2014 |
| **Time Stamp:** | 18:28:15 |
| **Application Type:** | Utility under 35 USC 111(a) |

## Payment information:

| | |
|---|---|
| Submitted with Payment | no |

## File Listing:

| Document Number | Document Description | File Name | File Size(Bytes)/ Message Digest | Multi Part /.zip | Pages (if appl.) |
|---|---|---|---|---|---|
| 1 | Applicant Arguments/Remarks Made in an Amendment | jm_foam_response_2017_0204.pdf | 276510<br>88eeacd28bb7bb71875debc7ba048104dd3d80fa | no | 32 |

**Warnings:**

| Information: | | | | | |
|---|---|---|---|---|---|
| 2 | Other Reference-Patent/App/Search documents | jm_refs_2017_0204.pdf | 9955615<br>ca3992d50a77ac90ac79300e5bedb043d97ebb7d | no | 89 |
| Warnings: | | | | | |
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**If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.**

**National Stage of an International Application under 35 U.S.C. 371**

**If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.**

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| PATENT APPLICATION FEE DETERMINATION RECORD<br>Substitute for Form PTO-875 | Application or Docket Number<br>14/316,489 | Filing Date<br>06/26/2014 | ☐ To be Mailed |
|---|---|---|---|

ENTITY: ☐ LARGE ☒ SMALL ☐ MICRO

## APPLICATION AS FILED – PART I

| FOR | NUMBER FILED (Column 1) | NUMBER EXTRA (Column 2) | RATE ($) | FEE ($) |
|---|---|---|---|---|
| ☐ BASIC FEE (37 CFR 1.16(a), (b), or (c)) | N/A | N/A | N/A | |
| ☐ SEARCH FEE (37 CFR 1.16(k), (i), or (m)) | N/A | N/A | N/A | |
| ☐ EXAMINATION FEE (37 CFR 1.16(o), (p), or (q)) | N/A | N/A | N/A | |
| TOTAL CLAIMS (37 CFR 1.16(i)) | minus 20 = | * | X $ = | |
| INDEPENDENT CLAIMS (37 CFR 1.16(h)) | minus 3 = | * | X $ = | |
| ☐ APPLICATION SIZE FEE (37 CFR 1.16(s)) | If the specification and drawings exceed 100 sheets of paper, the application size fee due is $310 ($155 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s). | | | |
| ☐ MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j)) | | | | |
| * If the difference in column 1 is less than zero, enter "0" in column 2. | | | TOTAL | |

## APPLICATION AS AMENDED – PART II

| AMENDMENT 02/04/2017 | CLAIMS REMAINING AFTER AMENDMENT (Column 1) | | HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2) | PRESENT EXTRA (Column 3) | RATE ($) | ADDITIONAL FEE ($) |
|---|---|---|---|---|---|---|
| Total (37 CFR 1.16(i)) | * 18 | Minus | ** 20 | = 0 | x $40 = | 0 |
| Independent (37 CFR 1.16(h)) | * 5 | Minus | ***5 | = 0 | x $210 = | 0 |
| ☐ Application Size Fee (37 CFR 1.16(s)) | | | | | | |
| ☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | |
| | | | | | TOTAL ADD'L FEE | 0 |

| AMENDMENT | CLAIMS REMAINING AFTER AMENDMENT (Column 1) | | HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2) | PRESENT EXTRA (Column 3) | RATE ($) | ADDITIONAL FEE ($) |
|---|---|---|---|---|---|---|
| Total (37 CFR 1.16(i)) | * | Minus | ** | = | X $ = | |
| Independent (37 CFR 1.16(h)) | * | Minus | *** | = | X $ = | |
| ☐ Application Size Fee (37 CFR 1.16(s)) | | | | | | |
| ☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | |
| | | | | | TOTAL ADD'L FEE | |

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20".
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3".
The "Highest Number Previously Paid For" (Total or Independent) is the highest number found in the appropriate box in column 1.

LIE
TARA WITCHER

This collection of information is required by 37 CFR 1.16. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

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| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

23497 7590 02/01/2017
JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

| EXAMINER | |
|---|---|
| WU, ZHEN Y | |

| ART UNIT | PAPER NUMBER |
|---|---|
| 2685 | |

| MAIL DATE | DELIVERY MODE |
|---|---|
| 02/01/2017 | PAPER |

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The time period for reply, if any, is set in the attached communication.

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JED MARGOLIN
1981 EMPIRE ROAD
RENO NV 89521-7430

In re Application of:
MARGOLIN, JED
Application Serial No.: 14/316,489
Filed: June 26, 2014
For: **FLAME SENSING SYSTEM**

DECISION ON PETITION TO WITHDRAW RESTRICTION REQUIREMENT UNDER 37 CFR 1.144

This is a decision on the petition filed January 25, 2017, under 37 CFR § 1.144 requesting withdrawal of the restriction requirement issued by the examiner on November 1, 2016.

Petitioner traverses the restriction requirement because the examiner did not respond to applicant's traverse he nonetheless withdrew from consideration the claims that applicant had conditionally withdrawn.

## REGULATIONS AND PRACTICE

**818.01(c) Traverse is Required To Preserve Right of Petition [R-07.2015]**

***37 C.F.R. 1.144 Petition from requirement for restriction.***

After a final requirement for restriction, the applicant, in addition to making any reply due on the remainder of the action, may petition the Director to review the requirement. Petition may be deferred until after final action on or allowance of claims to the invention elected, but must be filed not later than appeal. A petition will not be considered if reconsideration of the requirement was not requested (see **§ 1.181** ).

To preserve the right to petition from the requirement for restriction, all errors to be relied upon in the petition must be distinctly and specifically pointed out in a timely filed traverse by the applicant. The petition may be deferred until after final action on or allowance of the claims to the elected invention. In any event, the petition must not be filed later than the filing date of the notice of appeal. If applicant does not distinctly and specifically point out supposed errors in the restriction requirement, the election should be treated as an election without traverse and be so indicated to the applicant by use of form paragraph **8.25.02**.

## OPINION

Per 37 CFR 1.144, after a final requirement for the restriction, the applicant may petition the Director to review the requirement.

Therefore, since the restriction requirement has not yet been made final, the petition on restriction is premature.

## CONCLUSION

Accordingly, the petition to withdraw the restriction requirement is **DISMISSED.**

As a result of the petition decision, the application is being forwarded to the examiner for consideration of the request for reconsideration of restriction requirement filed on November 4, 2016.

Any inquiry regarding this decision should be directed to John Peng, Quality Assurance Specialist, at (571) 272-7272:

/John Peng/
John Peng
Quality Assurance Specialist
Technology Center 2600
Communications

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

| | |
|---|---|
| In re Application of: Jed Margolin | } |
| | } Confirmation No. 1025 |
| Application No. 14/316,489 | } |
| | } Group Art: 2685 |
| Filed: June 26, 2014 | } |
| | } Examiner: Wu, Zhen Y |
| Title: Flame Sensor | } |
| | } |

**PETITION TO WITHDRAW RESTRICTION REQUIREMENT**

MAIL STOP PETITION
Commissioner for Patents
P. O. Box 1450
Alexandria, VA 22313-1450

Jed Margolin, pro se Applicant

Customer Number 23497

January 25, 2017

Sir:

In response to the Office Action mailed January 19, 2017, Applicant hereby files this Petition to Withdraw the Restriction Requirement set forth by the Examiner under 35 U.S.C. 121 for the reasons set forth below.

**A.** Applicant filed the above titled nonprovisional patent application on June 26, 2014.

**B.** In an Office Action mailed November 1, 2016, the Examiner required a Restriction Requirement under 35 U.S.C. 121. *See Exhibit 1.*

**C.** In a response timely filed November 4, 2016 Applicant traversed the Examiner's Requirements for Restriction showing Examiner's errors in requiring the restriction. Applicant elected the Examiner's species represented by claims 1 - 5 and 12 - 14 in the event the Examiner failed to accept Applicant's traverse. *See Exhibit 2*.

**D.** In an Office Action mailed January 19, 2017 the Examiner acknowledged Applicant's traverse filed November 4, 2016 but failed to respond to it. He failed to even give it a pro forma rejection. All he said about it was:

**Response to Election/Restriction**

> Examiner acknowledges the applicant's election of claims 1-5 and 12-14 for review. Examiner acknowledges the applicant's conditionally withdrawn of non-elected claims 6-11 and 15-18 with traverse.

*See Exhibit 3*.

Although the Examiner did not respond to Applicant's traverse he nonetheless withdrew from consideration the claims that Applicant had conditionally withdrawn.

Applicant deserves a fair and honest response to his traverse. The main points of Applicant's traverse begin on page 3. Applicant will also present additional evidence to support his reasons why Examiner's restriction requirement is improper.

This Petition is timely filed because it is being filed within two months of the date the Examiner made his restriction requirement final (37 CFR 1.144 and 37 CFR 1.181) and no appeal has been filed.

According to a message from the Office of Patent Legal Administration (OPLA) on December 19, 2016 this is a 37 CFR 1.181 petition and no fee is due.

Applicant requests that the Director withdraw the Examiner's Restriction Requirement, withdraw the Examiner's FOAM of January 19, 2017, and direct the Examiner to conduct a fair and proper examination of Applicant's application as required by 35 U.S.C. 101.

**Applicant's Traverse**

**1.** Applicant will start by reproducing a portion of his Response filed 11/04/2016.

**A.** Although Flame Rectification does not produce a very good rectifier, the rectifier that it does produce is good enough to act as a mixer. A mixer performs the function of multiplication. It is this function of multiplication that produces both species:

1. Flame rectification causes harmonic distortion of a single selected signal;
2. Flame rectification causes two selected signals to mix, producing signals at the sum and difference frequencies of the two selected signals

From Paragraph 042 in the Specification (page 28)

**[042] Experiment 10 – Using flame rectification as a mixer to produce sum and difference frequencies of two signal sources.**

In this experiment the flame rectifier is used as a mixer. A mixer is a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. See IDS Cite *30* (Horowitz).

One type of mixer is a four-quadrant multiplier. For example, if you multiply two sine wave signals:

$\sin(\omega 1t) * \sin(\omega 2t)$ Equation 1

and use a well known trigonometric identity you get:

$\frac{1}{2} * \cos(\omega 1 - \omega 2)t - \frac{1}{2} * \cos(\omega 1 + \omega 2)t$ Equation 2

The trigonometric identity is:

$\sin(u) * \sin(v) = 1/2 [ \cos(u - v) - \cos(u + v)]$

which is:

$\sin(u) * \sin(v) = 1/2 * \cos(u - v) - 1/2 * \cos(u + v)]$

See **Appendix 1** under - **Product Formulas**

That is why a mixer (multiplier) produces the two signals: the sum of the two frequencies and the difference between the two frequencies.

What may not be so obvious is that when a single sine wave is presented to a mixer (multiplier) this formula still applies but both sin(ω1t) and sin(ω2t) are the same. The result is:

$$\sin(\omega t) * \sin(\omega t) = \tfrac{1}{2} * \cos[(\omega - \omega)t] - \tfrac{1}{2} * \cos[(\omega + \omega)t]$$

$$= \tfrac{1}{2} * \cos(0t) - \tfrac{1}{2} * \cos[(\omega + \omega)t]$$

1. cos(0t) = 1
2. The quantity (ω + ω) = 2 * ω

Therefore:

$$\sin(\omega t) * \sin(\omega t) = \tfrac{1}{2} - \tfrac{1}{2} * \cos[(2 * \omega)t]$$

Thus, the result is a DC term and a component at twice the frequency of ω, which is the second harmonic of ω.

That is why Flame Rectification causes harmonic distortion of a single selected signal. It is the same process by which Flame Rectification causes two selected signals to mix, producing the two signals: the sum of the two frequencies and the difference between the two frequencies.

These species are obvious variants of each other and are so intimately related that no separate search should be necessary.

**2.** Since Applicant did not think Examiner needed more than the above simple explanation Applicant will present more evidence here, starting with the specifics of a semiconductor diode.

**a.** The characteristics of a semiconductor diode were described by William Shockley starting in 1949. From https://en.wikipedia.org/wiki/Shockley_diode_equation (*See Exhibit 4*) :

> The ***Shockley diode equation*** or the *diode law*, named after transistor co-inventor William Shockley of Bell Telephone Laboratories, gives the I–V (current-voltage) characteristic of an idealized diode in either forward or reverse bias (applied voltage):

$$I = I_S \left( e^{\frac{V_D}{n V_T}} - 1 \right)$$

where

*I* is the diode current,
$I_S$ is the reverse bias saturation current (or scale current),
$V_D$ is the voltage across the diode,
$V_T$ is the thermal voltage *kT/q* (Boltzmann constant times temperature divided by electron charge), and
*n* is the *ideality factor*, also known as the *quality factor* or sometimes *emission coefficient*.

**b.** The equation contains an exponential function of "***e***" (approximately 2.718281828459)

A common method of calculating an exponential function of "*e*" is to use a Maclaurin Power Series.

From https://en.wikipedia.org/wiki/Taylor_series (**List of Maclaurin series of some common functions** is at end of page 6, reproduced as *Exhibit 5*)

Exponential function:

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \quad \text{for all } x$$

In Applicant's use of the Flame Diode as a mixer the term "***x***" is actually "***x(t)***". However, to avoid clutter it will simply be represented as "***x***",

Of the series:

$$1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

the first term ("**1**") is a DC term. The second term ("***x***") is the original signal. The third term ("$x^2$") is the original signal multiplied by itself. That is why applying a waveform to a diode produces second harmonic distortion which Applicant showed as:

$$\sin(\omega t) * \sin(\omega t) = \tfrac{1}{2} - \tfrac{1}{2} * \cos[(2 * \omega)t]$$

Although Applicant is not asserting that a Flame Diode has the exact same characteristics as a semiconductor diode (although it might) the Flame Diode produces materially the same results when a selected waveform is applied to it. The Flame Diode produces a second harmonic (and higher harmonics) in a waveform that does not otherwise have them.

It appears that despite the Examiner's comprehensive search no prior art was found that shows the use of flame rectification to cause two selected waveforms to mix, creating sum and difference frequency components. This should be interpreted to mean that this embodiment of Applicant's invention is also new and unobvious.

The usefulness of Applicant's invention would be obvious to anyone waking up at 4 AM to a cold house because the gas furnace has stopped working because it uses a standard primitive flame sensor.

**Conclusion**

For the above reasons Applicant requests that the Director withdraw the Examiner's Restriction Requirement, withdraw the Examiner's FOAM of January 19, 2017, and direct the Examiner to conduct a fair and proper examination of Applicant's application as required by 35 U.S.C. 101.

Respectfully submitted,

/Jed Margolin/

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pro se Applicant

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# Exhibits

Exhibits

# Exhibit 1

Exhibit 1

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| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

23497 7590 11/01/2016
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| EXAMINER | |
|---|---|
| WU, ZHEN Y | |

| ART UNIT | PAPER NUMBER |
|---|---|
| 2685 | |

| MAIL DATE | DELIVERY MODE |
|---|---|
| 11/01/2016 | PAPER |

**Please find below and/or attached an Office communication concerning this application or proceeding.**

The time period for reply, if any, is set in the attached communication.

Exhibits 3

| Office Action Summary | Application No. 14/316,489 | Applicant(s) MARGOLIN, JED | |
|---|---|---|---|
| | Examiner ZHEN Y. WU | Art Unit 2685 | AIA (First Inventor to File) Status Yes |

*-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --*

**Period for Reply**

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE *2* MONTHS FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

**Status**

1)☒ Responsive to communication(s) filed on *06/26/2014*.

☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2a)☐ This action is **FINAL**. 2b)☐ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

**Disposition of Claims***

5)☒ Claim(s) *1-18* is/are pending in the application.

5a) Of the above claim(s) _____ is/are withdrawn from consideration.

6)☐ Claim(s) _____ is/are allowed.

7)☐ Claim(s) _____ is/are rejected.

8)☐ Claim(s) _____ is/are objected to.

9)☒ Claim(s) *1-18* are subject to restriction and/or election requirement.

* If any claims have been determined allowable, you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

**Application Papers**

10)☐ The specification is objected to by the Examiner.

11)☐ The drawing(s) filed on _____ is/are: a)☐ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

**Priority under 35 U.S.C. § 119**

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

**Certified copies:**

a)☐ All b)☐ Some** c)☐ None of the:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

** See the attached detailed Office action for a list of the certified copies not received.

**Attachment(s)**

1) ☐ Notice of References Cited (PTO-892)

2) ☐ Information Disclosure Statement(s) (PTO/SB/08a and/or PTO/SB/08b) Paper No(s)/Mail Date _____.

3) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

4) ☐ Other: _____.

Exhibits 4

***Election/Restrictions***

This application contains claims directed to the following patentably distinct species. Claims 1-14 are drawn to harmonic distortion detection to determine a flame and claims15-18 are drawn to mixing of two signals by flame rectification to determine a flame. The species are independent or distinct because the method and system used to detect a flame are different. In addition, these species are not obvious variants of each other based on the current record.

Applicant is required under 35 U.S.C. 121 to elect a single disclosed species, or a single grouping of patentably indistinct species, for prosecution on the merits to which the claims shall be restricted if no generic claim is finally held to be allowable.

There is a search and/or examination burden for the patentably distinct species as set forth above because at least the following reason(s) apply:

These two distinctive inventions are directed toward two different species that would require very different search strategies.

**Applicant is advised that the reply to this requirement to be complete must include (i) an election of a species to be examined** even though the requirement may be traversed (37 CFR 1.143) **and (ii) identification of the claims encompassing the elected species or grouping of patentably indistinct species**, including any claims subsequently added. An argument that a claim is allowable or that all claims are generic is considered nonresponsive unless accompanied by an election.

The election may be made with or without traverse. To preserve a right to petition, the election must be made with traverse. If the reply does not distinctly and specifically point out supposed errors in the election of species requirement, the election shall be treated as an election without traverse. Traversal must be presented at the time of election in order to be considered timely. Failure to timely traverse the requirement will result in the loss of right to petition under 37 CFR 1.144. If claims are added after the election, applicant must indicate which of these claims are readable on the elected species or grouping of patentably indistinct species.

Should applicant traverse on the ground that the species, or groupings of patentably indistinct species from which election is required, are not patentably distinct, applicant should submit evidence or identify such evidence now of record showing them to be obvious variants or clearly admit on the record that this is the case. In either instance, if the examiner finds one of the species unpatentable over the prior art, the evidence or admission may be used in a rejection under 35 U.S.C. 103 or pre-AIA 35 U.S.C. 103(a) of the other species.

Upon the allowance of a generic claim, applicant will be entitled to consideration of claims to additional species which depend from or otherwise require all the limitations of an allowable generic claim as provided by 37 CFR 1.141.

### *Conclusion*

Any inquiry concerning this communication or earlier communications from the examiner should be directed to ZHEN Y. WU whose telephone number is (571)272-5711. The examiner can normally be reached on Monday to Friday, 8AM - 5PM, Alternate Friday, EST.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Hai Phan can be reached on (571) - 272-6338. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/ZHEN Y WU/
Examiner, Art Unit 2685

/Hai Phan/
Supervisory Patent Examiner, Art Unit 2685

# Exhibit 2

Exhibit 2

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of Jed Margolin

Serial No.: 14/316,489

Filed: 06/26/2014

For: FLAME SENSING SYSTEM

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Dear Sir:

This is in response to the Office Action mailed 11/01/2016 in which the Examiner issued a restriction and/or election requirement asserting:

> This application contains claims directed to the following patentably distinct species. Claims 1-14 are drawn to harmonic distortion detection to determine a flame and claims 15-18 are drawn to mixing of two signals by flame rectification to determine a flame. The species are independent or distinct because the method and system used to detect a flame are different. In addition, these species are not obvious variants of each other based on the current record.

Applicant respectfully disagrees and requests reconsideration and withdrawal of the requirement. Applicant's reasons begin on page 8. However, Applicant will note at this point that the Examiner has mismatched the species represented in the claims.

The claims which are drawn to harmonic distortion detection to determine a flame are Independent Claim 1 (Dependent Claims 2-5) and Independent Claim 12 (Dependent Claims 13 and 14).

The claims which are drawn to the mixing of two signals by flame rectification to determine a flame are Independent Claim 6 (Dependent Claims 7-11), Independent Claim 15 (Dependent Claims 16 and 17), and Independent Claim 18.

In order to move the case forward Applicant will proceed as if the Examiner had correctly matched the species to the claims.

If Applicant's traverse is not accepted Applicant elects the species which is drawn to harmonic distortion detection to determine a flame. These are the following claims: Independent Claim 1 (Dependent Claims 2-5) and Independent Claim 12 (Dependent Claims 13 and 14).

And if Applicant's traverse is not accepted Applicant withdraws the claims which are drawn to the mixing of two signals by flame rectification to determine a flame. These are: Independent Claim 6 (Dependent Claims 7-11), Independent Claim 15 (Dependent Claims 16 and 17), and Independent Claim 18. In this event Applicant reserves the right to pursue all legal remedies to obtain these claims.

The current conditional claims list is appended. It is to be expressly understood that this is conditional on the Examiner rejecting Applicant's traverse.

Respectfully submitted,

/Jed Margolin/ Date: November 4, 2016

Jed Margolin

Jed Margolin
1981 Empire Rd.
Reno, NV 89521-7430
775-847-7845

## Claims

1. A system for detecting the presence of a flame comprising:

a. a combustion burner;

b. a flame rod;

c. a signal source having a selected waveform connected to said flame rod;

d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

e. a harmonic signal detector having an input connected to the output of said high impedance buffer;

f. an indicator connected to the output of said harmonic signal detector;

whereas

g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and

h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.

2. The system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

3. The system of claim 1 whereby said harmonic signal detector comprises a phase locked loop tuned to the frequency of said harmonic signal.

4. The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising:

a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

5. The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is

approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

6. (Conditionally Withdrawn) A system for detecting the presence of a flame comprising:

a. a combustion burner;

b. a flame rod;

c. a first signal source having a selected waveform connected to said flame rod;

d. a second signal source having a selected waveform connected to said flame rod;

e. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

f. a signal detector having an input connected to the output of said high impedance buffer;

g. an indicator connected to the output of said signal detector;

whereas

h. said flame from said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a first mixing signal at the sum of the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform as well as a second mixing signal at the difference between the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform, and

i. said signal detector is configured to detect said first mixing signal or said second mixing signal and indicate the results on said indicator.

7. (Conditionally Withdrawn) The system of claim 6 whereby said signal detector comprises a phase locked loop tuned to said first mixing frequency or to said second mixing frequency.

8. (Conditionally Withdrawn) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, and a reference signal having the same frequency as said first mixing signal or said second mixing signal, and said signal detector comprises a simple synchronous detector comprising:

a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

9. (Conditionally Withdrawn) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, a first reference signal having the same frequency as said first mixing signal or said second mixing signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

10. (Conditionally Withdrawn) The system of claim 6 whereby said first signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

11. (Conditionally Withdrawn) The system of claim 6 whereby said second signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

12. A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a signal source having a selected waveform introduced to said flame rod;
d. providing a high impedance buffer to buffer a flame rod signal from said flame rod;
e. providing a harmonic signal detector to receive the output of said high impedance buffer;
f. providing an indicator to receive the output of said harmonic signal detector;

whereas

g. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said signal source having a selected waveform to produce harmonics of the fundamental frequency of said selected waveform,
h. said harmonic signal detector is used to detect the presence of at least one of said harmonics of said selected waveform and indicate the presence of said at least one of said harmonics of said selected waveform on said indicator, and
i. said presence of said at least one of said harmonics of said selected waveform is proof of the presence of said flame.

13. The method of claim 12 where said step of providing a harmonic signal detector comprises providing a phase locked loop.

14. The method of claim 12 where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

15. (Conditionally Withdrawn) A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a first signal source having a selected waveform introduced to said flame rod;
d. providing a second signal source having a selected waveform introduced to said flame rod;

e. providing a high impedance buffer to buffer a flame rod signal from said flame rod;

f. providing a signal detector to receive the output of said high impedance buffer;

g. providing an indicator to receive the output of said signal detector;

whereas

h. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a sum signal at the sum frequency of said first signal source and said second signal source and a difference signal at the difference frequency of said first signal source and said second signal source,

i. said signal detector is used to detect the presence of said sum signal or said difference signal and indicate the presence of said sum signal or said difference signal on said indicator, and

j. said presence of said sum signal or said difference signal is proof of the presence of said flame.

16. (Conditionally Withdrawn) The method of claim 15 where said step of providing a signal detector comprises providing a phase locked loop.

17. (Conditionally Withdrawn) The method of claim 15 where said step of providing a signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

18. (Conditionally Withdrawn) A method for detecting the presence of a flame comprising the steps of:

a. providing two signal sources to said flame;

b. using flame rectification to cause said two signal sources to mix;

c. providing a signal detector to detect a mixing signal produced by said two signal sources; and

d. providing an indicator to indicate the results of said signal detector.

## Applicant's Response

**A.** Although Flame Rectification does not produce a very good rectifier, the rectifier that it does produce is good enough to act as a mixer. A mixer performs the function of multiplication. It is this function of multiplication that produces both species:

1. Flame rectification causes harmonic distortion of a single selected signal;
2. Flame rectification causes two selected signals to mix, producing signals at the sum and difference frequencies of the two selected signals

From Paragraph 042 in the Specification (page 28)

> **[042] Experiment 10 – Using flame rectification as a mixer to produce sum and difference frequencies of two signal sources.**
>
> In this experiment the flame rectifier is used as a mixer. A mixer is a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. See IDS Cite *30* (Horowitz).
>
> One type of mixer is a four-quadrant multiplier. For example, if you multiply two sine wave signals:
>
> $$\sin(\omega 1t) * \sin(\omega 2t) \qquad \text{Equation 1}$$
>
> and use a well known trigonometric identity you get:
>
> $$½ * \cos(\omega 1 - \omega 2)t - ½ * \cos(\omega 1 + \omega 2)t \qquad \text{Equation 2}$$

The trigonometric identity is:

$$\sin(u) * \sin(v) = 1/2 [ \cos(u - v) - \cos(u + v)]$$

which is:

$$\sin(u) * \sin(v) = 1/2 * \cos(u - v) - 1/2 * \cos(u + v)]$$

See **Appendix 1** under - **Product Formulas**

That is why a mixer (multiplier) produces the two signals: the sum of the two frequencies and the difference between the two frequencies.

What may not be so obvious is that when a single sine wave is presented to a mixer (multiplier) this formula still applies but both sin(ω1t) and sin(ω2t) are the same. The result is:

$$\sin(\omega t) * \sin(\omega t) = ½ * \cos[(\omega - \omega)t] - ½ * \cos[(\omega + \omega)t]$$

$$= ½ * \cos(0t) - ½ * \cos[(\omega + \omega)t]$$

1. cos(0t) = 1
2. The quantity (ω + ω) = 2 * ω

Therefore:

$$\sin(\omega t) * \sin(\omega t) = ½ - ½ * \cos[(2 * \omega)t]$$

Thus, the result is a DC term and a component at twice the frequency of ω, which is the second harmonic of ω.

That is why Flame Rectification causes harmonic distortion of a single selected signal. It is the same process by which Flame Rectification causes two selected signals to mix, producing the two signals: the sum of the two frequencies and the difference between the two frequencies.

These species are obvious variants of each other and are so intimately related that no separate search should be necessary.

**B.** In one species Flame Rectification causes harmonic distortion of a selected signal. This harmonic signal is detected to prove the existence of a flame. In the other species Flame Rectification causes two selected signals to mix (multiply) producing two signals: the sum of the two frequencies of the two signals and the difference between the frequencies of the two signals. Since it only requires the detection of either the sum or difference of the two frequencies it only requires one of signals be detected to prove flame.

The methods used to detect either the harmonic of the single selected signal in species 1 or either the sum or difference signal produced in species 2 are the same.

| | |
|---|---|
| Independent Claim 1 (Apparatus Claim) - Flame Rectification causes harmonic distortion of a single signal. | Independent Claim 6 (Apparatus Claim) - Flame Rectification causes two selected signals to mix, producing sum and differences signals. |
| Dependent Claim 3 - The harmonic is detected using a phase locked loop. | Dependent Claim 7 - The signal detector comprises a phase locked loop tuned to said first mixing frequency or to said second mixing frequency. |
| Dependent claim 4 - A master clock produces the selected signal and a reference signal at the frequency of the harmonic. A synchronous detector uses the reference signal to detect the harmonic produced by Flame Rectification. | Dependent Claim 8 - A master clock produces the two selected signals and a reference signal at the frequency of either the sum or difference frequencies of the two selected signals. A synchronous detector uses the reference signal to detect either the sum or difference signal produced by Flame Rectification. |
| Dependent Claim 5 - Also uses a master clock but produces two reference signals 90 degrees out of phase so that a quadrature detector can be used. | Dependent Claim 9 - Also uses a master clock but produces two reference signals 90 degrees out of phase so that a quadrature detector can be used. |

| | |
|---|---|
| Independent Claim 12 (Method Claim) - Flame Rectification causes harmonic distortion of a single signal. | Independent Claim 15 (Method Claim) - Flame Rectification causes two selected signals to mix, producing sum and differences signals. |
| Dependent Claim 13 (Method Claim) - The harmonic is detected by providing a phase locked loop. | Dependent Claim 16 (Method Claim) - The signal is detected by providing a phase locked loop tuned to said first mixing frequency or to said second mixing frequency. |
| Dependent Claim 14 (Method Claim) - A Master Clock is provided so the harmonic signal is detected using either a simple synchronous detector or a quadrature detector. | Dependent Claim 17 (Method Claim) - A Master Clock is provided so the signal is detected using either a simple synchronous detector or a quadrature detector. |

Since the methods used to detect either the harmonic of the single selected signal in species 1 or either the sum or difference signal produced in species 2 are the same, no separate search should be necessary.

## Conclusion

Flame Rectification causes harmonic distortion of a single selected signal. It is the same process by which Flame Rectification causes two selected signals to mix, producing the two signals: the sum of the two frequencies and the difference between the two frequencies.

These species are obvious variants of each other and are so intimately related that no separate search should be necessary.

The methods used to detect either the harmonic of the single selected signal in species 1 or either the sum or difference signal produced in species 2 are the same.

The theory and practice of the use of mixers is well known to those persons having ordinary skill in the art of communications engineering. It is the use of flame rectification as a mixer to unambiguously detect the presence of a flame that is new, non-obvious, and useful.

For the above reasons Applicant respectfully requests reconsideration and withdrawal of the requirement for restriction/election.

**Appendix 1**

from http://web.mit.edu/wwmath/trig/identities02.html

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**Useful Trigonometric Identities**

This page is meant to be used as reference listing of useful trigonometric identities. No discussion of the proofs or the consequences of these identities will be give here.

---

## Pythagorean Identities

$$\sin^2(x) + \cos^2(x) = 1$$
$$1 + \tan^2(x) = \sec^2(x)$$
$$1 + \cot^2(x) = \csc^2(x)$$

---

## Addition Formulas

$$\sin(u+v) = \sin(u)\,\cos(v) + \cos(u)\,\sin(v)$$
$$\cos(u+v) = \cos(u)\,\cos(v) - \sin(u)\sin(v)$$
$$\tan(u+v) = \frac{\tan(u) + \tan(v)}{1 - \tan(u)\,\tan(v)}$$

---

## Subtraction formulas

$$\sin(u-v) = \sin(u)\,\cos(v) - \cos(u)\,\sin(v)$$
$$\cos(u-v) = \cos(u)\,\cos(v) + \sin(u)\sin(v)$$
$$\tan(u-v) = \frac{\tan(u) - \tan(v)}{1 + \tan(u)\,\tan(v)}$$

---

## Double Angle Formulas

$$\sin(2t) = 2\sin(t)\cos(t)$$
$$\cos(2t) = \cos^2(t) - \sin^2(t)$$
$$= 2\cos^2(t) - 1$$
$$= 1 - 2\sin^2(t)$$
$$\tan(2t) = \frac{2\tan(t)}{1 - \tan^2(t)}$$

---

## Half-Angle Formulas

$$\sin\left(\frac{u}{2}\right) = \sqrt{\frac{1-\cos(u)}{2}}$$
$$\cos\left(\frac{u}{2}\right) = \sqrt{\frac{1+\cos(u)}{2}}$$
$$\tan\left(\frac{u}{2}\right) = \sqrt{\frac{1-\cos(u)}{1+\cos(u)}}$$

---

## Product Formulas

$$\sin(u)\cos(v) = \frac{1}{2}\left[\sin(u+v) + \sin(u-v)\right]$$
$$\sin(u)\sin(v) = \frac{1}{2}\left[\cos(u-v) - \cos(u+v)\right]$$
$$\cos(u)\cos(v) = \frac{1}{2}\left[\cos(u+v) + \cos(u-v)\right]$$

---

**Factoring Formulas**

$$\sin(u) + \sin(v) = 2\sin\left(\frac{u+v}{2}\right)\cos\left(\frac{u-v}{2}\right)$$
$$\sin(u) - \sin(v) = 2\sin\left(\frac{u-v}{2}\right)\cos\left(\frac{u+v}{2}\right)$$
$$\cos(u) + \cos(v) = 2\cos\left(\frac{u+v}{2}\right)\cos\left(\frac{u-v}{2}\right)$$
$$\cos(u) - \cos(v) = 2\sin\left(\frac{v+u}{2}\right)\sin\left(\frac{v-u}{2}\right)$$

The following two formulas are of only limited use:

$$\cos(u) + \sin(v) = \left[\cos\left(\frac{u-v}{2}\right) - \sin\left(\frac{u-v}{2}\right)\right]\left[\cos\left(\frac{u+v}{2}\right) + \sin\left(\frac{u+v}{2}\right)\right]$$
$$\cos(u) - \sin(v) = \left[\cos\left(\frac{u+v}{2}\right) - \sin\left(\frac{u+v}{2}\right)\right]\left[\cos\left(\frac{u-v}{2}\right) + \sin\left(\frac{u-v}{2}\right)\right]$$

---

Back to the Trigonometry page | Back to the World Web Math Categories Page

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*watko@mit.edu*
Last modified August 1, 1998

# Exhibit 3

Exhibit 3

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
**United States Patent and Trademark Office**
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

23497 7590 01/19/2017
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| EXAMINER | |
|---|---|
| WU, ZHEN Y | |

| ART UNIT | PAPER NUMBER |
|---|---|
| 2685 | |

| MAIL DATE | DELIVERY MODE |
|---|---|
| 01/19/2017 | PAPER |

**Please find below and/or attached an Office communication concerning this application or proceeding.**

The time period for reply, if any, is set in the attached communication.

| *Office Action Summary* | **Application No.** 14/316,489 | **Applicant(s)** MARGOLIN, JED | |
|---|---|---|---|
| | **Examiner** ZHEN Y. WU | **Art Unit** 2685 | **AIA (First Inventor to File) Status** Yes |

***-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --***

**Period for Reply**

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE *3* MONTHS FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

**Status**

1)☒ Responsive to communication(s) filed on *11/04/2016*.

☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

**Disposition of Claims***

5)☒ Claim(s) *1-18* is/are pending in the application.

5a) Of the above claim(s) *6-11 and 15-18* is/are withdrawn from consideration.

6)☐ Claim(s) _____ is/are allowed.

7)☒ Claim(s) *1-3 and 12-14* is/are rejected.

8)☒ Claim(s) *4 and 5* is/are objected to.

9)☐ Claim(s) _____ are subject to restriction and/or election requirement.

* If any claims have been determined allowable, you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

**Application Papers**

10)☐ The specification is objected to by the Examiner.

11)☒ The drawing(s) filed on *06/26/2014* is/are: a)☒ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

**Priority under 35 U.S.C. § 119**

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

**Certified copies:**

a)☐ All b)☐ Some** c)☐ None of the:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

** See the attached detailed Office action for a list of the certified copies not received.

**Attachment(s)**

1) ☒ Notice of References Cited (PTO-892)

2) ☒ Information Disclosure Statement(s) (PTO/SB/08a and/or PTO/SB/08b) Paper No(s)/Mail Date _____.

3) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

4) ☐ Other: _____.

## DETAILED ACTION

### AIA Status

The present application, filed on or after March 16, 2013, is being examined under the first inventor to file provisions of the AIA.

### *Priority*

Application claims priority to a provisional application 62/005,199 filed on 05/30/2014.

### Response to Election / Restriction

Examiner acknowledges the applicant's election of claims 1-5 and 12-14 for review. Examiner acknowledges the applicant's conditionally withdrawn of non-elected claims 6-11 and 15-18 with traverse.

### Claim Status

Claims 1-5 and 12-14 are currently pending for examination and non-elected claims 6-11 and 15-18 are withdrawn from consideration.

### *Claim Rejections - 35 USC § 103*

In the event the determination of the status of the application as subject to AIA 35 U.S.C. 102 and 103 (or as subject to pre-AIA 35 U.S.C. 102 and 103) is incorrect, any correction of the statutory basis for the rejection will not be considered a new ground of rejection if the prior art relied upon, and the rationale supporting the rejection, would be the same under either status.

The following is a quotation of 35 U.S.C. 103 which forms the basis for all obviousness rejections set forth in this Office action:

> A patent for a claimed invention may not be obtained, notwithstanding that the claimed invention is not identically disclosed as set forth in section 102, if the differences between the claimed invention and the prior art are such that the claimed invention as a whole would have been obvious before the effective filing date of the claimed invention to a person having ordinary skill in the art to which the claimed invention pertains. Patentability shall not be negated by the manner in which the invention was made.

The factual inquiries set forth in *Graham v. John Deere Co.*, 383 U.S. 1, 148 USPQ 459 (1966), that are applied for establishing a background for determining obviousness under 35 U.S.C. 103 are summarized as follows:

1. Determining the scope and contents of the prior art.
2. Ascertaining the differences between the prior art and the claims at issue.
3. Resolving the level of ordinary skill in the pertinent art.
4. Considering objective evidence present in the application indicating obviousness or nonobviousness.

Claims 1, 2 and 12 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1).

<u>Regarding claim 1,</u> Haupenthal (383) teaches **a system for detecting the presence of a flame comprising:**

**a. a combustion burner** (Fig. 1);

**b. a flame rod** (Fig. 1, ionization electrodes 3);

**c. a signal source having a selected waveform connected to said flame rod** (Fig. 1, signal source having an ac waveform is connected to the electrode);

**d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame** (Fig. 1, and Col. 4, lines 36-50, "Ionization electrodes 3 or ultraviolet sensors 4,4a are supplied by way of a connecting terminal 1 with the ac voltage signal from a suitable source 5 and supply the signal which is generated by the flame and on which an unwanted alternating current signal is superimposed to the terminal 2 at which an evaluation circuit 6, here a filter member, detects the direct current signal I.sub.F.");

**e. a signal detector having an input connected to the output of said high impedance buffer** (Fig. 1, evaluation circuit 6);

**f. an indicator connected to the output of said signal detector** (Abstract "The direct current signal (I.sub.F) is detected by an evaluation circuit (6) and converted into a first output signal (A), wherein conversion is effected by various further circuit elements (7, 9, 10) in such a way that differently changing output signals (A.sub.1, A.sub.2) are obtained depending on the respective flame intensity.". Indicate the intensity of the flame);

**whereas**

**g. said flame from said combustion burner causes distortion of said signal source having a selected waveform producing a a** distorted **signal** (Fig. 5, Col. 7 lines 18-28, "The uppermost diagram shows the direct current signal I.sub.F on which the alternating current signal is superimposed, in which case the alternating current signal is only shown in part for the sake of enhanced clarity.". The ac source signal is distorted by the direct current generated by the flame)**, and**

**h. said signal detector is configured to detect said** distorted **signal and indicate the results on said indicator** (Fig. 5. Col. 7 line 29-43, detect flame intensity according to the dc component of the superimposed waveform)**.**

Haupenthal (383) teaches a flame monitoring system that detects flame intensity according to the dc current generated by the flame superimposed on the ac source signal instead of the **harmonic** distortion of the ac source signal.

However, in the same field of flame monitoring system, Haupenthal (486) teaches a system that detects the harmonic frequency signal by the flame. See Abstract, "A frequency-selective arrangement (6, 17, 18, 19) detects the presence of mains frequency-harmonic signals in the flame signal (U.sub.1) and activates the flame signal amplifier (40) when there are no mains frequency-harmonic signals in the flame signal (U.sub.1) and deactivates the flame signal amplifier (40) when there is a flame signal (U.sub.1) with periodic signals or no flames signal (U.sub.1) or a test signal (T).”.

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)’s evaluation circuit with Haupenthal (486)’s harmonic detection system to detect harmonic distortion to accurately detect the presence of a flame.

Regarding claim 2, Haupenthal (383) in the combination teaches **the system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave** (Fig. 1, ac voltage source. The ac voltage source is low distortion compare to the superimposed voltage)**.**

Regarding claim 12, recite limitation similar to claim 1. Therefore, claim 12 is rejected with the same rationale and claim 1.

Claims 3, 13 and 14 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 A1).

Regarding claim 3, Haupenthal (486) in the combination teaches **the system of claim 1 whereby said harmonic signal detector comprises** a detectors to detect harmonic but fails to expressly teach **a phase locked loop tuned to the frequency of said harmonic signal.**

However, in the same field of harmonic detection system, Ngo teaches a phase locked loop that is tuned to a harmonic frequency. See para [0005], "Based on an input reference signal, a digital frequency multiplier circuit utilizes a voltage controlled oscillator (VCO), which is tuned to a harmonic of the input frequency signal, along with a frequency divider and a phase-locked loop (PLL) to generate a desired output frequency.".

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (486)'s harmonic detector with Ngo's phase locked loop to detect a desired harmonic frequency that would accurately detect the presence of a flame.

Regarding claim 13, recite limitation similar to claim 3. Therefore, claim 13 is rejected with the same rationale and claim 3.

Regarding claim 14, the combination teaches **the method of claim 12** but fails to teach **where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.**

However, in the same field of harmonic detection system, Ngo teaches an external clock signal and a control circuit to align the internal signal with external clock signal. See Abstract, “The DCO generates an internal feedback signal. The phase detector detects a phase difference between the internal feedback signal and an external reference clock signal. Coupled between the phase detector and the DCO, the control circuit adjusts the DCO to align the internal feedback signal with the external reference clock signal after a phase difference between the internal feedback signal and the external reference clock signal has been detected.”.

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)’s harmonic detector with a clock and a synchronous detector to synchronous various signals to produce an accurate result.

***Allowable Subject Matter***

Claims 4 and 5 objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

The following is a statement of reasons for the indication of allowable subject matter: dependent claims 4 and 5 are indicated to be allowable as the prior art does not teach or fairly suggest the applicant’s claimed invention. The distinguishing elements of the claim 4 "**a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising: a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal; b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.**" and claim 5 "**a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising: a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal; b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal; c. a first absolute value amp having an input connected to the output of said first multiplier; d. a second absolute value amp having an input connected to the output of said second multiplier; e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp; f. a threshold detector having an input connected to the**

**output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.**" are allowable subject matter. The various claimed limitations mentioned in the claims are not taught or suggested by the prior art taken either singly or in combination, with emphasize that it is each claim, taken as a whole, including the interrelationships and interconnections between parent claims and various claimed elements make them allowable over the prior art of record.

## *Conclusion*

Any inquiry concerning this communication or earlier communications from the examiner should be directed to ZHEN Y. WU whose telephone number is (571)272-5711. The examiner can normally be reached on Monday to Friday, 8AM - 5PM, Alternate Friday, EST.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Hai Phan can be reached on (571) - 272-6338. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a

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/ZHEN Y WU/
Examiner, Art Unit 2685

| *Notice of References Cited* | Application/Control No. 14/316,489 | Applicant(s)/Patent Under Reexamination MARGOLIN, JED | |
|---|---|---|---|
| | Examiner ZHEN Y. WU | Art Unit 2685 | Page 1 of 1 |

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| | L | US- | | | | |
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| *Index of Claims* | Application/Control No.<br>14316489 | Applicant(s)/Patent Under Reexamination<br>MARGOLIN, JED |
|---|---|---|
| | Examiner<br>ZHEN Y WU | Art Unit<br>2685 |

| ✓ | Rejected | - | Cancelled | N | Non-Elected | A | Appeal |
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| = | Allowed | ÷ | Restricted | I | Interference | O | Objected |

☐ Claims renumbered in the same order as presented by applicant ☐ CPA ☐ T.D. ☐ R.1.47

| CLAIM | | DATE | | | | | | | | |
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| Final | Original | 01/17/2017 | | | | | | | | |
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| Search Notes | Application/Control No. | Applicant(s)/Patent Under Reexamination |
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| | 14316489 | MARGOLIN, JED |
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## CPC- SEARCHED

| Symbol | Date | Examiner |
|---|---|---|
| F23N5/123 | 1/17/2017 | ZYW |
| G08B17/125 | 1/17/2017 | ZYW |
| F23N2023/10 F23N2023/42 | 1/17/2017 | ZYW |

## CPC COMBINATION SETS - SEARCHED

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## US CLASSIFICATION SEARCHED

| Class | Subclass | Date | Examiner |
|---|---|---|---|
| 340 | 577 | 1/17/2017 | ZYW |

## SEARCH NOTES

| Search Notes | Date | Examiner |
|---|---|---|
| All CPC and USPC classifications listed were searched in combination with keywords in EAST | 1/17/2017 | ZYW |
| Inventor and assignee searches double patenting | 1/17/2017 | ZYW |
| NPL searches (eg. Google, Google scholar) | 1/17/2017 | ZYW |
| Consulted with SPE Hai Phan with claim and allowable subject matter | 1/17/2017 | ZYW |

## INTERFERENCE SEARCH

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| 14/316,489 | 06/26/2014<br>**RULE** | 340 | 2685 | |

**APPLICANTS**

**INVENTORS**
Jed Margolin, VC Highlands, NV;

** **CONTINUING DATA** *************************
This appln claims benefit of 62/005,199 05/30/2014

** **FOREIGN APPLICATIONS** *************************

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07/09/2014

| Foreign Priority claimed ☐ Yes ☑ No<br>35 USC 119(a-d) conditions met ☐ Yes ☑ No<br>Verified and Acknowledged /ZHEN Y WU/ Examiner's Signature | ☐ Met after Allowance<br>Initials | STATE OR COUNTRY | SHEETS DRAWINGS | TOTAL CLAIMS | INDEPENDENT CLAIMS |
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| | | NV | 66 | 18 | 5 |

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RENO, NV 89521-7430
UNITED STATES

**TITLE**

Flame Sensing System

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Sheet 1 of 4

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| Application Number | |
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| First Named Inventor | Jed Margolin |
| Art Unit | |
| Examiner Name | |
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| | | | | **Filing Date** | |
| | | | | **First Named Inventor** | Jed Margolin |
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**EAST Search History**

**EAST Search History (Prior Art)**

| Ref # | Hits | Search Query | DBs | Default Operator | Plurals | Time Stamp |
|---|---|---|---|---|---|---|
| S2 | 1 | (Margolin near jed).in. and (flame with burner).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 16:05 |
| S4 | 23 | ("1077628" \| "1688126" \| "2112736" \| "2136256" \| "2709799" \| "2804608" \| "3301307" \| "3956080" \| "0307031" \| "4082493" \| "4317487" \| "6404342" \| "8310801" \| "0803684").PN. | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 16:13 |
| S6 | 3 | detect$3 near8 harmonic near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:20 |
| S7 | 89 | sens$3 near4 (resistance or resistivit$3) near4 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:20 |
| S8 | 2 | (sens$3 or detect$3) with harmonic with distortion with flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:21 |
| S9 | 2 | harmonic near distortion near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S10 | 2 | harmonic near distortion near8 flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S11 | 3 | harmonic near distortion near8 fire | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S12 | 14399 | signal with flame | US-PGPUB; USPAT; | AND | ON | 2016/09/26 22:31 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| | | | USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S13 | 256 | two near2 signals with flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:31 |
| S14 | 38 | two near2 signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:32 |
| S15 | 94 | appl$3 with signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:36 |
| S16 | 59 | appl$3 near8 signals near8 flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:37 |
| S17 | 3255 | 340/577.ccls. F23N5/123 G08B17/125 F23N2023/10 F23N2023/42 | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:49 |
| S19 | 23 | ("1077628" \| "1688126" \| "2112736" \| "2136256" \| "2709799" \| "2804608" \| "3301307" \| "3956080" \| "0307031" \| "4082493" \| "4317487" \| "6404342" \| "8310801" \| "0803684").PN. | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 12:50 |
| S20 | 2 | S19 and harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 12:51 |
| S21 | 1 | S17 and harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:52 |
| S22 | 430 | harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:52 |
| S23 | 84 | (detect$3 or determin$3) with harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:53 |
| S24 | 23 | (detect$3 or determin$3) with harmonic near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:53 |
| S25 | 4183 | (detect$3 or determin$3) with current near6 (flame or fire) | US-PGPUB; USPAT; | OR | ON | 2017/01/13 12:58 |

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|---|---|---|---|---|---|---|
| | | | USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S26 | 734 | (detect$3 or determin$3) with electric with current near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:58 |
| S27 | 446 | (detect$3 or determin$3) with electric near3 current near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:58 |
| S28 | 102 | (detect$3 or determin$3) with electric near3 current near6 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 12:59 |
| S29 | 328 | signal with flame near rod | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:13 |
| S30 | 231 | signal near6 flame near rod | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:13 |
| S31 | 100 | signal near6 flame near rod | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:13 |
| S32 | 2 | signal near6 flame near rod and harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:13 |
| S33 | 3970 | (detect$3 or determin$3) with resistance with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:17 |
| S34 | 615356 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) ang harmonic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:17 |
| S35 | 11 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) and harmonic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:17 |
| S36 | 1720 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; | OR | ON | 2017/01/13 13:18 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| | | | IBM_TDB | | | |
| S37 | 379 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:19 |
| S38 | 296 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:19 |
| S39 | 1015 | (detect$3 or determin$3) near6 resistance near3 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:22 |
| S40 | 632 | (detect$3 or determin$3) near6 resistance near3 (flame) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:23 |
| S41 | 488 | (determin$3) near6 resistance near3 (flame) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:23 |
| S42 | 598 | (measur$3) near6 resistance near3 (flame) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:29 |
| S43 | 154 | (measur$3) near6 resistance near3 (flame) and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:30 |
| S44 | 729056 | ionization near3 current nera3 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:34 |
| S45 | 149 | ionization near3 current near3 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:34 |
| S46 | 1 | flame near rod with ionization near electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:20 |
| S47 | 458 | flame near rod electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:21 |
| S48 | 230 | flame near rod with electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:21 |
| S49 | 0 | flame near rod with ionic with electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:21 |
| S50 | 230 | flame near rod with electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; | AND | ON | 2017/01/13 15:21 |

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|---|---|---|---|---|---|---|
| | | | DERWENT; IBM_TDB | | | |
| S51 | 116 | flame near rod with electrodes | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 15:21 |
| S52 | 121142 | phase near locked near loop | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S53 | 54609 | phase near locked near loop with frequency | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S54 | 0 | phase near locked near loop with frequency with harmoic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S55 | 591 | phase near locked near loop with frequency with harmonic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S56 | 370 | phase near locked near loop with frequency with harmonic | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:20 |
| S57 | 1 | phase near locked near loop with frequency with harmonic and burner | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:21 |
| S58 | 51 | phase near locked near loop and burner | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:21 |
| S59 | 4 | phase near locked near loop with frequency with harmonic with turned | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:25 |
| S60 | 23 | phase near locked near loop with frequency with harmonic with tuned | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:25 |
| S61 | 1 | harmonic near detector with clock with synchronous | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:49 |
| S62 | 5 | harmonic near4 detector with clock with synchronous | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:49 |

**EAST Search History (Interference)**

Exhibits 48

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**1/17/2017 1:03:25 PM**
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Exhibits 49

# Exhibit 4

Exhibit 4

# Shockley diode equation

From Wikipedia, the free encyclopedia

The ***Shockley diode equation*** or the *diode law*, named after transistor co-inventor William Shockley of Bell Telephone Laboratories, gives the I–V (current-voltage) characteristic of an idealized diode in either forward or reverse bias (applied voltage):

$$I = I_\mathrm{S} \left( e^{\frac{V_\mathrm{D}}{n V_\mathrm{T}}} - 1 \right)$$

where

- $I$ is the diode current,
- $I_\mathrm{S}$ is the reverse bias saturation current (or scale current),
- $V_\mathrm{D}$ is the voltage across the diode,
- $V_\mathrm{T}$ is the thermal voltage $kT/q$ (Boltzmann constant times temperature divided by electron charge), and
- $n$ is the *ideality factor*, also known as the *quality factor* or sometimes *emission coefficient*.

The equation is called the *Shockley ideal diode equation* when $n$, the ideality factor, is set equal to 1. The ideality factor $n$ typically varies from 1 to 2 (though can in some cases be higher), depending on the fabrication process and semiconductor material and is set equal to 1 for the case of an "ideal" diode (thus the n is sometimes omitted). The ideality factor was added to account for imperfect junctions as observed in real transistors. The factor mainly accounts for carrier recombination as the charge carriers cross the depletion region.

The thermal voltage $V_\mathrm{T}$ is approximately 25.85 mV at 300 K, a temperature close to "room temperature" commonly used in device simulation software. At any temperature it is a known constant defined by:

$$V_\mathrm{T} = \frac{kT}{q},$$

where $k$ is the Boltzmann constant, $T$ is the absolute temperature of the p–n junction, and $q$ is the magnitude of charge of an electron (the elementary charge).

The reverse saturation current, $I_\mathrm{S}$, is not constant for a given device, but varies with temperature; usually more significantly than $V_\mathrm{T}$, so that $V_\mathrm{D}$ typically decreases as $T$ increases.

The Shockley diode equation doesn't describe the "leveling off" of the I–V curve at high forward bias due to internal resistance. This can be taken into account by adding a resistance in series.

Under *reverse bias* (when the n side is put at a more positive voltage than the p side) the exponential term in the diode equation is near zero and the current is near a constant (negative) reverse current value of $-I_S$. The reverse *breakdown region* is not modeled by the Shockley diode equation.

For even rather small *forward bias* voltages the exponential is very large, since the thermal voltage is very small in comparison. The subtracted '1' in the diode equation is then negligible and the forward diode current can be approximated by

$$I = I_\mathrm{S} e^{\frac{V_\mathrm{D}}{n V_\mathrm{T}}}$$

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The use of the diode equation in circuit problems is illustrated in the article on diode modeling.

# Derivation

Shockley derives an equation for the voltage across a p-n junction in a long article published in 1949.[1] Later he gives a corresponding equation for current as a function of voltage under additional assumptions, which is the equation we call the Shockley ideal diode equation.[2] He calls it "a theoretical rectification formula giving the maximum rectification", with a footnote referencing a paper by Carl Wagner, *Physikalische Zeitschrift* **32**, pp. 641–645 (1931).

To derive his equation for the voltage, Shockley argues that the total voltage drop can be divided into three parts:

- the drop of the quasi-Fermi level of holes from the level of the applied voltage at the p terminal to its value at the point where doping is neutral (which we may call the junction)
- the difference between the quasi-Fermi level of the holes at the junction and that of the electrons at the junction
- the drop of the quasi-Fermi level of the electrons from the junction to the n terminal.

He shows that the first and the third of these can be expressed as a resistance times the current, $R_1 I$. As for the second, the difference between the quasi-Fermi levels at the junction, he says that we can estimate the current flowing through the diode from this difference. He points out that the current at the p terminal is all holes, whereas at the n terminal it is all electrons, and the sum of these two is the constant total current. So the total current is equal to the decrease in hole current from one side of the diode to the other. This decrease is due to an excess of recombination of electron-hole pairs over generation of electron-hole pairs. The rate of recombination is equal to the rate of generation when at equilibrium, that is, when the two quasi-Fermi levels are equal. But when the quasi-Fermi levels are not equal, then the recombination rate is $\exp((\phi_p - \phi_n)/V_T)$ times the rate of generation. We then assume that most of the excess recombination (or decrease in hole current) takes place in a layer going by one hole diffusion length ($L_p$) into the n material and one electron diffusion length ($L_n$) into the p material, and that the difference between the quasi-Fermi levels is constant in this layer at $V_J$. Then we find that the total current, or the drop in hole current, is

$$I = I_s[e^{V_J/V_T} - 1]$$

where

$$I_s = gq(L_p + L_n)$$

and $g$ is the generation rate. We can solve for $V_J$ in terms of $I$:

$$V_J = V_T \ln\left(1 + \frac{I}{I_s}\right)$$

and the total voltage drop is then

$$V = IR_1 + V_T \ln\left(1 + \frac{I}{I_s}\right).$$

When we assume that $R_1$ is small, we obtain $V = V_J$ and the Shockley ideal diode equation.

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The small current that flows under high reverse bias is then the result of thermal generation of electron-hole pairs in the layer. The electrons then flow to the n terminal and the holes to the p terminal. The concentrations of electrons and holes in the layer is so small that recombination there is negligible.

In 1950 Shockley and coworkers published a short article describing a germanium diode that closely followed the ideal equation.[3]

In 1954, Bill Pfann and W. van Roosbroek (who were also of Bell Telephone Laboratories) reported that while Shockley's equation was applicable to certain germanium junctions, for many silicon junctions the current (under appreciable forward bias) was proportional to $e^{V_J/(AV_T)}$, with $A$ having a value as high as 2 or 3.[4] This is the "ideality factor" called *n* above.

In 1981, Alexis de Vos and Herman Pauwels showed that a more careful analysis of the quantum mechanics of a junction, under certain assumptions, gives a current versus voltage characteristic of the form

$$I(V) = -q[F_i - 2F_o(V)]$$

in which $F_i$ is the number of in-coming photons per unit area with energy over the band-gap energy, and $F_o(V)$ is out-going photons, given by[5]

$$F_o(V) = \int_{\nu_g}^{\infty} \frac{1}{\exp\left(\frac{h\nu - qV}{kT_c}\right) - 1} \frac{2\pi\nu^2}{c^2} d\nu.$$

Although this analysis was done for photovoltaic cells under illumination, it applies also when the illumination is simply background thermal radiation. It gives a more rigorous form of expression for ideal diodes in general, except that it assumes that the cell is thick enough that it can produce this flux of photons. When the illumination is just background thermal radiation, the characteristic is

$$I(V) = 2q[F_o(V) - F_o(0)]$$

Note that, in contrast to the Shockley law, the current goes to infinity as the voltage goes to the gap voltage $h\nu_g/q$. This of course would require an infinite thickness to provide an infinite amount of recombination.

# References

1. William Shockley (Jul 1949). "The Theory of *p-n* Junctions in Semiconductors and *p-n* Junction Transistors". *The Bell System Technical Journal*. **28** (3): 435–489.. Equation 3.13 on page 454.
2. *Ibid.* p. 456.
3. F.S. Goucher; et al. (Dec 1950). "Theory and Experiment for a Germanium p-n Junction". *Physical Review*. doi:10.1103/PhysRev.81.637.2.
4. W. G. Pfann; W. van Roosbroek (Nov 1954). "Radioactive and Photoelectric p-n Junction Power Sources". *Journal of Applied Physics*. **25** (11): 1422–1434. doi:10.1063/1.1721579.
5. A. De Vos and H. Pauwels (1981). "On the Thermodynamic Limit of Photovoltaic Energy Conversion". *Appl. Phys.* **25**: 119–125. doi:10.1007/BF00901283.. Appendix.



Categories: Diodes | Equations

- This page was last modified on 13 June 2016, at 12:37.
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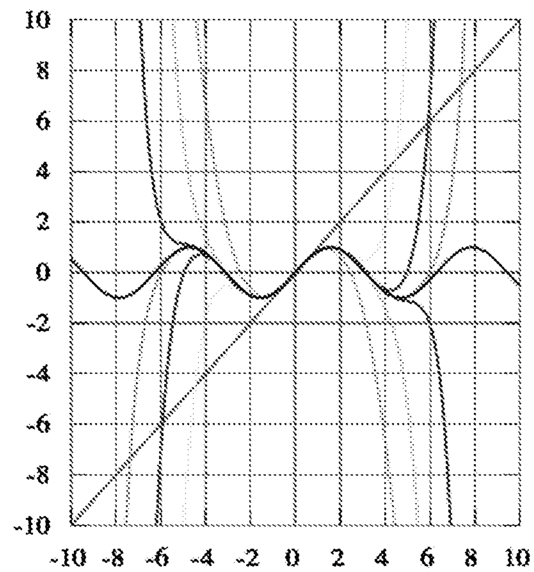
# Exhibit 5

Exhibit 5

# Taylor series

From Wikipedia, the free encyclopedia

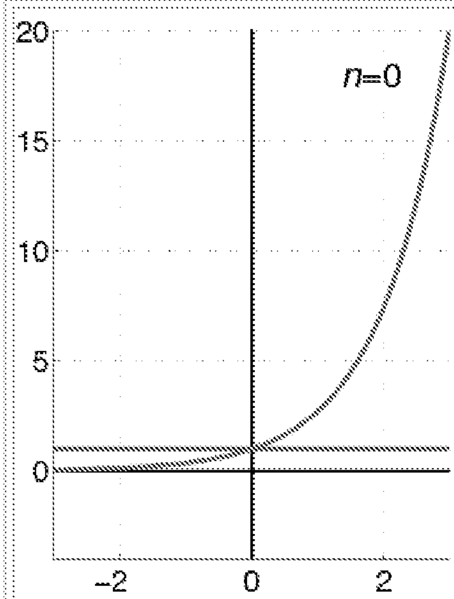
In mathematics, a **Taylor series** is a representation of a function as an infinite sum of terms that are calculated from the values of the function's derivatives at a single point.




As the degree of the Taylor polynomial rises, it approaches the correct function. This image shows $\sin x$ and its Taylor approximations, polynomials of degree 1, 3, , 7, 9, 11 and 13.

The concept of a Taylor series was formulated by the Scottish mathematician James Gregory and formally introduced by the English mathematician Brook Taylor in 1715. If the Taylor series is centered at zero, then that series is also called a **Maclaurin series**, named after the Scottish mathematician Colin Maclaurin, who made extensive use of this special case of Taylor series in the 18th century.

A function can be approximated by using a finite number of terms of its Taylor series. Taylor's theorem gives quantitative estimates on the error introduced by the use of such an approximation. The polynomial formed by taking some initial terms of the Taylor series is called a Taylor polynomial. The Taylor series of a function is the limit of that function's Taylor polynomials as the degree increases, provided that the limit exists. A function may not be equal to its Taylor series, even if its Taylor series converges at every point. A function that is equal to its Taylor series in an open interval (or a disc in the complex plane) is known as an analytic function in that interval.




The exponential function $e^x$ (in blue), and the sum of the first $n + 1$ terms of its Taylor series at 0 (in red).

## Contents

# Definition

The Taylor series of a real or complex-valued function $f(x)$ that is infinitely differentiable at a real or complex number $a$ is the power series

$$f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \cdots.$$

which can be written in the more compact sigma notation as

$$\sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!}(x-a)^n$$

where $n!$ denotes the factorial of $n$ and $f^{(n)}(a)$ denotes the $n$th derivative of $f$ evaluated at the point $a$. The derivative of order zero of $f$ is defined to be $f$ itself and $(x-a)^0$ and $0!$ are both defined to be 1. When $a = 0$, the series is also called a Maclaurin series.

# Examples

The Maclaurin series for any polynomial is the polynomial itself.

The Maclaurin series for $\frac{1}{1-x}$ is the geometric series

$$1 + x + x^2 + x^3 + \cdots$$

so the Taylor series for $\frac{1}{x}$ at $a = 1$ is

$$1 - (x-1) + (x-1)^2 - (x-1)^3 + \cdots.$$

By integrating the above Maclaurin series, we find the Maclaurin series for $\log(1-x)$, where log denotes the natural logarithm:

$$-x - \tfrac{1}{2}x^2 - \tfrac{1}{3}x^3 - \tfrac{1}{4}x^4 - \cdots$$

and the corresponding Taylor series for $\log x$ at $a = 1$ is

$$(x-1) - \tfrac{1}{2}(x-1)^2 + \tfrac{1}{3}(x-1)^3 - \tfrac{1}{4}(x-1)^4 + \cdots,$$

and more generally, the corresponding Taylor series for $\log x$ at some $a = x_0$ is:

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$$\log(x_0) + \frac{1}{x_0}(x - x_0) - \frac{1}{x_0^2}\frac{(x - x_0)^2}{2} + \cdots.$$

The Taylor series for the exponential function $e^x$ at $a = 0$ is

$$\frac{x^0}{0!} + \frac{x^1}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \frac{x^5}{5!} + \cdots = 1 + x + \frac{x^2}{2} + \frac{x^3}{6} + \frac{x^4}{24} + \frac{x^5}{120} + \cdots = \sum_{n=0}^{\infty} \frac{x^n}{n!}.$$

The above expansion holds because the derivative of $e^x$ with respect to $x$ is also $e^x$ and $e^0$ equals 1. This leaves the terms $(x - 0)^n$ in the numerator and $n!$ in the denominator for each term in the infinite sum.

# History

The Greek philosopher Zeno considered the problem of summing an infinite series to achieve a finite result, but rejected it as an impossibility: the result was Zeno's paradox. Later, Aristotle proposed a philosophical resolution of the paradox, but the mathematical content was apparently unresolved until taken up by Archimedes, as it had been prior to Aristotle by the Presocratic Atomist Democritus. It was through Archimedes's method of exhaustion that an infinite number of progressive subdivisions could be performed to achieve a finite result.[1] Liu Hui independently employed a similar method a few centuries later.[2]

In the 14th century, the earliest examples of the use of Taylor series and closely related methods were given by Madhava of Sangamagrama.[3][4] Though no record of his work survives, writings of later Indian mathematicians suggest that he found a number of special cases of the Taylor series, including those for the trigonometric functions of sine, cosine, tangent, and arctangent. The Kerala school of astronomy and mathematics further expanded his works with various series expansions and rational approximations until the 16th century.

In the 17th century, James Gregory also worked in this area and published several Maclaurin series. It was not until 1715 however that a general method for constructing these series for all functions for which they exist was finally provided by Brook Taylor,[5] after whom the series are now named.

The Maclaurin series was named after Colin Maclaurin, a professor in Edinburgh, who published the special case of the Taylor result in the 18th century.

# Analytic functions

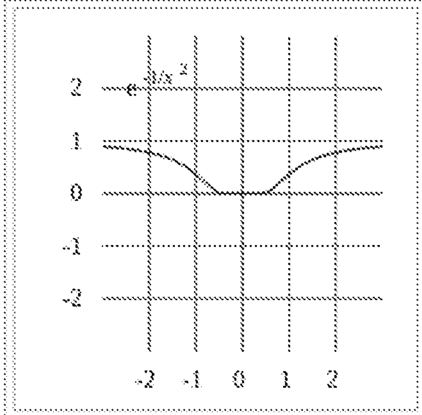
If $f(x)$ is given by a convergent power series in an open disc (or interval in the real line) centered at $b$ in the complex plane, it is said to be analytic in this disc. Thus for $x$ in this disc, $f$ is given by a convergent power series

$$f(x) = \sum_{n=0}^{\infty} a_n (x - b)^n.$$

Differentiating by $x$ the above formula $n$ times, then setting $x = b$ gives:

$$\frac{f^{(n)}(b)}{n!} = a_n$$

and so the power series expansion agrees with the Taylor series. Thus a function is analytic in an open disc centered at $b$ if and only if its Taylor series converges to the value of the function at each point of the disc.




The function $e^{-1/x^2}$ is not analytic at $x = 0$: the Taylor series is identically 0, although the function is not.

If $f(x)$ is equal to its Taylor series for all $x$ in the complex plane, it is called entire. The polynomials, exponential function $e^x$, and the trigonometric functions sine and cosine, are examples of entire functions. Examples of functions that are not entire include the square root, the logarithm, the trigonometric function tangent, and its inverse, arctan. For these functions the Taylor series do not converge if $x$ is far from $b$. That is, the Taylor series diverges at $x$ if the distance between $x$ and $b$ is larger than the radius of convergence. The Taylor series can be used to calculate the value of an entire function at every point, if the value of the function, and of all of its derivatives, are known at a single point.

Uses of the Taylor series for analytic functions include:

1. The partial sums (the Taylor polynomials) of the series can be used as approximations of the entire function. These approximations are good if sufficiently many terms are included.
2. Differentiation and integration of power series can be performed term by term and is hence particularly easy.
3. An analytic function is uniquely extended to a holomorphic function on an open disk in the complex plane. This makes the machinery of complex analysis available.
4. The (truncated) series can be used to compute function values numerically, (often by recasting the polynomial into the Chebyshev form and evaluating it with the Clenshaw algorithm).
5. Algebraic operations can be done readily on the power series representation; for instance, Euler's formula follows from Taylor series expansions for trigonometric and exponential functions. This result is of fundamental importance in such fields as harmonic analysis.
6. Approximations using the first few terms of a Taylor series can make otherwise unsolvable problems possible for a restricted domain; this approach is often used in physics.

# Approximation and convergence

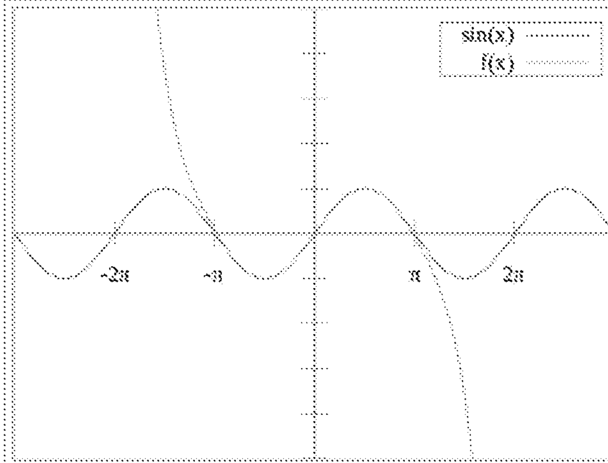
Pictured on the right is an accurate approximation of $\sin x$ around the point $x = 0$. The pink curve is a polynomial of degree seven:

$$\sin(x) \approx x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!}.$$

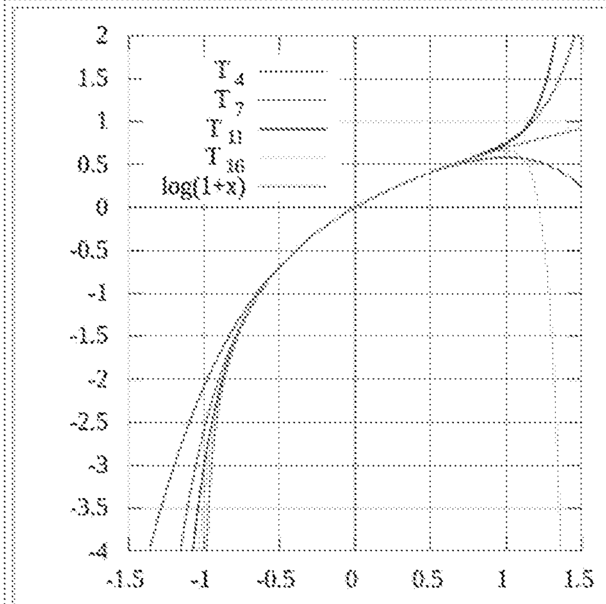
The error in this approximation is no more than $\frac{|x|^9}{9!}$. In particular, for $-1 < x < 1$, the error is less than 0.000003.

In contrast, also shown is a picture of the natural logarithm function $\log(1 + x)$ and some of its Taylor polynomials around $a = 0$. These approximations converge to the function only in the region $-1 < x \leq 1$; outside of this region the higher-degree Taylor polynomials are *worse* approximations for the function. This is similar to Runge's phenomenon.

The *error* incurred in approximating a function by its $n$th-degree Taylor polynomial is called the *remainder* or *residual* and is denoted by the function $R_n(x)$. Taylor's theorem can be used to obtain a bound on the size of the remainder.




The sine function (blue) is closely approximated by its Taylor polynomial of degree 7 (pink) for a full period centered at the origin.




The Taylor polynomials for $\log(1+x)$ only provide accurate approximations in the range $-1 < x \leq 1$. Note that, for $x > 1$, the Taylor polynomials of higher degree are ***worse*** approximations.

In general, Taylor series need not be convergent at all. And in fact the set of functions with a convergent Taylor series is a meager set in the Fréchet space of smooth functions. And even if the Taylor series of a function $f$ does converge, its limit need not in general be equal to the value of the function $f(x)$. For example, the function

$$f(x) = \begin{cases} e^{-\frac{1}{x^2}} & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$$

is infinitely differentiable at $x = 0$, and has all derivatives zero there. Consequently, the Taylor series of $f(x)$ about $x = 0$ is identically zero. However, $f(x)$ is not the zero function, so does not equal its Taylor series around the origin. Thus, $f(x)$ is an example of a non-analytic smooth function.

In real analysis, this example shows that there are infinitely differentiable functions $f(x)$ whose Taylor series are *not* equal to $f(x)$ even if they converge. By contrast, the holomorphic functions studied in complex analysis always possess a convergent Taylor series, and even the Taylor series of meromorphic functions, which might have singularities, never converge to a value different from the function itself. The complex function $e^{-1/z^2}$, however, does not approach 0 when $z$ approaches 0 along the imaginary axis, so it is not continuous in the complex plane and its Taylor series is undefined at 0.

More generally, every sequence of real or complex numbers can appear as coefficients in the Taylor series of an infinitely differentiable function defined on the real line, a consequence of Borel's lemma. As a result, the radius of convergence of a Taylor series can be zero. There are even infinitely differentiable functions defined on the real line whose Taylor series have a radius of convergence 0 everywhere.[6]

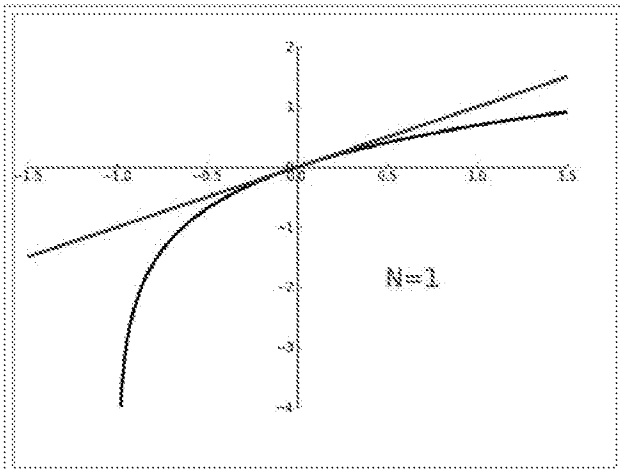
Some functions cannot be written as Taylor series because they have a singularity; in these cases, one can often still achieve a series expansion if one allows also negative powers of the variable $x$; see Laurent series. For example, $f(x) = e^{-1/x^2}$ can be written as a Laurent series.

## Generalization

There is, however, a generalization[7][8] of the Taylor series that does converge to the value of the function itself for any bounded continuous function on $(0,\infty)$, using the calculus of finite differences. Specifically, one has the following theorem, due to Einar Hille, that for any $t > 0$,

$$\lim_{h\to 0^+}\sum_{n=0}^{\infty}\frac{t^n}{n!}\frac{\Delta_h^n f(a)}{h^n} = f(a+t).$$

Here $\Delta_h^n$ is the $n$th finite difference operator with step size $h$. The series is precisely the Taylor series, except that divided differences appear in place of differentiation: the series is formally similar to the Newton series. When the function $f$ is analytic at $a$, the terms in the series converge to the terms of the Taylor series, and in this sense generalizes the usual Taylor series.




The Taylor approximations for $\log(1 + x)$ (black). For $x > 1$, the approximations diverge.

In general, for any infinite sequence $a_i$, the following power series identity holds:

$$\sum_{n=0}^{\infty}\frac{u^n}{n!}\Delta^n a_i = e^{-u}\sum_{j=0}^{\infty}\frac{u^j}{j!}a_{i+j}.$$

So in particular,

$$f(a+t) = \lim_{h\to 0^+} e^{-\frac{t}{h}}\sum_{j=0}^{\infty} f(a+jh)\frac{\left(\frac{t}{h}\right)^j}{j!}.$$

The series on the right is the expectation value of $f(a + X)$, where $X$ is a Poisson-distributed random variable that takes the value $jh$ with probability $e^{-t/h}\cdot\frac{(t/h)^j}{j!}$. Hence,

$$f(a+t) = \lim_{h\to 0^+}\int_{-\infty}^{\infty} f(a+x)dP_{\frac{t}{h},h}(x).$$

The law of large numbers implies that the identity holds.[9]

# List of Maclaurin series of some common functions

Several important Maclaurin series expansions follow.[10] All these expansions are valid for complex arguments $x$.

Exponential function:

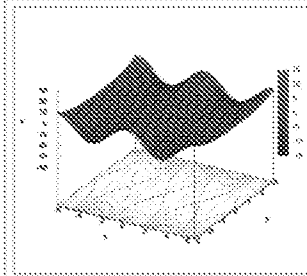
$$e^x = \sum_{n=0}^{\infty}\frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \quad \text{for all } x$$

Exhibits 61

Natural logarithm:

$$\log(1-x) = -\sum_{n=1}^{\infty} \frac{x^n}{n} = -x - \frac{x^2}{2} - \frac{x^3}{3} - \cdots \qquad \text{for } |x| < 1$$

$$\log(1+x) = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{x^n}{n} = x - \frac{x^2}{2} + \frac{x^3}{3} - \cdots \qquad \text{for } |x| < 1$$



The real part of the cosine function in the complex plane

Geometric series and its derivatives (see article for variants):

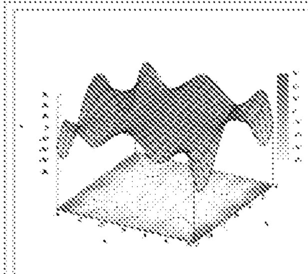
$$\frac{1}{1-x} = \sum_{n=0}^{\infty} x^n \qquad \text{for } |x| < 1$$

$$\frac{1}{(1-x)^2} = \sum_{n=1}^{\infty} n x^{n-1} \qquad \text{for } |x| < 1$$

$$\frac{x}{(1-x)^2} = \sum_{n=1}^{\infty} n x^{n} \qquad \text{for } |x| < 1$$

$$\frac{2}{(1-x)^3} = \sum_{n=2}^{\infty} (n-1) n x^{n-2} \qquad \text{for } |x| < 1$$

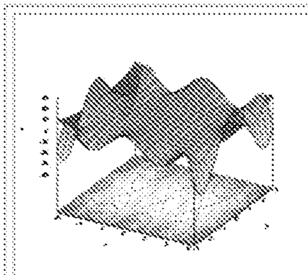
$$\frac{2x^2}{(1-x)^3} = \sum_{n=0}^{\infty} (n-1) n x^{n} \qquad \text{for } |x| < 1$$



An 8th-degree approximation of the cosine function in the complex plane

Binomial series (includes the square root for $\alpha = \frac{1}{2}$ and the infinite geometric series for $\alpha = -1$):

$$(1+x)^\alpha = \sum_{n=0}^{\infty} \binom{\alpha}{n} x^n \qquad \text{for all } |x| < 1 \text{ and all complex } \alpha$$



The two above curves put together

with generalized binomial coefficients

$$\binom{\alpha}{n} = \prod_{k=1}^{n} \frac{\alpha - k + 1}{k} = \frac{\alpha(\alpha-1)\cdots(\alpha-n+1)}{n!}.$$

For instance, with the first several terms written out explicitly for the common square root cases, is:

$$(1+x)^{\frac{1}{2}} = 1 + \tfrac{1}{2}x - \tfrac{1}{8}x^2 + \tfrac{1}{16}x^3 - \tfrac{5}{128}x^4 + \tfrac{7}{256}x^5 - \cdots$$

$$(1+x)^{-\frac{1}{2}} = 1 - \tfrac{1}{2}x + \tfrac{3}{8}x^2 - \tfrac{5}{16}x^3 + \tfrac{35}{128}x^4 - \tfrac{63}{256}x^5 + \cdots$$

Trigonometric functions:

$$\sin x = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)!} x^{2n+1} = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \cdots \quad \text{for all } x$$

$$\cos x = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n)!} x^{2n} = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \cdots \quad \text{for all } x$$

$$\tan x = \sum_{n=1}^{\infty} \frac{B_{2n}(-4)^n\left(1-4^n\right)}{(2n)!} x^{2n-1} = x + \frac{x^3}{3} + \frac{2x^5}{15} + \cdots \quad \text{for } |x| < \frac{\pi}{2}$$

$$\sec x = \sum_{n=0}^{\infty} \frac{(-1)^n E_{2n}}{(2n)!} x^{2n} \quad \text{for } |x| < \frac{\pi}{2}$$

$$\arcsin x = \sum_{n=0}^{\infty} \frac{(2n)!}{4^n (n!)^2 (2n+1)} x^{2n+1} \quad \text{for } |x| \le 1$$

$$\arccos x = \frac{\pi}{2} - \arcsin x$$
$$= \frac{\pi}{2} - \sum_{n=0}^{\infty} \frac{(2n)!}{4^n (n!)^2 (2n+1)} x^{2n+1} \quad \text{for } |x| \le 1$$

$$\arctan x = \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} x^{2n+1} \quad \text{for } |x| \le 1,\ x \ne \pm$$

Hyperbolic functions:

$$\sinh x = \sum_{n=0}^{\infty} \frac{x^{2n+1}}{(2n+1)!} = x + \frac{x^3}{3!} + \frac{x^5}{5!} + \cdots \quad \text{for all } x$$

$$\cosh x = \sum_{n=0}^{\infty} \frac{x^{2n}}{(2n)!} = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \cdots \quad \text{for all } x$$

$$\tanh x = \sum_{n=1}^{\infty} \frac{B_{2n}4^n\left(4^n-1\right)}{(2n)!} x^{2n-1} = x - \frac{x^3}{3} + \frac{2x^5}{15} - \frac{17x^7}{315} + \cdots \quad \text{for } |x| < \frac{\pi}{2}$$

$$\operatorname{arsinh} x = \sum_{n=0}^{\infty} \frac{(-1)^n (2n)!}{4^n (n!)^2 (2n+1)} x^{2n+1} \quad \text{for } |x| \le 1$$

$$\operatorname{artanh} x = \sum_{n=0}^{\infty} \frac{x^{2n+1}}{2n+1} \quad \text{for } |x| \le 1,\ x$$

The numbers $B_k$ appearing in the *summation* expansions of $\tan x$ and $\tanh x$ are the Bernoulli numbers. The $E_k$ in the expansion of $\sec x$ are Euler numbers.

# Calculation of Taylor series

Several methods exist for the calculation of Taylor series of a large number of functions. One can attempt to use the definition of the Taylor series, though this often requires generalizing the form of the coefficients according to a readily apparent pattern. Alternatively, one can use manipulations such as substitution, multiplication or division, addition or subtraction of standard Taylor series to construct the Taylor series of a function, by virtue of Taylor series being power series. In some cases, one can also derive the Taylor series by repeatedly applying integration by parts. Particularly convenient is the use of computer algebra systems to calculate Taylor series.

## First example

In order to compute the 7th degree Maclaurin polynomial for the function

$$f(x) = \log(\cos x), \quad x \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right),$$

one may first rewrite the function as

$$f(x) = \log\bigl(1 + (\cos x - 1)\bigr).$$

The Taylor series for the natural logarithm is (using the big O notation)

$$\log(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} + O\left(x^4\right)$$

and for the cosine function

$$\cos x - 1 = -\frac{x^2}{2} + \frac{x^4}{24} - \frac{x^6}{720} + O\left(x^8\right).$$

The latter series expansion has a zero constant term, which enables us to substitute the second series into the first one and to easily omit terms of higher order than the 7th degree by using the big $O$ notation:

$$\begin{aligned} f(x) &= \log\bigl(1 + (\cos x - 1)\bigr) \\ &= (\cos x - 1) - \tfrac{1}{2}(\cos x - 1)^2 + \tfrac{1}{3}(\cos x - 1)^3 + O\left((\cos x - 1)^4\right) \\ &= \left(-\frac{x^2}{2} + \frac{x^4}{24} - \frac{x^6}{720} + O\left(x^8\right)\right) - \frac{1}{2}\left(-\frac{x^2}{2} + \frac{x^4}{24} + O\left(x^6\right)\right)^2 + \frac{1}{3}\left(-\frac{x^2}{2} + O\left(x^4\right)\right)^3 \\ &= -\frac{x^2}{2} + \frac{x^4}{24} - \frac{x^6}{720} - \frac{x^4}{8} + \frac{x^6}{48} - \frac{x^6}{24} + O\left(x^8\right) \\ &= -\frac{x^2}{2} - \frac{x^4}{12} - \frac{x^6}{45} + O\left(x^8\right). \end{aligned}$$

Since the cosine is an even function, the coefficients for all the odd powers $x$, $x^3$, $x^5$, $x^7$, ... have to be zero.

## Second example

Suppose we want the Taylor series at 0 of the function

$$g(x) = \frac{e^x}{\cos x}.$$

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We have for the exponential function

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots$$

and, as in the first example,

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \cdots$$

Assume the power series is

$$\frac{e^x}{\cos x} = c_0 + c_1 x + c_2 x^2 + c_3 x^3 + \cdots$$

Then multiplication with the denominator and substitution of the series of the cosine yields

$$\begin{aligned} e^x &= \left(c_0 + c_1 x + c_2 x^2 + c_3 x^3 + \cdots\right) \cos x \\ &= \left(c_0 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 x^4 + \cdots\right) \left(1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \cdots\right) \\ &= c_0 - \frac{c_0}{2} x^2 + \frac{c_0}{4!} x^4 + c_1 x - \frac{c_1}{2} x^3 + \frac{c_1}{4!} x^5 + c_2 x^2 - \frac{c_2}{2} x^4 + \frac{c_2}{4!} x^6 + c_3 x^3 - \frac{c_3}{2} x^5 + \frac{c_3}{4!} x \end{aligned}$$

Collecting the terms up to fourth order yields

$$e^x = c_0 + c_1 x + \left(c_2 - \frac{c_0}{2}\right) x^2 + \left(c_3 - \frac{c_1}{2}\right) x^3 + \left(c_4 - \frac{c_2}{2} + \frac{c_0}{4!}\right) x^4 + \cdots$$

Comparing coefficients with the above series of the exponential function yields the desired Taylor series

$$\frac{e^x}{\cos x} = 1 + x + x^2 + \frac{2x^3}{3} + \frac{x^4}{2} + \cdots.$$

## Third example

Here we employ a method called "indirect expansion" to expand the given function. This method uses the known Taylor expansion of the exponential function. In order to expand $(1 + x)e^x$ as a Taylor series in $x$, we use the known Taylor series of function $e^x$:

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots.$$

Thus,

Exhibits 65

$$\begin{aligned}(1+x)e^x &= e^x + xe^x = \sum_{n=0}^{\infty}\frac{x^n}{n!} + \sum_{n=0}^{\infty}\frac{x^{n+1}}{n!} = 1 + \sum_{n=1}^{\infty}\frac{x^n}{n!} + \sum_{n=0}^{\infty}\frac{x^{n+1}}{n!}\\ &= 1 + \sum_{n=1}^{\infty}\frac{x^n}{n!} + \sum_{n=1}^{\infty}\frac{x^n}{(n-1)!} = 1 + \sum_{n=1}^{\infty}\left(\frac{1}{n!} + \frac{1}{(n-1)!}\right)x^n\\ &= 1 + \sum_{n=1}^{\infty}\frac{n+1}{n!}x^n\\ &= \sum_{n=0}^{\infty}\frac{n+1}{n!}x^n.\end{aligned}$$

# Taylor series as definitions

Classically, algebraic functions are defined by an algebraic equation, and transcendental functions (including those discussed above) are defined by some property that holds for them, such as a differential equation. For example, the exponential function is the function which is equal to its own derivative everywhere, and assumes the value 1 at the origin. However, one may equally well define an analytic function by its Taylor series.

Taylor series are used to define functions and "operators" in diverse areas of mathematics. In particular, this is true in areas where the classical definitions of functions break down. For example, using Taylor series, one may define analytical functions of matrices and operators, such as the matrix exponential or matrix logarithm.

In other areas, such as formal analysis, it is more convenient to work directly with the power series themselves. Thus one may define a solution of a differential equation *as* a power series which, one hopes to prove, is the Taylor series of the desired solution.

# Taylor series in several variables

The Taylor series may also be generalized to functions of more than one variable with[11][12]

$$\begin{aligned}T(x_1,\dots,x_d) &= \sum_{n_1=0}^{\infty}\cdots\sum_{n_d=0}^{\infty}\frac{(x_1-a_1)^{n_1}\cdots(x_d-a_d)^{n_d}}{n_1!\cdots n_d!}\left(\frac{\partial^{n_1+\cdots+n_d}f}{\partial x_1^{n_1}\cdots\partial x_d^{n_d}}\right)(a_1,\dots,a_d)\\ &= f(a_1,\dots,a_d) + \sum_{j=1}^{d}\frac{\partial f(a_1,\dots,a_d)}{\partial x_j}(x_j-a_j) + \frac{1}{2!}\sum_{j=1}^{d}\sum_{k=1}^{d}\frac{\partial^2 f(a_1,\dots,a_d)}{\partial x_j\partial x_k}(x\\ &\quad + \frac{1}{3!}\sum_{j=1}^{d}\sum_{k=1}^{d}\sum_{l=1}^{d}\frac{\partial^3 f(a_1,\dots,a_d)}{\partial x_j\partial x_k\partial x_l}(x_j-a_j)(x_k-a_k)(x_l-a_l)+\cdots\end{aligned}$$

For example, for a function that depends on two variables, $x$ and $y$, the Taylor series to second order about the point $(a, b)$ is

$$f(a,b) + (x-a)f_x(a,b) + (y-b)f_y(a,b) + \frac{1}{2!}\Big((x-a)^2 f_{xx}(a,b) + 2(x-a)(y-b)f_{xy}(a,b) +$$

where the subscripts denote the respective partial derivatives.

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A second-order Taylor series expansion of a scalar-valued function of more than one variable can be written compactly as

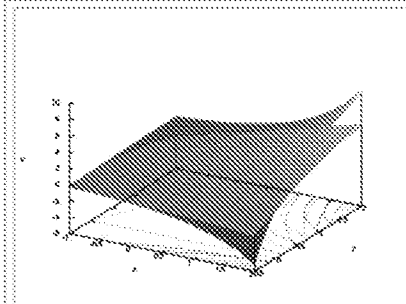
$$T(\mathbf{x}) = f(\mathbf{a}) + (\mathbf{x}-\mathbf{a})^\mathsf{T} Df(\mathbf{a}) + \frac{1}{2!}(\mathbf{x}-\mathbf{a})^\mathsf{T} \left\{D^2 f(\mathbf{a})\right\} (\mathbf{x}-\mathbf{a}) + \cdots,$$

where $Df(\mathbf{a})$ is the gradient of $f$ evaluated at $\mathbf{x} = \mathbf{a}$ and $D^2 f(\mathbf{a})$ is the Hessian matrix. Applying the multi-index notation the Taylor series for several variables becomes

$$T(\mathbf{x}) = \sum_{|\alpha|\geqslant 0} \frac{(\mathbf{x}-\mathbf{a})^\alpha}{\alpha!} (\partial^\alpha f)(\mathbf{a}),$$

which is to be understood as a still more abbreviated multi-index version of the first equation of this paragraph, again in full analogy to the single variable case.

## Example



Second-order Taylor series approximation (in orange) of a function $f(x,y) = e^x \log(1 + y)$ around the origin.

In order to compute a second-order Taylor series expansion around point $(a, b) = (0, 0)$ of the function

$$f(x,y) = e^x \log(1+y),$$

one first computes all the necessary partial derivatives:

$$\begin{aligned} f_x &= e^x \log(1+y) \\ f_y &= \frac{e^x}{1+y} \\ f_{xx} &= e^x \log(1+y) \\ f_{yy} &= -\frac{e^x}{(1+y)^2} \\ f_{xy} &= f_{yx} = \frac{e^x}{1+y}. \end{aligned}$$

Evaluating these derivatives at the origin gives the Taylor coefficients

$$\begin{aligned} f_x(0,0) &= 0 \\ f_y(0,0) &= 1 \\ f_{xx}(0,0) &= 0 \\ f_{yy}(0,0) &= -1 \\ f_{xy}(0,0) &= f_{yx}(0,0) = 1. \end{aligned}$$

Substituting these values in to the general formula

$$T(x,y) = f(a,b) + (x-a)f_x(a,b) + (y-b)f_y(a,b) + \frac{1}{2!}\Big((x-a)^2 f_{xx}(a,b) + 2(x-a)(y-b)$$

produces

$$\begin{aligned}T(x,y) &= 0 + 0(x-0) + 1(y-0) + \frac{1}{2}\Big(0(x-0)^2 + 2(x-0)(y-0) + (-1)(y-0)^2\Big) + \cdots \\ &= y + xy - \frac{y^2}{2} + \cdots\end{aligned}$$

Since $\log(1+y)$ is analytic in $|y| < 1$, we have

$$e^x \log(1+y) = y + xy - \frac{y^2}{2} + \cdots, \qquad |y| < 1.$$

# Comparison with Fourier series

The trigonometric Fourier series enables one to express a periodic function (or a function defined on a closed interval $[a,b]$) as an infinite sum of trigonometric functions (sines and cosines). In this sense, the Fourier series is analogous to Taylor series, since the latter allows one to express a function as an infinite sum of powers. Nevertheless, the two series differ from each other in several relevant issues:

- Obviously the finite truncations of the Taylor series of $f(x)$ about the point $x = a$ are all exactly equal to $f$ at $a$. In contrast, the Fourier series is computed by integrating over an entire interval, so there is generally no such point where all the finite truncations of the series are exact.
- Indeed, the computation of Taylor series requires the knowledge of the function on an arbitrary small neighbourhood of a point, whereas the computation of the Fourier series requires knowing the function on its whole domain interval. In a certain sense one could say that the Taylor series is "local" and the Fourier series is "global".
- The Taylor series is defined for a function which has infinitely many derivatives at a single point, whereas the Fourier series is defined for any integrable function. In particular, the function could be nowhere differentiable. (For example, $f(x)$ could be a Weierstrass function.)
- The convergence of both series has very different properties. Even if the Taylor series has positive convergence radius, the resulting series may not coincide with the function; but if the function is analytic then the series converges pointwise to the function, and uniformly on every compact subset of the convergence interval. Concerning the Fourier series, if the function is square-integrable then the series converges in quadratic mean, but additional requirements are needed to ensure the pointwise or uniform convergence (for instance, if the function is periodic and of class $C^1$ then the convergence is uniform).
- Finally, in practice one wants to approximate the function with a finite number of terms, say with a Taylor polynomial or a partial sum of the trigonometric series, respectively. In the case of the Taylor series the error is very small in a neighbourhood of the point where it is computed, while it may be very large at a distant point. In the case of the Fourier series the error is distributed along the domain of the function.

# See also

- Laurent series
- Madhava series
- Newton's divided difference interpolation
- Puiseux series
- Padé approximant

# Notes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- Madhava of Sangamagramma (http://www-groups.dcs.st-and.ac.uk/~history/Projects/Pearce/Chapters/Ch9_3.html)
- Taylor Series Representation Module by John H. Mathews (http://mathfaculty.fullerton.edu/mathews/c2003/TaylorSeriesMod.html)
- "Discussion of the Parker-Sochacki Method (http://csma31.csm.jmu.edu/physics/rudmin/ParkerSochacki.htm)"
- Another Taylor visualisation (http://stud3.tuwien.ac.at/~e0004876/taylor/Taylor_en.html) — where you can choose the point of the approximation and the number of derivatives
- Taylor series revisited for numerical methods (http://numericalmethods.eng.usf.edu/topics/taylor_series.html) at Numerical Methods for the STEM Undergraduate

(http://numericalmethods.eng.usf.edu)
- Cinderella 2: Taylor expansion (http://cinderella.de/files/HTMLDemos/2C02_Taylor.html)
- Taylor series (http://www.sosmath.com/calculus/tayser/tayser01/tayser01.html)
- Inverse trigonometric functions Taylor series (http://www.efunda.com/math/taylor_series/inverse_trig.cfm)



Categories: Real analysis | Complex analysis | Series expansions

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# Electronic Acknowledgement Receipt

| | |
|---|---|
| **EFS ID:** | 28159002 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 25-JAN-2017 |
| **Filing Date:** | 26-JUN-2014 |
| **Time Stamp:** | 10:35:42 |
| **Application Type:** | Utility under 35 USC 111(a) |

## Payment information:

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|---|---|
| Submitted with Payment | no |

## File Listing:

| Document Number | Document Description | File Name | File Size(Bytes)/ Message Digest | Multi Part /.zip | Pages (if appl.) |
|---|---|---|---|---|---|
| 1 | Petition for review by the Technology Center SPRE | jm_petition_2017_0125.pdf | 76888<br>7a07db894a1842ce0191c87a4dc5faf12cbf2ab5 | no | 6 |

**Warnings:**

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|---|---|---|---|---|---|
| **Information:** | | | | | |
| 2 | Petition for review by the Technology Center SPRE | jm_petition_exhibits.pdf | 3777075<br>68ecaff449137095859ae40c79755b82a5b7a8d6 | no | 70 |
| **Warnings:** | | | | | |
| **Information:** | | | | | |
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**New Applications Under 35 U.S.C. 111**
**If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.**

**National Stage of an International Application under 35 U.S.C. 371**
**If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.**

**New International Application Filed with the USPTO as a Receiving Office**
**If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.**

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| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

23497 7590 01/19/2017

JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

| EXAMINER | |
|---|---|
| WU, ZHEN Y | |

| ART UNIT | PAPER NUMBER |
|---|---|
| 2685 | |

| MAIL DATE | DELIVERY MODE |
|---|---|
| 01/19/2017 | PAPER |

**Please find below and/or attached an Office communication concerning this application or proceeding.**

The time period for reply, if any, is set in the attached communication.

| *Office Action Summary* | **Application No.** 14/316,489 | **Applicant(s)** MARGOLIN, JED | |
|---|---|---|---|
| | **Examiner** ZHEN Y. WU | **Art Unit** 2685 | **AIA (First Inventor to File) Status** Yes |

***-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --***

**Period for Reply**

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE _3_ MONTHS FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

**Status**

1)☒ Responsive to communication(s) filed on _11/04/2016_.

☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

**Disposition of Claims***

5)☒ Claim(s) _1-18_ is/are pending in the application.

5a) Of the above claim(s) _6-11 and 15-18_ is/are withdrawn from consideration.

6)☐ Claim(s) _____ is/are allowed.

7)☒ Claim(s) _1-3 and 12-14_ is/are rejected.

8)☒ Claim(s) _4 and 5_ is/are objected to.

9)☐ Claim(s) _____ are subject to restriction and/or election requirement.

* If any claims have been determined allowable, you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

**Application Papers**

10)☐ The specification is objected to by the Examiner.

11)☒ The drawing(s) filed on _06/26/2014_ is/are: a)☒ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

**Priority under 35 U.S.C. § 119**

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

**Certified copies:**

a)☐ All b)☐ Some** c)☐ None of the:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

** See the attached detailed Office action for a list of the certified copies not received.

**Attachment(s)**

1) ☒ Notice of References Cited (PTO-892)

2) ☒ Information Disclosure Statement(s) (PTO/SB/08a and/or PTO/SB/08b) Paper No(s)/Mail Date _____.

3) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

4) ☐ Other: _____.

## DETAILED ACTION

### AIA Status

The present application, filed on or after March 16, 2013, is being examined under the first inventor to file provisions of the AIA.

### *Priority*

Application claims priority to a provisional application 62/005,199 filed on 05/30/2014.

### Response to Election / Restriction

Examiner acknowledges the applicant's election of claims 1-5 and 12-14 for review. Examiner acknowledges the applicant's conditionally withdrawn of non-elected claims 6-11 and 15-18 with traverse.

### Claim Status

Claims 1-5 and 12-14 are currently pending for examination and non-elected claims 6-11 and 15-18 are withdrawn from consideration.

### *Claim Rejections - 35 USC § 103*

In the event the determination of the status of the application as subject to AIA 35 U.S.C. 102 and 103 (or as subject to pre-AIA 35 U.S.C. 102 and 103) is incorrect, any correction of the statutory basis for the rejection will not be considered a new ground of rejection if the prior art relied upon, and the rationale supporting the rejection, would be the same under either status.

The following is a quotation of 35 U.S.C. 103 which forms the basis for all obviousness rejections set forth in this Office action:

> A patent for a claimed invention may not be obtained, notwithstanding that the claimed invention is not identically disclosed as set forth in section 102, if the differences between the claimed invention and the prior art are such that the claimed invention as a whole would have been obvious before the effective filing date of the claimed invention to a person having ordinary skill in the art to which the claimed invention pertains. Patentability shall not be negated by the manner in which the invention was made.

The factual inquiries set forth in *Graham v. John Deere Co.*, 383 U.S. 1, 148 USPQ 459 (1966), that are applied for establishing a background for determining obviousness under 35 U.S.C. 103 are summarized as follows:

1. Determining the scope and contents of the prior art.
2. Ascertaining the differences between the prior art and the claims at issue.
3. Resolving the level of ordinary skill in the pertinent art.
4. Considering objective evidence present in the application indicating obviousness or nonobviousness.

Claims 1, 2 and 12 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1).

<u>Regarding claim 1,</u> Haupenthal (383) teaches **a system for detecting the presence of a flame comprising:**

**a. a combustion burner** (Fig. 1);

**b. a flame rod** (Fig. 1, ionization electrodes 3);

**c. a signal source having a selected waveform connected to said flame rod** (Fig. 1, signal source having an ac waveform is connected to the electrode);

**d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame** (Fig. 1, and Col. 4, lines 36-50, "Ionization electrodes 3 or ultraviolet sensors 4,4a are supplied by way of a connecting terminal 1 with the ac voltage signal from a suitable source 5 and supply the signal which is generated by the flame and on which an unwanted alternating current signal is superimposed to the terminal 2 at which an evaluation circuit 6, here a filter member, detects the direct current signal I.sub.F.");

**e. a signal detector having an input connected to the output of said high impedance buffer** (Fig. 1, evaluation circuit 6);

**f. an indicator connected to the output of said signal detector** (Abstract "The direct current signal (I.sub.F) is detected by an evaluation circuit (6) and converted into a first output signal (A), wherein conversion is effected by various further circuit elements (7, 9, 10) in such a way that differently changing output signals (A.sub.1, A.sub.2) are obtained depending on the respective flame intensity.". Indicate the intensity of the flame);

**whereas**

**g. said flame from said combustion burner causes distortion of said signal source having a selected waveform producing a a** distorted **signal** (Fig. 5, Col. 7 lines 18-28, “The uppermost diagram shows the direct current signal I.sub.F on which the alternating current signal is superimposed, in which case the alternating current signal is only shown in part for the sake of enhanced clarity.”. The ac source signal is distorted by the direct current generated by the flame)**, and**

**h. said signal detector is configured to detect said** distorted **signal and indicate the results on said indicator** (Fig. 5. Col. 7 line 29-43, detect flame intensity according to the dc component of the superimposed waveform)**.**

Haupenthal (383) teaches a flame monitoring system that detects flame intensity according to the dc current generated by the flame superimposed on the ac source signal instead of the **harmonic** distortion of the ac source signal.

However, in the same field of flame monitoring system, Haupenthal (486) teaches a system that detects the harmonic frequency signal by the flame. See Abstract, “A frequency-selective arrangement (6, 17, 18, 19) detects the presence of mains frequency-harmonic signals in the flame signal (U.sub.1) and activates the flame signal amplifier (40) when there are no mains frequency-harmonic signals in the flame signal (U.sub.1) and deactivates the flame signal amplifier (40) when there is a flame signal (U.sub.1) with periodic signals or no flames signal (U.sub.1) or a test signal (T).”.

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)’s evaluation circuit with Haupenthal (486)’s harmonic detection system to detect harmonic distortion to accurately detect the presence of a flame.

Regarding claim 2, Haupenthal (383) in the combination teaches **the system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave** (Fig. 1, ac voltage source. The ac voltage source is low distortion compare to the superimposed voltage)**.**

Regarding claim 12, recite limitation similar to claim 1. Therefore, claim 12 is rejected with the same rationale and claim 1.

Claims 3, 13 and 14 are rejected under 35 U.S.C. 103 as being unpatentable over Haupenthal (Pat. No.: US 6,501,383 B1) in view of Haupenthal (Pat. No.: US 6,486,486 B1) as applied to claim 1 and further in view of Ngo (Pub. No.: US 2008/0266000 A1).

Regarding claim 3, Haupenthal (486) in the combination teaches **the system of claim 1 whereby said harmonic signal detector comprises** a detectors to detect harmonic but fails to expressly teach **a phase locked loop tuned to the frequency of said harmonic signal.**

However, in the same field of harmonic detection system, Ngo teaches a phase locked loop that is tuned to a harmonic frequency. See para [0005], "Based on an input reference signal, a digital frequency multiplier circuit utilizes a voltage controlled oscillator (VCO), which is tuned to a harmonic of the input frequency signal, along with a frequency divider and a phase-locked loop (PLL) to generate a desired output frequency.".

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (486)'s harmonic detector with Ngo's phase locked loop to detect a desired harmonic frequency that would accurately detect the presence of a flame.

Regarding claim 13, recite limitation similar to claim 3. Therefore, claim 13 is rejected with the same rationale and claim 3.

Regarding claim 14, the combination teaches **the method of claim 12** but fails to teach **where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.**

However, in the same field of harmonic detection system, Ngo teaches an external clock signal and a control circuit to align the internal signal with external clock signal. See Abstract, “The DCO generates an internal feedback signal. The phase detector detects a phase difference between the internal feedback signal and an external reference clock signal. Coupled between the phase detector and the DCO, the control circuit adjusts the DCO to align the internal feedback signal with the external reference clock signal after a phase difference between the internal feedback signal and the external reference clock signal has been detected.”.

Therefore, it would have been obvious to a person having ordinary skill in the art before the effective filing date of the claimed invention to modify Haupenthal (383)’s harmonic detector with a clock and a synchronous detector to synchronous various signals to produce an accurate result.

***Allowable Subject Matter***

Claims 4 and 5 objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

The following is a statement of reasons for the indication of allowable subject matter: dependent claims 4 and 5 are indicated to be allowable as the prior art does not teach or fairly suggest the applicant’s claimed invention. The distinguishing elements of the claim 4 “**a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising: a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal; b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.**” and claim 5 “**a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising: a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal; b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal; c. a first absolute value amp having an input connected to the output of said first multiplier; d. a second absolute value amp having an input connected to the output of said second multiplier; e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp; f. a threshold detector having an input connected to the**

**output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.**" are allowable subject matter. The various claimed limitations mentioned in the claims are not taught or suggested by the prior art taken either singly or in combination, with emphasize that it is each claim, taken as a whole, including the interrelationships and interconnections between parent claims and various claimed elements make them allowable over the prior art of record.

### *Conclusion*

Any inquiry concerning this communication or earlier communications from the examiner should be directed to ZHEN Y. WU whose telephone number is (571)272-5711. The examiner can normally be reached on Monday to Friday, 8AM - 5PM, Alternate Friday, EST.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Hai Phan can be reached on (571) - 272-6338. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a

USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/ZHEN Y WU/
Examiner, Art Unit 2685

| *Notice of References Cited* | Application/Control No. 14/316,489 | Applicant(s)/Patent Under Reexamination MARGOLIN, JED | |
|---|---|---|---|
| | Examiner ZHEN Y. WU | Art Unit 2685 | Page 1 of 1 |

**U.S. PATENT DOCUMENTS**

| * | | Document Number Country Code-Number-Kind Code | Date MM-YYYY | Name | CPC Classification | US Classification |
|---|---|---|---|---|---|---|
| * | A | US-6,486,486 B1 | 11-2002 | Haupenthal; Karl-Friedrich | F23N5/082 | 250/554 |
| * | B | US-6,501,383 B1 | 12-2002 | Haupenthal; Karl-Friedrich | F23N5/123 | 340/577 |
| * | C | US-2008/0266000 A1 | 10-2008 | Ngo; Hung C. | H03L7/093 | 331/25 |
| | D | US- | | | | |
| | E | US- | | | | |
| | F | US- | | | | |
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**FOREIGN PATENT DOCUMENTS**

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**NON-PATENT DOCUMENTS**

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*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

| *Index of Claims* | Application/Control No.<br>14316489 | Applicant(s)/Patent Under Reexamination<br>MARGOLIN, JED |
|---|---|---|
| | Examiner<br>ZHEN Y WU | Art Unit<br>2685 |

| ✓ | Rejected | - | Cancelled | N | Non-Elected | A | Appeal |
|---|---|---|---|---|---|---|---|
| = | Allowed | ÷ | Restricted | I | Interference | O | Objected |

☐ Claims renumbered in the same order as presented by applicant ☐ CPA ☐ T.D. ☐ R.1.47

| CLAIM | | DATE | | | | | | | | |
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| Final | Original | 01/17/2017 | | | | | | | | |
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| | 17 | N | | | | | | | | |
| | 18 | N | | | | | | | | |

| Search Notes | Application/Control No. | Applicant(s)/Patent Under Reexamination |
|---|---|---|
| | 14316489 | MARGOLIN, JED |
| | **Examiner** | **Art Unit** |
| | ZHEN Y WU | 2685 |

## CPC- SEARCHED

| Symbol | Date | Examiner |
|---|---|---|
| F23N5/123 | 1/17/2017 | ZYW |
| G08B17/125 | 1/17/2017 | ZYW |
| F23N2023/10 F23N2023/42 | 1/17/2017 | ZYW |

## CPC COMBINATION SETS - SEARCHED

| Symbol | Date | Examiner |
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| | | |

## US CLASSIFICATION SEARCHED

| Class | Subclass | Date | Examiner |
|---|---|---|---|
| 340 | 577 | 1/17/2017 | ZYW |

## SEARCH NOTES

| Search Notes | Date | Examiner |
|---|---|---|
| All CPC and USPC classifications listed were searched in combination with keywords in EAST | 1/17/2017 | ZYW |
| Inventor and assignee searches double patenting | 1/17/2017 | ZYW |
| NPL searches (eg. Google, Google scholar) | 1/17/2017 | ZYW |
| Consulted with SPE Hai Phan with claim and allowable subject matter | 1/17/2017 | ZYW |

## INTERFERENCE SEARCH

| US Class/ CPC Symbol | US Subclass / CPC Group | Date | Examiner |
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| /ZHEN Y WU/<br>Examiner.Art Unit 2685 | |

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**CONFIRMATION NO. 1025**

| SERIAL NUMBER | FILING or 371(c) DATE | CLASS | GROUP ART UNIT | ATTORNEY DOCKET NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014<br>**RULE** | 340 | 2685 | |

**APPLICANTS**

**INVENTORS**
Jed Margolin, VC Highlands, NV;

** **CONTINUING DATA** *************************
This appln claims benefit of 62/005,199 05/30/2014

** **FOREIGN APPLICATIONS** *************************

** **IF REQUIRED, FOREIGN FILING LICENSE GRANTED** ** ** SMALL ENTITY **
07/09/2014

| Foreign Priority claimed ☐ Yes ☑ No<br>35 USC 119(a-d) conditions met ☐ Yes ☑ No<br>Verified and Acknowledged /ZHEN Y WU/ Examiner's Signature | ☐ Met after Allowance<br>Initials | STATE OR COUNTRY | SHEETS DRAWINGS | TOTAL CLAIMS | INDEPENDENT CLAIMS |
|---|---|---|---|---|---|
| | | NV | 66 | 18 | 5 |

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1981 EMPIRE ROAD
RENO, NV 89521-7430
UNITED STATES

**TITLE**

Flame Sensing System

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# INFORMATION DISCLOSURE STATEMENT BY APPLICANT

*(Use as many sheets as necessary)*

Sheet 1 of 4

| Complete if Known | |
|---|---|
| Application Number | |
| Filing Date | |
| First Named Inventor | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |

## U. S. PATENT DOCUMENTS

| Examiner Initials* | Cite No.[1] | Document Number<br>Number-Kind Code[2] (if known) | Publication Date MM-DD-YYYY | Name of Patentee or Applicant of Cited Document | Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear |
|---|---|---|---|---|---|
| | 1 | US- 1,688,126 | 10/16/1928 | Metcalfe | Fig 1; Page 3: 70–79 |
| | 2 | US- 2,112,736 | 03/29/1938 | Cockrell | Page 1:41– Page 2:15 |
| | 3 | US- 2,136,256 | 11/08/1938 | Sweet | Page 1:4–Page 2:2 |
| | 4 | US- 3,301,307 | 01/31/1967 | Kobayashi, et al. | Col 2: 3 -15 |
| | 5 | US- 4,082,493 | 04/04/1978 | Dahlgren | Fig 2; C3:32–42; Tbl:C3:20-30 |
| | 6 | US- 8,310,801 | 11/13/2012 | McDonald, et al. | Col 2: 10–44 |
| | 7 | US- 6,404,342 | 06/11/2002 | Planer, et al. | Col 1: 21–32 |
| | 16 | US- 4,317,487 | 03/02/1982 | Merkl | Col 2:59 – Col 3: 11 |
| | 19 | US- 307,031 | 10/21/1884 | Edison | Page 1:16–29 |
| | 20 | US- 803,684 | 11/07/1905 | Fleming | Page 1:11–37 |
| | 23 | US- 1,077,628 | 11/04/1913 | Mershon | Page 1:40-50 |
| | 27 | US- 3,956,080 | 05/11/1976 | Hradcovsky, et al. | Col 2: 10–48 |
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| | 34 | US- 2,804,608 | 08/27/1957 | Carbauh | |
| | | US- | | | |
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| Examiner Initials* | Cite No.[1] | Foreign Patent Document<br>Country Code[3]-Number[4]-Kind Code[5] (if known) | Publication Date MM-DD-YYYY | Name of Patentee or Applicant of Cited Document | Pages, Columns, Lines, Where Relevant Passages Or Relevant Figures Appear | T[6] |
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| Examiner Signature | /ZHEN Y WU/ | Date Considered | 01/17/2017 |
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Substitute for form 1449/PTO

# INFORMATION DISCLOSURE STATEMENT BY APPLICANT

*(Use as many sheets as necessary)*

Sheet 2 of 4

| *Complete if Known* | |
|---|---|
| **Application Number** | |
| **Filing Date** | |
| **First Named Inventor** | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |

**NON PATENT LITERATURE DOCUMENTS**

| Examiner Initials* | Cite No.[1] | Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published. | T[2] |
|---|---|---|---|
| | 8 | Prediction and Measurement of Electron Density and Collision Frequency in a Weakly Ionised Pine Fire; by MPHALE, MOHAN, and HERON; Int J Infrared Milli Waves (2007) 28:251-262; DOI 10.1007/s10762-007-9199-7; http://eprints.jcu.edu.au/2655/1/17300_Mphale_et_al_2007 | |
| | 9 | Conduction of Electricity Through Gases by J. J. THOMSON; Cambridge Cambridge University Press; 1903,1906; Chapter IX Ionization in Gases from Flames; page 228, PDF page 8; http://trove.nla.gov.au/goto?i=book&w=808233&d=http%3A%2F%2Fopenlibrary.org %2Fbooks%2FOL7102511M | |
| | 10 | About Plasmas from the Coalition For Plasma Science; Plasma and Flames - The Burning Question; http://www.plasmacoalition.org/plasma_writeups/flame.pdf | |
| | 11 | Plasma Fundamentals and Applications; by Dr. I.J. VAN DER WALT, Senior Scientist Necsa contains a chart (PDF page 8) http://www.nstf.org.za/ShowProperty?nodePath=/NSTF%20Repository/ NSTF/files/ScienceCouncils/2012/PlasmaFundamentals.pdf | |
| | 12 | Introduction to Combustion; by Stephen R. Turns, McGraw Hill Education (India); Page 108, PDF page 3; page 159, bottom of PDF page 5. | |
| | 13 | Burning Sulfur Compounds; Banks Engineering - Tulsa; http://www.banksengineering.com/Burning%20Sulfur%20Compounds.pdf | |

| Examiner Signature | /ZHEN Y WU/ | Date Considered | 01/17/2017 |
|---|---|---|---|

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PTO/SB/08b (07-09)
Approved for use through 07/31/2012. OMB 0651-0031
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# INFORMATION DISCLOSURE STATEMENT BY APPLICANT

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| **First Named Inventor** | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |

Sheet 3 of 4

## NON PATENT LITERATURE DOCUMENTS

| Examiner Initials* | Cite No.[1] | Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published. | T[2] |
|---|---|---|---|
| | 14 | Alkali metal halide, Wikipedia January 19, 2014; http://en.wikipedia.org/wiki/Alkali_metal_halide | |
| | 15 | Alkali Metal, Wikipedia January 19, 2014; http://en.wikipedia.org/wiki/Alkali_metal | |
| | 17 | Grades of Propane - Gas Purity and Quality http://www.propane101.com/propanegradesandquality.htm | |
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| | 21 | Definition of "Electrolyte" retrieved from Wikipedia 1/31/2014 http://en.wikipedia.org/wiki/Electrolyte | |
| | 22 | Dissertation Counter Electromotive Force in the Aluminum Rectifier; ALBERT LEWIS FITCH; Press of the New Era Printing Co.; Lancaster, Pa; 1917; Pages 15-17). | |
| | 24 | General Descriptions of Aluminum Electrolytic Capacitors, 1-1 Principles of Aluminum Electrolytic Capacitors' Nichicon; Page 1. http://www.nichicon.co.jp/english/products/pdf/aluminum.pdf | |

| Examiner Signature | /ZHEN Y WU/ | Date Considered | 01/17/2017 |
|---|---|---|---|

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Sheet 4 of 4

| Complete if Known | |
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| Application Number | |
| Filing Date | |
| First Named Inventor | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |

## NON PATENT LITERATURE DOCUMENTS

| Examiner Initials* | Cite No.[1] | Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published. | T[2] |
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| | 25 | Batteries and electrochemical capacitors; HECTOR D. ABRUNA, YASUKUKI KIYA, and JAY C. HENDERSON; Physics Today Physics Today December 2008, page 43-47 | |
| | 26 | Electroplating; from Wikipedia, retrieved 2/1/2014. http://en.wikipedia.org/wiki/Electroplating | |
| | 28 | Front pages from datasheets for 5U4GT, 5Y3GT, and 6X4/12X4 vacuum tube rectifiers. | |
| | 29 | Visual Analyzer 2011 XE Beta 0.3.2 - Visual Analyzer is a real time software program that contains a comprehensive set of measurement instruments, including an FFT Analyzer. It runs on a PC running Windows. http://www.sillanumsoft.org/ | |
| | 30 | The Art of Electronics, PAUL HOROWITZ and WINFIELD HILL, Cambridge University Press, 1991, pages 885-886. | |
| | 31 | Sine-Wave Oscillator, RON MANCINI and RICHARD PALMER, Texas Instruments, Application Note SLOA060 - March 2001; http://www.ti.com/litv/pdf/sloa060 | |
| | 32 | Datasheet for LM13700, Texas Instruments, Figure 37 Sinusoidal VCO. http://www.ti.com/cn/lit/gpn/lm13700 | |

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**EAST Search History**

**EAST Search History (Prior Art)**

| Ref # | Hits | Search Query | DBs | Default Operator | Plurals | Time Stamp |
|---|---|---|---|---|---|---|
| S2 | 1 | (Margolin near jed).in. and (flame with burner).clm. | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 16:05 |
| S4 | 23 | ("1077628" \| "1688126" \| "2112736" \| "2136256" \| "2709799" \| "2804608" \| "3301307" \| "3956080" \| "0307031" \| "4082493" \| "4317487" \| "6404342" \| "8310801" \| "0803684").PN. | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 16:13 |
| S6 | 3 | detect$3 near8 harmonic near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:20 |
| S7 | 89 | sens$3 near4 (resistance or resistivit$3) near4 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:20 |
| S8 | 2 | (sens$3 or detect$3) with harmonic with distortion with flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:21 |
| S9 | 2 | harmonic near distortion near8 flame and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S10 | 2 | harmonic near distortion near8 flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S11 | 3 | harmonic near distortion near8 fire | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:26 |
| S12 | 14399 | signal with flame | US-PGPUB; USPAT; | AND | ON | 2016/09/26 22:31 |

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|---|---|---|---|---|---|---|
| | | | USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S13 | 256 | two near2 signals with flame | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2016/09/26 22:31 |
| S14 | 38 | two near2 signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:32 |
| S15 | 94 | appl$3 with signals with flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:36 |
| S16 | 59 | appl$3 near8 signals near8 flame and detect with signal | US-PGPUB; USPAT; USOCR | AND | ON | 2016/09/26 22:37 |
| S17 | 3255 | 340/577.ccls. F23N5/123 G08B17/125 F23N2023/10 F23N2023/42 | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:49 |
| S19 | 23 | ("1077628" \| "1688126" \| "2112736" \| "2136256" \| "2709799" \| "2804608" \| "3301307" \| "3956080" \| "0307031" \| "4082493" \| "4317487" \| "6404342" \| "8310801" \| "0803684").PN. | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 12:50 |
| S20 | 2 | S19 and harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 12:51 |
| S21 | 1 | S17 and harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:52 |
| S22 | 430 | harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:52 |
| S23 | 84 | (detect$3 or determin$3) with harmonic with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:53 |
| S24 | 23 | (detect$3 or determin$3) with harmonic near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:53 |
| S25 | 4183 | (detect$3 or determin$3) with current near6 (flame or fire) | US-PGPUB; USPAT; | OR | ON | 2017/01/13 12:58 |

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| | | | USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | | | |
| S26 | 734 | (detect$3 or determin$3) with electric with current near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:58 |
| S27 | 446 | (detect$3 or determin$3) with electric near3 current near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 12:58 |
| S28 | 102 | (detect$3 or determin$3) with electric near3 current near6 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 12:59 |
| S29 | 328 | signal with flame near rod | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:13 |
| S30 | 231 | signal near6 flame near rod | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:13 |
| S31 | 100 | signal near6 flame near rod | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:13 |
| S32 | 2 | signal near6 flame near rod and harmonic | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:13 |
| S33 | 3970 | (detect$3 or determin$3) with resistance with (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:17 |
| S34 | 615356 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) ang harmonic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:17 |
| S35 | 11 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) and harmonic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:17 |
| S36 | 1720 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; | OR | ON | 2017/01/13 13:18 |

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| | | | IBM_TDB | | | |
| S37 | 379 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) and burner | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | OR | ON | 2017/01/13 13:19 |
| S38 | 296 | (detect$3 or determin$3) near6 resistance near6 (flame or fire) and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:19 |
| S39 | 1015 | (detect$3 or determin$3) near6 resistance near3 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:22 |
| S40 | 632 | (detect$3 or determin$3) near6 resistance near3 (flame) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:23 |
| S41 | 488 | (determin$3) near6 resistance near3 (flame) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:23 |
| S42 | 598 | (measur$3) near6 resistance near3 (flame) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:29 |
| S43 | 154 | (measur$3) near6 resistance near3 (flame) and burner | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:30 |
| S44 | 729056 | ionization near3 current nera3 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:34 |
| S45 | 149 | ionization near3 current near3 (flame or fire) | US-PGPUB; USPAT; USOCR | OR | ON | 2017/01/13 13:34 |
| S46 | 1 | flame near rod with ionization near electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:20 |
| S47 | 458 | flame near rod electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:21 |
| S48 | 230 | flame near rod with electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:21 |
| S49 | 0 | flame near rod with ionic with electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 15:21 |
| S50 | 230 | flame near rod with electrodes | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; | AND | ON | 2017/01/13 15:21 |

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|---|---|---|---|---|---|---|
| | | | DERWENT; IBM_TDB | | | |
| S51 | 116 | flame near rod with electrodes | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 15:21 |
| S52 | 121142 | phase near locked near loop | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S53 | 54609 | phase near locked near loop with frequency | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S54 | 0 | phase near locked near loop with frequency with harmoic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S55 | 591 | phase near locked near loop with frequency with harmonic | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:20 |
| S56 | 370 | phase near locked near loop with frequency with harmonic | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:20 |
| S57 | 1 | phase near locked near loop with frequency with harmonic and burner | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:21 |
| S58 | 51 | phase near locked near loop and burner | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:21 |
| S59 | 4 | phase near locked near loop with frequency with harmonic with turned | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:25 |
| S60 | 23 | phase near locked near loop with frequency with harmonic with tuned | US-PGPUB; USPAT; USOCR | AND | ON | 2017/01/13 16:25 |
| S61 | 1 | harmonic near detector with clock with synchronous | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:49 |
| S62 | 5 | harmonic near4 detector with clock with synchronous | US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB | AND | ON | 2017/01/13 16:49 |

**EAST Search History (Interference)**

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**1/17/2017 1:03:25 PM**
**C:\Users\zwu1\Documents\EAST\Workspaces\14316489 (Flame Sensing system).wsp**

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of Jed Margolin

Serial No.: 14/316,489

Filed: 06/26/2014

For: FLAME SENSING SYSTEM

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Dear Sir:

This is in response to the Office Action mailed 11/01/2016 in which the Examiner issued a restriction and/or election requirement asserting:

> This application contains claims directed to the following patentably distinct species. Claims 1-14 are drawn to harmonic distortion detection to determine a flame and claims 15-18 are drawn to mixing of two signals by flame rectification to determine a flame. The species are independent or distinct because the method and system used to detect a flame are different. In addition, these species are not obvious variants of each other based on the current record.

Applicant respectfully disagrees and requests reconsideration and withdrawal of the requirement. Applicant's reasons begin on page 8. However, Applicant will note at this point that the Examiner has mismatched the species represented in the claims.

The claims which are drawn to harmonic distortion detection to determine a flame are Independent Claim 1 (Dependent Claims 2-5) and Independent Claim 12 (Dependent Claims 13 and 14).

The claims which are drawn to the mixing of two signals by flame rectification to determine a flame are Independent Claim 6 (Dependent Claims 7-11), Independent Claim 15 (Dependent Claims 16 and 17), and Independent Claim 18.

In order to move the case forward Applicant will proceed as if the Examiner had correctly matched the species to the claims.

If Applicant's traverse is not accepted Applicant elects the species which is drawn to harmonic distortion detection to determine a flame. These are the following claims: Independent Claim 1 (Dependent Claims 2-5) and Independent Claim 12 (Dependent Claims 13 and 14).

And if Applicant's traverse is not accepted Applicant withdraws the claims which are drawn to the mixing of two signals by flame rectification to determine a flame. These are: Independent Claim 6 (Dependent Claims 7-11), Independent Claim 15 (Dependent Claims 16 and 17), and Independent Claim 18. In this event Applicant reserves the right to pursue all legal remedies to obtain these claims.

The current conditional claims list is appended. It is to be expressly understood that this is conditional on the Examiner rejecting Applicant's traverse.

Respectfully submitted,

/Jed Margolin/ Date: November 4, 2016

Jed Margolin

Jed Margolin
1981 Empire Rd.
Reno, NV 89521-7430
775-847-7845

# Claims

1. A system for detecting the presence of a flame comprising:
   a. a combustion burner;
   b. a flame rod;
   c. a signal source having a selected waveform connected to said flame rod;
   d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;
   e. a harmonic signal detector having an input connected to the output of said high impedance buffer;
   f. an indicator connected to the output of said harmonic signal detector;

whereas

   g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and
   h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.

2. The system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

3. The system of claim 1 whereby said harmonic signal detector comprises a phase locked loop tuned to the frequency of said harmonic signal.

4. The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising:
   a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;
   b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

5. The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is

approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

6. (Conditionally Withdrawn) A system for detecting the presence of a flame comprising:

a. a combustion burner;

b. a flame rod;

c. a first signal source having a selected waveform connected to said flame rod;

d. a second signal source having a selected waveform connected to said flame rod;

e. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

f. a signal detector having an input connected to the output of said high impedance buffer;

g. an indicator connected to the output of said signal detector;

whereas

h. said flame from said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a first mixing signal at the sum of the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform as well as a second mixing signal at the difference between the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform, and

i. said signal detector is configured to detect said first mixing signal or said second mixing signal and indicate the results on said indicator.

7. (Conditionally Withdrawn) The system of claim 6 whereby said signal detector comprises a phase locked loop tuned to said first mixing frequency or to said second mixing frequency.

8. (Conditionally Withdrawn) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, and a reference signal having the same frequency as said first mixing signal or said second mixing signal, and said signal detector comprises a simple synchronous detector comprising:

a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

9. (Conditionally Withdrawn) The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, a first reference signal having the same frequency as said first mixing signal or said second mixing signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

10. (Conditionally Withdrawn) The system of claim 6 whereby said first signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

11. (Conditionally Withdrawn) The system of claim 6 whereby said second signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

12. A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a signal source having a selected waveform introduced to said flame rod;
d. providing a high impedance buffer to buffer a flame rod signal from said flame rod;
e. providing a harmonic signal detector to receive the output of said high impedance buffer;
f. providing an indicator to receive the output of said harmonic signal detector;

whereas

g. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said signal source having a selected waveform to produce harmonics of the fundamental frequency of said selected waveform,
h. said harmonic signal detector is used to detect the presence of at least one of said harmonics of said selected waveform and indicate the presence of said at least one of said harmonics of said selected waveform on said indicator, and
i. said presence of said at least one of said harmonics of said selected waveform is proof of the presence of said flame.

13. The method of claim 12 where said step of providing a harmonic signal detector comprises providing a phase locked loop.

14. The method of claim 12 where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

15. (Conditionally Withdrawn) A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a first signal source having a selected waveform introduced to said flame rod;
d. providing a second signal source having a selected waveform introduced to said flame rod;

e. providing a high impedance buffer to buffer a flame rod signal from said flame rod;

f. providing a signal detector to receive the output of said high impedance buffer;

g. providing an indicator to receive the output of said signal detector;

whereas

h. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a sum signal at the sum frequency of said first signal source and said second signal source and a difference signal at the difference frequency of said first signal source and said second signal source,

i. said signal detector is used to detect the presence of said sum signal or said difference signal and indicate the presence of said sum signal or said difference signal on said indicator, and

j. said presence of said sum signal or said difference signal is proof of the presence of said flame.

16. (Conditionally Withdrawn) The method of claim 15 where said step of providing a signal detector comprises providing a phase locked loop.

17. (Conditionally Withdrawn) The method of claim 15 where said step of providing a signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

18. (Conditionally Withdrawn) A method for detecting the presence of a flame comprising the steps of:

a. providing two signal sources to said flame;

b. using flame rectification to cause said two signal sources to mix;

c. providing a signal detector to detect a mixing signal produced by said two signal sources; and

d. providing an indicator to indicate the results of said signal detector.

## Applicant's Response

**A.** Although Flame Rectification does not produce a very good rectifier, the rectifier that it does produce is good enough to act as a mixer. A mixer performs the function of multiplication. It is this function of multiplication that produces both species:

1. Flame rectification causes harmonic distortion of a single selected signal;
2. Flame rectification causes two selected signals to mix, producing signals at the sum and difference frequencies of the two selected signals

From Paragraph 042 in the Specification (page 28)

> **[042] Experiment 10 – Using flame rectification as a mixer to produce sum and difference frequencies of two signal sources.**
>
> In this experiment the flame rectifier is used as a mixer. A mixer is a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. See IDS Cite *30* (Horowitz).
>
> One type of mixer is a four-quadrant multiplier. For example, if you multiply two sine wave signals:
>
> $$\sin(\omega 1t) * \sin(\omega 2t) \qquad \text{Equation 1}$$
>
> and use a well known trigonometric identity you get:
>
> $$½ * \cos(\omega 1 - \omega 2)t - ½ * \cos(\omega 1 + \omega 2)t \qquad \text{Equation 2}$$

The trigonometric identity is:

$$\sin(u) * \sin(v) = 1/2 [ \cos(u - v) - \cos(u + v)]$$

which is:

$$\sin(u) * \sin(v) = 1/2 * \cos(u - v) - 1/2 * \cos(u + v)]$$

See **Appendix 1** under - **Product Formulas**

That is why a mixer (multiplier) produces the two signals: the sum of the two frequencies and the difference between the two frequencies.

What may not be so obvious is that when a single sine wave is presented to a mixer (multiplier) this formula still applies but both sin(ω1t) and sin(ω2t) are the same. The result is:

$$\sin(\omega t) * \sin(\omega t) = ½ * \cos[(\omega - \omega)t] - ½ * \cos[(\omega + \omega)t]$$

$$= ½ * \cos(0t) - ½ * \cos[(\omega + \omega)t]$$

1. $\cos(0t) = 1$
2. The quantity $(\omega + \omega) = 2 * \omega$

Therefore:

$$\sin(\omega t) * \sin(\omega t) = ½ - ½ * \cos[(2 * \omega)t]$$

Thus, the result is a DC term and a component at twice the frequency of ω, which is the second harmonic of ω.

That is why Flame Rectification causes harmonic distortion of a single selected signal. It is the same process by which Flame Rectification causes two selected signals to mix, producing the two signals: the sum of the two frequencies and the difference between the two frequencies.

These species are obvious variants of each other and are so intimately related that no separate search should be necessary.

**B.** In one species Flame Rectification causes harmonic distortion of a selected signal. This harmonic signal is detected to prove the existence of a flame. In the other species Flame Rectification causes two selected signals to mix (multiply) producing two signals: the sum of the two frequencies of the two signals and the difference between the frequencies of the two signals. Since it only requires the detection of either the sum or difference of the two frequencies it only requires one of signals be detected to prove flame.

The methods used to detect either the harmonic of the single selected signal in species 1 or either the sum or difference signal produced in species 2 are the same.

| | |
|---|---|
| Independent Claim 1 (Apparatus Claim) - Flame Rectification causes harmonic distortion of a single signal. | Independent Claim 6 (Apparatus Claim) - Flame Rectification causes two selected signals to mix, producing sum and differences signals. |
| Dependent Claim 3 - The harmonic is detected using a phase locked loop. | Dependent Claim 7 - The signal detector comprises a phase locked loop tuned to said first mixing frequency or to said second mixing frequency. |
| Dependent claim 4 - A master clock produces the selected signal and a reference signal at the frequency of the harmonic. A synchronous detector uses the reference signal to detect the harmonic produced by Flame Rectification. | Dependent Claim 8 - A master clock produces the two selected signals and a reference signal at the frequency of either the sum or difference frequencies of the two selected signals. A synchronous detector uses the reference signal to detect either the sum or difference signal produced by Flame Rectification. |
| Dependent Claim 5 - Also uses a master clock but produces two reference signals 90 degrees out of phase so that a quadrature detector can be used. | Dependent Claim 9 - Also uses a master clock but produces two reference signals 90 degrees out of phase so that a quadrature detector can be used. |

| | |
|---|---|
| Independent Claim 12 (Method Claim) - Flame Rectification causes harmonic distortion of a single signal. | Independent Claim 15 (Method Claim) - Flame Rectification causes two selected signals to mix, producing sum and differences signals. |
| Dependent Claim 13 (Method Claim) - The harmonic is detected by providing a phase locked loop. | Dependent Claim 16 (Method Claim) - The signal is detected by providing a phase locked loop tuned to said first mixing frequency or to said second mixing frequency. |
| Dependent Claim 14 (Method Claim) - A Master Clock is provided so the harmonic signal is detected using either a simple synchronous detector or a quadrature detector. | Dependent Claim 17 (Method Claim) - A Master Clock is provided so the signal is detected using either a simple synchronous detector or a quadrature detector. |

Since the methods used to detect either the harmonic of the single selected signal in species 1 or either the sum or difference signal produced in species 2 are the same, no separate search should be necessary.

## Conclusion

Flame Rectification causes harmonic distortion of a single selected signal. It is the same process by which Flame Rectification causes two selected signals to mix, producing the two signals: the sum of the two frequencies and the difference between the two frequencies.

These species are obvious variants of each other and are so intimately related that no separate search should be necessary.

The methods used to detect either the harmonic of the single selected signal in species 1 or either the sum or difference signal produced in species 2 are the same.

The theory and practice of the use of mixers is well known to those persons having ordinary skill in the art of communications engineering. It is the use of flame rectification as a mixer to unambiguously detect the presence of a flame that is new, non-obvious, and useful.

For the above reasons Applicant respectfully requests reconsideration and withdrawal of the requirement for restriction/election.

**Appendix 1**

from http://web.mit.edu/wwmath/trig/identities02.html

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**Useful Trigonometric Identities**

This page is meant to be used as reference listing of useful trigonometric identities. No discussion of the proofs or the consequences of these identities will be give here.

## Pythagorean Identities

$$\sin^2(x) + \cos^2(x) = 1$$
$$1 + \tan^2(x) = \sec^2(x)$$
$$1 + \cot^2(x) = \csc^2(x)$$

## Addition Formulas

$$\sin(u + v) = \sin(u)\ \cos(v) + \cos(u)\ \sin(v)$$
$$\cos(u + v) = \cos(u)\ \cos(v) - \sin(u)\sin(v)$$
$$\tan(u + v) = \frac{\tan(u) + \tan(v)}{1 - \tan(u)\ \tan(v)}$$

## Subtraction formulas

$$\sin(u - v) = \sin(u)\ \cos(v) - \cos(u)\ \sin(v)$$
$$\cos(u - v) = \cos(u)\ \cos(v) + \sin(u)\sin(v)$$
$$\tan(u - v) = \frac{\tan(u) - \tan(v)}{1 + \tan(u)\ \tan(v)}$$

## Double Angle Formulas

$$\begin{aligned} \sin(2t) &= 2\sin(t)\,\cos(t) \\ \cos(2t) &= \cos^2(t) - \sin^2(t) \\ &= 2\cos^2(t) - 1 \\ &= 1 - 2\sin^2(t) \\ \tan(2t) &= \frac{2\tan(t)}{1 - \tan^2(t)} \end{aligned}$$

---

## Half-Angle Formulas

$$\begin{aligned} \sin\left(\frac{u}{2}\right) &= \sqrt{\frac{1-\cos(u)}{2}} \\ \cos\left(\frac{u}{2}\right) &= \sqrt{\frac{1+\cos(u)}{2}} \\ \tan\left(\frac{u}{2}\right) &= \sqrt{\frac{1-\cos(u)}{1+\cos(u)}} \end{aligned}$$

---

## Product Formulas

$$\begin{aligned} \sin(u)\,\cos(v) &= \frac{1}{2}\left[\sin(u+v) + \sin(u-v)\right] \\ \sin(u)\,\sin(v) &= \frac{1}{2}\left[\cos(u-v) - \cos(u+v)\right] \\ \cos(u)\,\cos(v) &= \frac{1}{2}\left[\cos(u+v) + \cos(u-v)\right] \end{aligned}$$

---

## Factoring Formulas

$$\sin(u) + \sin(v) = 2\sin\left(\frac{u+v}{2}\right)\cos\left(\frac{u-v}{2}\right)$$
$$\sin(u) - \sin(v) = 2\sin\left(\frac{u-v}{2}\right)\cos\left(\frac{u+v}{2}\right)$$
$$\cos(u) + \cos(v) = 2\cos\left(\frac{u+v}{2}\right)\cos\left(\frac{u-v}{2}\right)$$
$$\cos(u) - \cos(v) = 2\sin\left(\frac{v+u}{2}\right)\sin\left(\frac{v-u}{2}\right)$$

The following two formulas are of only limited use:

$$\cos(u) + \sin(v) = \left[\cos\left(\frac{u-v}{2}\right) - \sin\left(\frac{u-v}{2}\right)\right]\left[\cos\left(\frac{u+v}{2}\right) + \sin\left(\frac{u+v}{2}\right)\right]$$
$$\cos(u) - \sin(v) = \left[\cos\left(\frac{u+v}{2}\right) - \sin\left(\frac{u+v}{2}\right)\right]\left[\cos\left(\frac{u-v}{2}\right) + \sin\left(\frac{u-v}{2}\right)\right]$$

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Back to the Trigonometry page | Back to the World Web Math Categories Page

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*watko@mit.edu*
Last modified August 1, 1998

# Electronic Acknowledgement Receipt

| | |
|---|---|
| **EFS ID:** | 27422630 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 04-NOV-2016 |
| **Filing Date:** | 26-JUN-2014 |
| **Time Stamp:** | 14:50:38 |
| **Application Type:** | Utility under 35 USC 111(a) |

## Payment information:

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|---|---|
| Submitted with Payment | no |

## File Listing:

| Document Number | Document Description | File Name | File Size(Bytes)/ Message Digest | Multi Part /.zip | Pages (if appl.) |
|---|---|---|---|---|---|
| 1 | Response to Election / Restriction Filed | jm_restriction_response_flame.pdf | 126420<br>34e545635d1ffb9d8792b51db0da7e9799920959 | no | 14 |

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PTO/SB/06 (09-11)
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| **PATENT APPLICATION FEE DETERMINATION RECORD** Substitute for Form PTO-875 | Application or Docket Number 14/316,489 | Filing Date 06/26/2014 | ☐ To be Mailed |
|---|---|---|---|

**ENTITY:** ☐ LARGE ☒ SMALL ☐ MICRO

## APPLICATION AS FILED – PART I

| FOR | NUMBER FILED (Column 1) | NUMBER EXTRA (Column 2) | RATE ($) | FEE ($) |
|---|---|---|---|---|
| ☐ BASIC FEE (37 CFR 1.16(a), (b), or (c)) | N/A | N/A | N/A | |
| ☐ SEARCH FEE (37 CFR 1.16(k), (i), or (m)) | N/A | N/A | N/A | |
| ☐ EXAMINATION FEE (37 CFR 1.16(o), (p), or (q)) | N/A | N/A | N/A | |
| TOTAL CLAIMS (37 CFR 1.16(i)) | minus 20 = | * | X $ = | |
| INDEPENDENT CLAIMS (37 CFR 1.16(h)) | minus 3 = | * | X $ = | |
| ☐ APPLICATION SIZE FEE (37 CFR 1.16(s)) | If the specification and drawings exceed 100 sheets of paper, the application size fee due is $310 ($155 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s). | | | |
| ☐ MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j)) | | | | |
| * If the difference in column 1 is less than zero, enter "0" in column 2. | | | TOTAL | |

## APPLICATION AS AMENDED – PART II

| AMENDMENT 11/04/2016 | CLAIMS REMAINING AFTER AMENDMENT (Column 1) | | HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2) | PRESENT EXTRA (Column 3) | RATE ($) | ADDITIONAL FEE ($) |
|---|---|---|---|---|---|---|
| Total (37 CFR 1.16(i)) | * 18 | Minus | ** 20 | = 0 | x $40 = | 0 |
| Independent (37 CFR 1.16(h)) | * 5 | Minus | ***5 | = 0 | x $210 = | 0 |
| ☐ Application Size Fee (37 CFR 1.16(s)) | | | | | | |
| ☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | |
| | | | | | TOTAL ADD'L FEE | **0** |

| AMENDMENT | CLAIMS REMAINING AFTER AMENDMENT (Column 1) | | HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2) | PRESENT EXTRA (Column 3) | RATE ($) | ADDITIONAL FEE ($) |
|---|---|---|---|---|---|---|
| Total (37 CFR 1.16(i)) | * | Minus | ** | = | X $ = | |
| Independent (37 CFR 1.16(h)) | * | Minus | *** | = | X $ = | |
| ☐ Application Size Fee (37 CFR 1.16(s)) | | | | | | |
| ☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | |
| | | | | | TOTAL ADD'L FEE | |

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20".
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3".
The "Highest Number Previously Paid For" (Total or Independent) is the highest number found in the appropriate box in column 1.

LIE
TAMARA DARKO

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| APPLICATION NO. | FILING DATE | FIRST NAMED INVENTOR | ATTORNEY DOCKET NO. | CONFIRMATION NO. |
|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | | 1025 |

23497 7590 11/01/2016

JED MARGOLIN
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| EXAMINER | |
|---|---|
| WU, ZHEN Y | |

| ART UNIT | PAPER NUMBER |
|---|---|
| 2685 | |

| MAIL DATE | DELIVERY MODE |
|---|---|
| 11/01/2016 | PAPER |

**Please find below and/or attached an Office communication concerning this application or proceeding.**

The time period for reply, if any, is set in the attached communication.

| *Office Action Summary* | **Application No.** 14/316,489 | **Applicant(s)** MARGOLIN, JED | |
|---|---|---|---|
| | **Examiner** ZHEN Y. WU | **Art Unit** 2685 | **AIA (First Inventor to File) Status** Yes |

***-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --***

**Period for Reply**

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE *2* MONTHS FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

**Status**

1)☒ Responsive to communication(s) filed on *06/26/2014*.

☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2a)☐ This action is **FINAL**. 2b)☐ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

**Disposition of Claims***

5)☒ Claim(s) *1-18* is/are pending in the application.

5a) Of the above claim(s) _____ is/are withdrawn from consideration.

6)☐ Claim(s) _____ is/are allowed.

7)☐ Claim(s) _____ is/are rejected.

8)☐ Claim(s) _____ is/are objected to.

9)☒ Claim(s) *1-18* are subject to restriction and/or election requirement.

* If any claims have been determined allowable, you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

**Application Papers**

10)☐ The specification is objected to by the Examiner.

11)☐ The drawing(s) filed on _____ is/are: a)☐ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

**Priority under 35 U.S.C. § 119**

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

**Certified copies:**

a)☐ All b)☐ Some** c)☐ None of the:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

** See the attached detailed Office action for a list of the certified copies not received.

**Attachment(s)**

1) ☐ Notice of References Cited (PTO-892)

2) ☐ Information Disclosure Statement(s) (PTO/SB/08a and/or PTO/SB/08b) Paper No(s)/Mail Date _____.

3) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

4) ☐ Other: _____.

***Election/Restrictions***

This application contains claims directed to the following patentably distinct species. Claims 1-14 are drawn to harmonic distortion detection to determine a flame and claims15-18 are drawn to mixing of two signals by flame rectification to determine a flame. The species are independent or distinct because the method and system used to detect a flame are different. In addition, these species are not obvious variants of each other based on the current record.

Applicant is required under 35 U.S.C. 121 to elect a single disclosed species, or a single grouping of patentably indistinct species, for prosecution on the merits to which the claims shall be restricted if no generic claim is finally held to be allowable.

There is a search and/or examination burden for the patentably distinct species as set forth above because at least the following reason(s) apply:

These two distinctive inventions are directed toward two different species that would require very different search strategies.

**Applicant is advised that the reply to this requirement to be complete must include (i) an election of a species to be examined** even though the requirement may be traversed (37 CFR 1.143) **and (ii) identification of the claims encompassing the elected species or grouping of patentably indistinct species**, including any claims subsequently added. An argument that a claim is allowable or that all claims are generic is considered nonresponsive unless accompanied by an election.

The election may be made with or without traverse. To preserve a right to petition, the election must be made with traverse. If the reply does not distinctly and specifically point out supposed errors in the election of species requirement, the election shall be treated as an election without traverse. Traversal must be presented at the time of election in order to be considered timely. Failure to timely traverse the requirement will result in the loss of right to petition under 37 CFR 1.144. If claims are added after the election, applicant must indicate which of these claims are readable on the elected species or grouping of patentably indistinct species.

Should applicant traverse on the ground that the species, or groupings of patentably indistinct species from which election is required, are not patentably distinct, applicant should submit evidence or identify such evidence now of record showing them to be obvious variants or clearly admit on the record that this is the case. In either instance, if the examiner finds one of the species unpatentable over the prior art, the evidence or admission may be used in a rejection under 35 U.S.C. 103 or pre-AIA 35 U.S.C. 103(a) of the other species.

Upon the allowance of a generic claim, applicant will be entitled to consideration of claims to additional species which depend from or otherwise require all the limitations of an allowable generic claim as provided by 37 CFR 1.141.

## *Conclusion*

Any inquiry concerning this communication or earlier communications from the examiner should be directed to ZHEN Y. WU whose telephone number is (571)272-5711. The examiner can normally be reached on Monday to Friday, 8AM - 5PM, Alternate Friday, EST.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Hai Phan can be reached on (571) - 272-6338. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/ZHEN Y WU/
Examiner, Art Unit 2685

/Hai Phan/
Supervisory Patent Examiner, Art Unit 2685

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

| APPLICATION NUMBER | FILING OR 371(C) DATE | FIRST NAMED APPLICANT | ATTY. DOCKET NO./TITLE |
|---|---|---|---|
| 14/316,489 | 06/26/2014 | Jed Margolin | |

**CONFIRMATION NO. 1025**

**PUBLICATION NOTICE**

*OC000000079064707*

23497
JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

**Title:** Flame Sensing System

**Publication No.** US-2015-0348393-A1
**Publication Date:** 12/03/2015

## NOTICE OF PUBLICATION OF APPLICATION

The above-identified application will be electronically published as a patent application publication pursuant to 37 CFR 1.211, et seq. The patent application publication number and publication date are set forth above.

The publication may be accessed through the USPTO's publically available Searchable Databases via the Internet at www.uspto.gov. The direct link to access the publication is currently http://www.uspto.gov/patft/.

The publication process established by the Office does not provide for mailing a copy of the publication to applicant. A copy of the publication may be obtained from the Office upon payment of the appropriate fee set forth in 37 CFR 1.19(a)(1). Orders for copies of patent application publications are handled by the USPTO's Office of Public Records. The Office of Public Records can be reached by telephone at (703) 308-9726 or (800) 972-6382, by facsimile at (703) 305-8759, by mail addressed to the United States Patent and Trademark Office, Office of Public Records, Alexandria, VA 22313-1450 or via the Internet.

In addition, information on the status of the application, including the mailing date of Office actions and the dates of receipt of correspondence filed in the Office, may also be accessed via the Internet through the Patent Electronic Business Center at www.uspto.gov using the public side of the Patent Application Information and Retrieval (PAIR) system. The direct link to access this status information is currently http://pair.uspto.gov/. Prior to publication, such status information is confidential and may only be obtained by applicant using the private side of PAIR.

Further assistance in electronically accessing the publication, or about PAIR, is available by calling the Patent Electronic Business Center at 1-866-217-9197.

Office of Data Managment, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

| APPLICATION NUMBER | FILING or 371(c) DATE | GRP ART UNIT | FIL FEE REC'D | ATTY.DOCKET.NO | TOT CLAIMS | IND CLAIMS |
|---|---|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | 3749 | 1150 | | 18 | 5 |

**CONFIRMATION NO. 1025**

**CORRECTED FILING RECEIPT**

*OC000000070559381*

23497
JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

Date Mailed: 09/05/2014

Receipt is acknowledged of this non-provisional patent application. The application will be taken up for examination in due course. Applicant will be notified as to the results of the examination. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

**Inventor(s)**

Jed Margolin, VC Highlands, NV;

**Applicant(s)**

Jed Margolin, VC Highlands, NV;

**Power of Attorney:** None

**Domestic Priority data as claimed by applicant**

This appln claims benefit of 62/005,199 05/30/2014

**Foreign Applications** for which priority is claimed (You may be eligible to benefit from the **Patent Prosecution Highway** program at the USPTO. Please see http://www.uspto.gov for more information.) - None.
*Foreign application information must be provided in an Application Data Sheet in order to constitute a claim to foreign priority. See 37 CFR 1.55 and 1.76.*

Permission to Access - A proper **Authorization to Permit Access to Application by Participating Offices** (PTO/SB/39 or its equivalent) has been received by the USPTO.

**If Required, Foreign Filing License Granted:** 07/09/2014

The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 14/316,489**

**Projected Publication Date:** 12/03/2015

**Non-Publication Request:** No

**Early Publication Request:** No

**** SMALL ENTITY ****

**Title**

Flame Sensing System

**Preliminary Class**

431

**Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications:** No

## PROTECTING YOUR INVENTION OUTSIDE THE UNITED STATES

Since the rights granted by a U.S. patent extend only throughout the territory of the United States and have no effect in a foreign country, an inventor who wishes patent protection in another country must apply for a patent in a specific country or in regional patent offices. Applicants may wish to consider the filing of an international application under the Patent Cooperation Treaty (PCT). An international (PCT) application generally has the same effect as a regular national patent application in each PCT-member country. The PCT process **simplifies** the filing of patent applications on the same invention in member countries, but **does not result** in a grant of "an international patent" and does not eliminate the need of applicants to file additional documents and fees in countries where patent protection is desired.

Almost every country has its own patent law, and a person desiring a patent in a particular country must make an application for patent in that country in accordance with its particular laws. Since the laws of many countries differ in various respects from the patent law of the United States, applicants are advised to seek guidance from specific foreign countries to ensure that patent rights are not lost prematurely.

Applicants also are advised that in the case of inventions made in the United States, the Director of the USPTO must issue a license before applicants can apply for a patent in a foreign country. The filing of a U.S. patent application serves as a request for a foreign filing license. The application's filing receipt contains further information and guidance as to the status of applicant's license for foreign filing.

Applicants may wish to consult the USPTO booklet, "General Information Concerning Patents" (specifically, the section entitled "Treaties and Foreign Patents") for more information on timeframes and deadlines for filing foreign patent applications. The guide is available either by contacting the USPTO Contact Center at 800-786-9199, or it can be viewed on the USPTO website at http://www.uspto.gov/web/offices/pac/doc/general/index.html.

For information on preventing theft of your intellectual property (patents, trademarks and copyrights), you may wish to consult the U.S. Government website, http://www.stopfakes.gov. Part of a Department of Commerce initiative, this website includes self-help "toolkits" giving innovators guidance on how to protect intellectual property in specific countries such as China, Korea and Mexico. For questions regarding patent enforcement issues, applicants may call the U.S. Government hotline at 1-866-999-HALT (1-866-999-4258).

## LICENSE FOR FOREIGN FILING UNDER

## Title 35, United States Code, Section 184

## Title 37, Code of Federal Regulations, 5.11 & 5.15

**GRANTED**

The applicant has been granted a license under 35 U.S.C. 184, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" followed by a date appears on this form. Such licenses are issued in all applications where the conditions for issuance of a license have been met, regardless of whether or not a license may be required as set forth in 37 CFR 5.15. The scope and limitations of this license are set forth in 37 CFR 5.15(a) unless an earlier license has been issued under 37 CFR 5.15(b). The license is subject to revocation upon written notification. The date indicated is the effective date of the license, unless an earlier license of similar scope has been granted under 37 CFR 5.13 or 5.14.

This license is to be retained by the licensee and may be used at any time on or after the effective date thereof unless it is revoked. This license is automatically transferred to any related applications(s) filed under 37 CFR 1.53(d). This license is not retroactive.

The grant of a license does not in any way lessen the responsibility of a licensee for the security of the subject matter as imposed by any Government contract or the provisions of existing laws relating to espionage and the national security or the export of technical data. Licensees should apprise themselves of current regulations especially with respect to certain countries, of other agencies, particularly the Office of Defense Trade Controls, Department of State (with respect to Arms, Munitions and Implements of War (22 CFR 121-128)); the Bureau of Industry and Security, Department of Commerce (15 CFR parts 730-774); the Office of Foreign AssetsControl, Department of Treasury (31 CFR Parts 500+) and the Department of Energy.

**NOT GRANTED**

No license under 35 U.S.C. 184 has been granted at this time, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" DOES NOT appear on this form. Applicant may still petition for a license under 37 CFR 5.12, if a license is desired before the expiration of 6 months from the filing date of the application. If 6 months has lapsed from the filing date of this application and the licensee has not received any indication of a secrecy order under 35 U.S.C. 181, the licensee may foreign file the application pursuant to 37 CFR 5.15(b).

---

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of Jed Margolin

Serial No.: 14/316,489

Filed: 06/26/2014

For: FLAME SENSING SYSTEM

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

**First Corrected ADS**

Dear Sir:

In the ADS filed with the above application the section for claiming priority from Provisional Application 62/005,199 filed 5/30/2014 was inadvertently left out. A corrected ADS is attached.

1. The Section **Domestic Benefit/National Stage Application** is filled out with the correct information (and underlined).
2. The **Signature** section has been changed to have today's date. If that is not the correct protocol let me know and I will correct it again.

Please issue a new Filing Receipt showing the priority from the Provisional Application 62/005,199.

Respectfully submitted,

/Jed Margolin/ Date: July 10, 2014

Jed Margolin
1981 Empire Rd.
Reno, NV 89521-7430
775-847-7845

| **Application Data Sheet 37 CFR 1.76** | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

## Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

## Inventor Information:

**Inventor 1** Remove
**Legal Name**

| Prefix | Given Name | Middle Name | Family Name | Suffix |
|---|---|---|---|---|
| Mr. | Jed | | Margolin | |

**Residence Information (Select One)** ◉ US Residency ○ Non US Residency ○ Active US Military Service

| City | VC Highlands | State/Province | NV | Country of Residence | US |
|---|---|---|---|---|---|

**Mailing Address of Inventor:**

| | | | |
|---|---|---|---|
| **Address 1** | 1981 Empire Rd. | | |
| **Address 2** | | | |
| **City** | Reno | **State/Province** | NV |
| **Postal Code** | 89521-7430 | **Country** i | US |

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

## Correspondence Information:

**Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).**

☐ **An Address is being provided for the correspondence Information of this application.**

| | | |
|---|---|---|
| **Customer Number** | 23497 | |
| **Email Address** | jm@jmargolin.com | Add Email Remove Email |

## Application Information:

| | | | |
|---|---|---|---|
| **Title of the Invention** | Flame Sensing System | | |
| **Attorney Docket Number** | | **Small Entity Status Claimed** | ☒ |
| **Application Type** | Nonprovisional | | |
| **Subject Matter** | Utility | | |
| **Total Number of Drawing Sheets (if any)** | 66 | **Suggested Figure for Publication (if any)** | 90 |

## Filing By Reference :

| Application Data Sheet 37 CFR 1.76 | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

| Application number of the previously filed application | Filing date (YYYY-MM-DD) | Intellectual Property Authority or Country |
|---|---|---|
| | | |

## Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

## Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

| Please Select One: | ◉ Customer Number | ○ US Patent Practitioner | ○ Limited Recognition (37 CFR 11.9) |
|---|---|---|---|
| Customer Number | 23497 | | |

## Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.
When referring to the current application, please leave the application number blank.

| Prior Application Status | Pending | | Remove |
|---|---|---|---|
| Application Number | Continuity Type | Prior Application Number | Filing Date (YYYY-MM-DD) |
| 14316489 | Claims benefit of provisional | 62005199 | 2014-05-30 |

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button.

## Foreign Priority Information:

| Application Data Sheet 37 CFR 1.76 | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(d). When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX)[i] the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(h)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

Remove

| Application Number | Country[i] | Filing Date (YYYY-MM-DD) | Access Code[i] (if applicable) |
|---|---|---|---|
| | | | |

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button.

## Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.
NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

## Authorization to Permit Access:

☒ Authorization to Permit Access to the Instant Application by the Participating Offices

| **Application Data Sheet 37 CFR 1.76** | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date o f filing this Authorization.

## Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

**Applicant 1**

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Clear

○ Assignee ○ Legal Representative under 35 U.S.C. 117 ○ Joint Inventor

○ Person to whom the inventor is obligated to assign. ○ Person who shows sufficient proprietary interest

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :

If the Applicant is an Organization check here. ☐

| Prefix | **Given Name** | Middle Name | **Family Name** | Suffix |
|---|---|---|---|---|
| | | | | |

| **Application Data Sheet 37 CFR 1.76** | Attorney Docket Number | |
|---|---|---|
| | Application Number | |

| Title of Invention | Flame Sensing System |
|---|---|

| **Mailing Address Information For Applicant:** | | | |
|---|---|---|---|
| **Address 1** | | | |
| Address 2 | | | |
| **City** | | **State/Province** | |
| **Country** | | Postal Code | |
| Phone Number | | Fax Number | |
| Email Address | | | |

Additional Applicant Data may be generated within this form by selecting the Add button.

## Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not subsitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

**Assignee 1**

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication . An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

If the Assignee or Non-Applicant Assignee is an Organization check here. ☐

| Prefix | **Given Name** | Middle Name | **Family Name** | Suffix |
|---|---|---|---|---|
| | | | | |

| **Mailing Address Information For Assignee including Non-Applicant Assignee:** | | | |
|---|---|---|---|
| **Address 1** | | | |
| Address 2 | | | |
| **City** | | **State/Province** | |
| **Country** | | Postal Code | |
| Phone Number | | Fax Number | |
| Email Address | | | |

Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button.

| Application Data Sheet 37 CFR 1.76 | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

## Signature:

| NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications. | | | | | |
|---|---|---|---|---|---|
| **Signature** | /Jed Margolin/ | | | Date (YYYY-MM-DD) | ~~2014-06-26~~ 2014-07-10 |
| First Name | Jed | Last Name | Margolin | Registration Number | |
| Additional Signature may be generated within this form by selecting the Add button. | | | | | |

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

# Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent C o o p eration Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

# Electronic Acknowledgement Receipt

| | |
|---|---|
| **EFS ID:** | 19538242 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 10-JUL-2014 |
| **Filing Date:** | 26-JUN-2014 |
| **Time Stamp:** | 07:15:13 |
| **Application Type:** | Utility under 35 USC 111(a) |

## Payment information:

| | |
|---|---|
| Submitted with Payment | no |

## File Listing:

| Document Number | Document Description | File Name | File Size(Bytes)/ Message Digest | Multi Part /.zip | Pages (if appl.) |
|---|---|---|---|---|---|
| 1 | Application Data Sheet | jm_flame_ads2_aia0014.pdf | 403636<br>14d6374fa61cf52fac114960bc5ea059ecd90a28 | no | 8 |

**Warnings:**

**Information:**

| This is not an USPTO supplied ADS fillable form | |
|---|---|
| **Total Files Size (in bytes):** | 403636 |

**This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.**

**<u>New Applications Under 35 U.S.C. 111</u>**
**If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.**

**<u>National Stage of an International Application under 35 U.S.C. 371</u>**
**If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.**

**<u>New International Application Filed with the USPTO as a Receiving Office</u>**
**If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.**

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

| APPLICATION NUMBER | FILING or 371(c) DATE | GRP ART UNIT | FIL FEE REC'D | ATTY.DOCKET.NO | TOT CLAIMS | IND CLAIMS |
|---|---|---|---|---|---|---|
| 14/316,489 | 06/26/2014 | 3749 | 1150 | | 18 | 5 |

**CONFIRMATION NO. 1025**

**FILING RECEIPT**

*OC000000069494950*

23497
JED MARGOLIN
1981 EMPIRE ROAD
RENO, NV 89521-7430

Date Mailed: 07/09/2014

Receipt is acknowledged of this non-provisional patent application. The application will be taken up for examination in due course. Applicant will be notified as to the results of the examination. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

**Inventor(s)**

Jed Margolin, VC Highlands, NV;

**Applicant(s)**

Jed Margolin, VC Highlands, NV;

**Power of Attorney:** None

**Domestic Applications for which benefit is claimed - None.**
*A proper domestic benefit claim must be provided in an Application Data Sheet in order to constitute a claim for domestic benefit. See 37 CFR 1.76 and 1.78.*

**Foreign Applications** for which priority is claimed (You may be eligible to benefit from the **Patent Prosecution Highway** program at the USPTO. Please see http://www.uspto.gov for more information.) - None.
*Foreign application information must be provided in an Application Data Sheet in order to constitute a claim to foreign priority. See 37 CFR 1.55 and 1.76.*

Permission to Access - A proper **Authorization to Permit Access to Application by Participating Offices** (PTO/SB/39 or its equivalent) has been received by the USPTO.

**If Required, Foreign Filing License Granted:** 07/09/2014
The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 14/316,489**
**Projected Publication Date:** 12/31/2015
**Non-Publication Request:** No
**Early Publication Request:** No
**** SMALL ENTITY ****

**Title**

Flame Sensing System

**Preliminary Class**

431

**Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications:** No

## PROTECTING YOUR INVENTION OUTSIDE THE UNITED STATES

Since the rights granted by a U.S. patent extend only throughout the territory of the United States and have no effect in a foreign country, an inventor who wishes patent protection in another country must apply for a patent in a specific country or in regional patent offices. Applicants may wish to consider the filing of an international application under the Patent Cooperation Treaty (PCT). An international (PCT) application generally has the same effect as a regular national patent application in each PCT-member country. The PCT process **simplifies** the filing of patent applications on the same invention in member countries, but **does not result** in a grant of "an international patent" and does not eliminate the need of applicants to file additional documents and fees in countries where patent protection is desired.

Almost every country has its own patent law, and a person desiring a patent in a particular country must make an application for patent in that country in accordance with its particular laws. Since the laws of many countries differ in various respects from the patent law of the United States, applicants are advised to seek guidance from specific foreign countries to ensure that patent rights are not lost prematurely.

Applicants also are advised that in the case of inventions made in the United States, the Director of the USPTO must issue a license before applicants can apply for a patent in a foreign country. The filing of a U.S. patent application serves as a request for a foreign filing license. The application's filing receipt contains further information and guidance as to the status of applicant's license for foreign filing.

Applicants may wish to consult the USPTO booklet, "General Information Concerning Patents" (specifically, the section entitled "Treaties and Foreign Patents") for more information on timeframes and deadlines for filing foreign patent applications. The guide is available either by contacting the USPTO Contact Center at 800-786-9199, or it can be viewed on the USPTO website at http://www.uspto.gov/web/offices/pac/doc/general/index.html.

For information on preventing theft of your intellectual property (patents, trademarks and copyrights), you may wish to consult the U.S. Government website, http://www.stopfakes.gov. Part of a Department of Commerce initiative, this website includes self-help "toolkits" giving innovators guidance on how to protect intellectual property in specific countries such as China, Korea and Mexico. For questions regarding patent enforcement issues, applicants may call the U.S. Government hotline at 1-866-999-HALT (1-866-999-4258).

## LICENSE FOR FOREIGN FILING UNDER

## Title 35, United States Code, Section 184

## Title 37, Code of Federal Regulations, 5.11 & 5.15

**GRANTED**

The applicant has been granted a license under 35 U.S.C. 184, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" followed by a date appears on this form. Such licenses are issued in all applications where the conditions for issuance of a license have been met, regardless of whether or not a license may be required as set forth in 37 CFR 5.15. The scope and limitations of this license are set forth in 37 CFR 5.15(a) unless an earlier license has been issued under 37 CFR 5.15(b). The license is subject to revocation upon written notification. The date indicated is the effective date of the license, unless an earlier license of similar scope has been granted under 37 CFR 5.13 or 5.14.

This license is to be retained by the licensee and may be used at any time on or after the effective date thereof unless it is revoked. This license is automatically transferred to any related applications(s) filed under 37 CFR 1.53(d). This license is not retroactive.

The grant of a license does not in any way lessen the responsibility of a licensee for the security of the subject matter as imposed by any Government contract or the provisions of existing laws relating to espionage and the national security or the export of technical data. Licensees should apprise themselves of current regulations especially with respect to certain countries, of other agencies, particularly the Office of Defense Trade Controls, Department of State (with respect to Arms, Munitions and Implements of War (22 CFR 121-128)); the Bureau of Industry and Security, Department of Commerce (15 CFR parts 730-774); the Office of Foreign AssetsControl, Department of Treasury (31 CFR Parts 500+) and the Department of Energy.

**NOT GRANTED**

No license under 35 U.S.C. 184 has been granted at this time, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" DOES NOT appear on this form. Applicant may still petition for a license under 37 CFR 5.12, if a license is desired before the expiration of 6 months from the filing date of the application. If 6 months has lapsed from the filing date of this application and the licensee has not received any indication of a secrecy order under 35 U.S.C. 181, the licensee may foreign file the application pursuant to 37 CFR 5.15(b).

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## *SelectUSA*

The United States represents the largest, most dynamic marketplace in the world and is an unparalleled location for business investment, innovation, and commercialization of new technologies. The U.S. offers tremendous resources and advantages for those who invest and manufacture goods here. Through SelectUSA, our nation works to promote and facilitate business investment. SelectUSA provides information assistance to the international investor community; serves as an ombudsman for existing and potential investors; advocates on behalf of U.S. cities, states, and regions competing for global investment; and counsels U.S. economic development organizations on investment attraction best practices. To learn more about why the United States is the best country in the world to develop technology, manufacture products, deliver services, and grow your business, visit http://www.SelectUSA.gov or call +1-202-482-6800.

# PATENT APPLICATION FEE DETERMINATION RECORD

Substitute for Form PTO-875

Application or Docket Number
14/316,489

## APPLICATION AS FILED - PART I

| FOR | NUMBER FILED (Column 1) | NUMBER EXTRA (Column 2) | SMALL ENTITY RATE($) | SMALL ENTITY FEE($) | OR | OTHER THAN SMALL ENTITY RATE($) | OTHER THAN SMALL ENTITY FEE($) |
|---|---|---|---|---|---|---|---|
| BASIC FEE (37 CFR 1.16(a), (b), or (c)) | N/A | N/A | N/A | 70 | | N/A | |
| SEARCH FEE (37 CFR 1.16(k), (i), or (m)) | N/A | N/A | N/A | 300 | | N/A | |
| EXAMINATION FEE (37 CFR 1.16(o), (p), or (q)) | N/A | N/A | N/A | 360 | | N/A | |
| TOTAL CLAIMS (37 CFR 1.16(i)) | 18 minus 20 = | * | x 40 = | 0.00 | OR | | |
| INDEPENDENT CLAIMS (37 CFR 1.16(h)) | 5 minus 3 = | * 2 | x 210 = | 420 | | | |
| APPLICATION SIZE FEE (37 CFR 1.16(s)) | If the specification and drawings exceed 100 sheets of paper, the application size fee due is $310 ($155 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s). | | | 0.00 | | | |
| MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j)) | | | | 0.00 | | | |
| | | | TOTAL | 1150 | | TOTAL | |

* If the difference in column 1 is less than zero, enter "0" in column 2.

## APPLICATION AS AMENDED - PART II

### AMENDMENT A

| | CLAIMS REMAINING AFTER AMENDMENT (Column 1) | | HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2) | PRESENT EXTRA (Column 3) | SMALL ENTITY RATE($) | SMALL ENTITY ADDITIONAL FEE($) | OR | OTHER THAN SMALL ENTITY RATE($) | OTHER THAN SMALL ENTITY ADDITIONAL FEE($) |
|---|---|---|---|---|---|---|---|---|---|
| Total (37 CFR 1.16(i)) | * | Minus | ** | = | x = | | OR | x = | |
| Independent (37 CFR 1.16(h)) | * | Minus | *** | = | x = | | OR | x = | |
| Application Size Fee (37 CFR 1.16(s)) | | | | | | | | | |
| FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | | OR | | |
| | | | | | TOTAL ADD'L FEE | | OR | TOTAL ADD'L FEE | |

### AMENDMENT B

| | CLAIMS REMAINING AFTER AMENDMENT (Column 1) | | HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2) | PRESENT EXTRA (Column 3) | RATE($) | ADDITIONAL FEE($) | OR | RATE($) | ADDITIONAL FEE($) |
|---|---|---|---|---|---|---|---|---|---|
| Total (37 CFR 1.16(i)) | * | Minus | ** | = | x = | | OR | x = | |
| Independent (37 CFR 1.16(h)) | * | Minus | *** | = | x = | | OR | x = | |
| Application Size Fee (37 CFR 1.16(s)) | | | | | | | | | |
| FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j)) | | | | | | | OR | | |
| | | | | | TOTAL ADD'L FEE | | OR | TOTAL ADD'L FEE | |

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20".
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3".
The "Highest Number Previously Paid For" (Total or Independent) is the highest found in the appropriate box in column 1.

PTO/AIA/15 (03-13)
Approved for use through 01/31/2014. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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# UTILITY PATENT APPLICATION TRANSMITTAL

*(Only for new nonprovisional applications under 37 CFR 1.53(b))*

| | |
|---|---|
| *Attorney Docket No.* | |
| *First Named Inventor* | Jed Margolin |
| *Title* | Flame Sensing System |
| *Express Mail Label No.* | |

## APPLICATION ELEMENTS

*See MPEP chapter 600 concerning utility patent application contents.*

*ADDRESS TO:* **Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450**

1. ☑ **Fee Transmittal Form** (PTO/SB/17 or equivalent)
2. ☑ **Applicant asserts small entity status.** See 37 CFR 1.27
3. ☐ **Applicant certifies micro entity status.** See 37 CFR 1.29. Applicant must attach form PTO/SB/15A or B or equivalent.
4. ☑ **Specification** [*Total Pages* 61]
   Both the claims and abstract must start on a new page.
   *(See MPEP § 608.01(a) for information on the preferred arrangement)*
5. ☑ **Drawing(s)** (35 U.S.C. 113) [*Total Sheets* 66]
6. **Inventor's Oath or Declaration** [*Total Pages* 127]
   *(including substitute statements under 37 CFR 1.64 and assignments serving as an oath or declaration under 37 CFR 1.63(e))*
   a. ☑ Newly executed (original or copy)
   b. ☐ A copy from a prior application (37 CFR 1.63(d))
7. ☑ **Application Data Sheet** ** See note below.*
   See 37 CFR 1.76 (PTO/AIA/14 or equivalent)
8. **CD-ROM or CD-R**
   in duplicate, large table, or Computer Program (*Appendix*)
   ☐ Landscape Table on CD
9. **Nucleotide and/or Amino Acid Sequence Submission**
   (*if applicable, items a. – c. are required*)
   a. ☐ Computer Readable Form (CRF)
   b. ☐ Specification Sequence Listing on:
      i. ☐ CD-ROM or CD-R (2 copies); or
      ii. ☐ Paper
   c. ☐ Statements verifying identity of above copies

## ACCOMPANYING APPLICATION PAPERS

10. ☐ **Assignment Papers** (cover sheet & document(s))
    Name of Assignee ____________
11. ☐ **37 CFR 3.73(c) Statement** (*when there is an assignee*) ☐ **Power of Attorney**
12. ☐ **English Translation Document** (*if applicable*)
13. ☑ **Information Disclosure Statement** (PTO/SB/08 or PTO-1449)
    ☑ Copies of citations attached
14. ☐ **Preliminary Amendment**
15. ☐ **Return Receipt Postcard** (*MPEP § 503*) (*Should be specifically itemized*)
16. ☐ **Certified Copy of Priority Document(s)** (*if foreign priority is claimed*)
17. ☐ **Nonpublication Request**
    Under 35 U.S.C. 122(b)(2)(B)(i). Applicant must attach form PTO/SB/35 or equivalent.
18. ☐ **Other:** ____________

***Note**: (1) Benefit claims under 37 CFR 1.78 and foreign priority claims under 1.55 **must** be included in an Application Data Sheet (ADS).
(2) For applications filed under 35 U.S.C. 111, the application must contain an ADS specifying the applicant if the applicant is an assignee, person to whom the inventor is under an obligation to assign, or person who otherwise shows sufficient proprietary interest in the matter. See 37 CFR 1.46(b).

## 19. CORRESPONDENCE ADDRESS

☑ The address associated with Customer Number: 23497 **OR** ☐ Correspondence address below

| | | | | | |
|---|---|---|---|---|---|
| Name | | | | | |
| Address | | | | | |
| City | | State | | Zip Code | |
| Country | | Telephone | | Email | |

| | | | |
|---|---|---|---|
| Signature | /Jed Margolin/ | Date | 06/26/2014 |
| Name (Print/Type) | Jed Margolin | Registration No. (Attorney/Agent) | |

# Privacy Act Statement

The **Privacy Act of 1974 (P.L. 93-579)** requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (*i.e.*, GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

| **Application Data Sheet 37 CFR 1.76** | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

## Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

## Inventor Information:

**Inventor 1** [Remove]

**Legal Name**

| **Prefix** | **Given Name** | **Middle Name** | **Family Name** | **Suffix** |
|---|---|---|---|---|
| Mr. | Jed | | Margolin | |

**Residence Information (Select One)** ◉ US Residency ○ Non US Residency ○ Active US Military Service

| **City** | VC Highlands | **State/Province** | NV | **Country of Residence** i | US |
|---|---|---|---|---|---|

**Mailing Address of Inventor:**

| | | | |
|---|---|---|---|
| **Address 1** | 1981 Empire Rd. | | |
| **Address 2** | | | |
| **City** | Reno | **State/Province** | NV |
| **Postal Code** | 89521-7430 | **Country** i | US |

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. [Add]

## Correspondence Information:

**Enter either Customer Number or complete the Correspondence Information section below.**
**For further information see 37 CFR 1.33(a).**

☐ **An Address is being provided for the correspondence Information of this application.**

| | | |
|---|---|---|
| **Customer Number** | 23497 | |
| **Email Address** | jm@jmargolin.com | [Add Email] [Remove Email] |

## Application Information:

| | | | |
|---|---|---|---|
| **Title of the Invention** | Flame Sensing System | | |
| **Attorney Docket Number** | | **Small Entity Status Claimed** | ☒ |
| **Application Type** | Nonprovisional | | |
| **Subject Matter** | Utility | | |
| **Total Number of Drawing Sheets (if any)** | 66 | **Suggested Figure for Publication (if any)** | 90 |

**Filing By Reference :**

| Application Data Sheet 37 CFR 1.76 | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

| Application number of the previously filed application | Filing date (YYYY-MM-DD) | Intellectual Property Authority or Country i |
|---|---|---|
| | | |

## Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

## Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

| | | | |
|---|---|---|---|
| Please Select One: | ◉ Customer Number | ○ US Patent Practitioner | ○ Limited Recognition (37 CFR 11.9) |
| Customer Number | 23497 | | |

## Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.
When referring to the current application, please leave the application number blank.

| Prior Application Status | | | Remove |
|---|---|---|---|
| Application Number | Continuity Type | Prior Application Number | Filing Date (YYYY-MM-DD) |
| | | | |

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button. Add

## Foreign Priority Information:

| Application Data Sheet 37 CFR 1.76 | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(d). When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX) i the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(h)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

Remove

| Application Number | Country i | Filing Date (YYYY-MM-DD) | Access Code i (if applicable) |
|---|---|---|---|
| | | | |

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button. Add

## Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.
NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

## Authorization to Permit Access:

☒ Authorization to Permit Access to the Instant Application by the Participating Offices

| **Application Data Sheet 37 CFR 1.76** | Attorney Docket Number | |
|---|---|---|
| | Application Number | |

| Title of Invention | Flame Sensing System |
|---|---|

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date of filing this Authorization.

## Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

**Applicant 1** Remove

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Clear

○ Assignee ○ Legal Representative under 35 U.S.C. 117 ○ Joint Inventor

○ Person to whom the inventor is obligated to assign. ○ Person who shows sufficient proprietary interest

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :

If the Applicant is an Organization check here. ☐

| Prefix | **Given Name** | Middle Name | **Family Name** | Suffix |
|---|---|---|---|---|
| | | | | |

| Application Data Sheet 37 CFR 1.76 | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

| **Mailing Address Information:** | | | |
|---|---|---|---|
| **Address 1** | | | |
| Address 2 | | | |
| **City** | | **State/Province** | |
| **Country** i | | Postal Code | |
| Phone Number | | Fax Number | |
| Email Address | | | |

Additional Applicant Data may be generated within this form by selecting the Add button. Add

## Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not subsitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

**Assignee 1**

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication . An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

Remove

If the Assignee or Non-Applicant Assignee is an Organization check here. ☐

| Prefix | **Given Name** | Middle Name | **Family Name** | Suffix |
|---|---|---|---|---|
| | | | | |

**Mailing Address Information For Assignee including Non-Applicant Assignee:**

| **Address 1** | | | |
|---|---|---|---|
| Address 2 | | | |
| **City** | | **State/Province** | |
| **Country** i | | Postal Code | |
| Phone Number | | Fax Number | |
| Email Address | | | |

Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button. Add

| Application Data Sheet 37 CFR 1.76 | Attorney Docket Number | |
|---|---|---|
| | Application Number | |
| Title of Invention | Flame Sensing System | |

## Signature:

Remove

| NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications | | | | | |
|---|---|---|---|---|---|
| **Signature** | /Jed Margolin/ | | | Date (YYYY-MM-DD) | 2014-06-26 |
| First Name | Jed | Last Name | Margolin | Registration Number | |
| Additional Signature may be generated within this form by selecting the Add button. Add | | | | | |

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

# Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

# FEE TRANSMITTAL

☑ Applicant asserts small entity status. See 37 CFR 1.27.

☐ Applicant certifies micro entity status. See 37 CFR 1.29. Form PTO/SB/15A or B or equivalent must either be enclosed or have been submitted previously.

TOTAL AMOUNT OF PAYMENT ($) 1,150

| Complete if known | |
|---|---|
| Application Number | |
| Filing Date | |
| First Named Inventor | Jed Margolin |
| Examiner Name | |
| Art Unit | |
| Practitioner Docket No. | |

**METHOD OF PAYMENT** (check all that apply)

☐ Check ☑ Credit Card ☐ Money Order ☐ None ☐ Other (please identify): ____

☐ Deposit Account Deposit Account Number: ____ Deposit Account Name: ____

For the above-identified deposit account, the Director is hereby authorized to (check all that apply):

☐ Charge fee(s) indicated below ☐ Charge fee(s) indicated below, **except for the filing fee**

☐ Charge any additional fee(s) or underpayment of fee(s) under 37 CFR 1.16 and 1.17 ☐ Credit any overpayment of fee(s)

**WARNING**: Information on this form may become public. Credit card information should not be included on this form. Provide credit card information and authorization on PTO-2038.

**FEE CALCULATION**

**1. BASIC FILING, SEARCH, AND EXAMINATION FEES (U = undiscounted fee; S = small entity fee; M = micro entity fee)**

| | FILING FEES | | | SEARCH FEES | | | EXAMINATION FEES | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Application Type** | **U ($)** | **S ($)** | **M ($)** | **U ($)** | **S ($)** | **M ($)** | **U ($)** | **S ($)** | **M ($)** | **Fees Paid ($)** |
| Utility | 280 | 140* | 70 | 600 | 300 | 150 | 720 | 360 | 180 | 730 |
| Design | 180 | 90 | 45 | 120 | 60 | 30 | 460 | 230 | 115 | |
| Plant | 180 | 90 | 45 | 380 | 190 | 95 | 580 | 290 | 145 | |
| Reissue | 280 | 140 | 70 | 600 | 300 | 150 | 2,160 | 1,080 | 540 | |
| Provisional | 260 | 130 | 65 | 0 | 0 | 0 | 0 | 0 | 0 | |

* The $140 small entity status filing fee for a utility application is further reduced to $70 for a small entity status applicant who files the application via EFS-Web.

**2. EXCESS CLAIM FEES**

| **Fee Description** | **Undiscounted Fee ($)** | **Small Entity Fee ($)** | **Micro Entity Fee ($)** |
|---|---|---|---|
| Each claim over 20 (including Reissues) | 80 | 40 | 20 |
| Each independent claim over 3 (including Reissues) | 420 | 210 | 105 |
| Multiple dependent claims | 780 | 390 | 195 |

| **Total Claims** | | **Extra Claims** | | **Fee ($)** | | **Fee Paid ($)** |
|---|---|---|---|---|---|---|
| 18 | -20 or HP = | 0 | x | | = | 0 |

HP = highest number of total claims paid for, if greater than 20.

| **Indep. Claims** | | **Extra Claims** | | **Fee ($)** | | **Fee Paid ($)** |
|---|---|---|---|---|---|---|
| 5 | -3 or HP = | 2 | x | 210 | = | 420 |

HP = highest number of independent claims paid for, if greater than 3.

**Multiple Dependent Claims**

| **Fee ($)** | **Fee Paid ($)** |
|---|---|
| | 0 |

**3. APPLICATION SIZE FEE**

If the specification and drawings exceed 100 sheets of paper (excluding electronically filed sequence or computer listings under 37 CFR 1.52(e)), the application size fee due is $400 ($200 for small entity) ($100 for micro entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s).

| **Total Sheets** | | **Extra Sheets** | | **Number of each additional 50 or fraction thereof** | | **Fee ($)** | | **Fee Paid ($)** |
|---|---|---|---|---|---|---|---|---|
| 96 | - 100 = | 0 | / 50 = | 0 (round **up** to a whole number) | x | | = | 0 |

**4. OTHER FEE(S)**

| | **Fees Paid ($)** |
|---|---|
| Non-English specification, $130 fee (no small or micro entity discount) | 0 |
| **Non-electronic filing fee under 37 CFR 1.16(t) for a utility application, $400 fee ($200 small or micro entity)** | 0 |
| Other (e.g., late filing surcharge): ____ | 0 |

SUBMITTED BY

| | | | |
|---|---|---|---|
| Signature | /Jed Margolin/ | Registration No. (Attorney/Agent) | Telephone 775-847-7845 |
| Name (Print/Type) | Jed Margolin | | Date 06/26/2014 |

# Privacy Act Statement

The **Privacy Act of 1974 (P.L. 93-579)** requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (*i.e.*, GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

PTO/AIA/01 (06-12)
Approved for use through 01/31/2014. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

# DECLARATION (37 CFR 1.63) FOR UTILITY OR DESIGN APPLICATION USING AN APPLICATION DATA SHEET (37 CFR 1.76)

| **Title of Invention** | Flame Sensing System |
|---|---|

As the below named inventor, I hereby declare that:

This declaration is directed to:

- [x] The attached application, or
- [ ] United States application or PCT international application number ____________________

filed on ____________________.

The above-identified application was made or authorized to be made by me.

I believe that I am the original inventor or an original joint inventor of a claimed invention in the application.

I hereby acknowledge that any willful false statement made in this declaration is punishable under 18 U.S.C. 1001 by fine or imprisonment of not more than five (5) years, or both.

## WARNING:

Petitioner/applicant is cautioned to avoid submitting personal information in documents filed in a patent application that may contribute to identity theft. Personal information such as social security numbers, bank account numbers, or credit card numbers (other than a check or credit card authorization form PTO-2038 submitted for payment purposes) is never required by the USPTO to support a petition or an application. If this type of personal information is included in documents submitted to the USPTO, petitioners/applicants should consider redacting such personal information from the documents before submitting them to the USPTO. Petitioner/applicant is advised that the record of a patent application is available to the public after publication of the application (unless a non-publication request in compliance with 37 CFR 1.213(a) is made in the application) or issuance of a patent. Furthermore, the record from an abandoned application may also be available to the public if the application is referenced in a published application or an issued patent (see 37 CFR 1.14). Checks and credit card authorization forms PTO-2038 submitted for payment purposes are not retained in the application file and therefore are not publicly available.

LEGAL NAME OF INVENTOR

Inventor: Jed Margolin Date (Optional) : 06/26/2014

Signature: Jed Margolin

Note: An application data sheet (PTO/SB/14 or equivalent), including naming the entire inventive entity, must accompany this form or must have been previously filed. Use an additional PTO/AIA/01 form for each additional inventor.

PTO/SB/08a (07-09)
Approved for use through 07/31/2012. OMB 0651-0031
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE


Substitute for form 1449/PTO

# INFORMATION DISCLOSURE STATEMENT BY APPLICANT

*(Use as many sheets as necessary)*

Sheet 1 of 4

| Complete if Known | |
|---|---|
| Application Number | |
| Filing Date | |
| First Named Inventor | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |

**U. S. PATENT DOCUMENTS**

| Examiner Initials* | Cite No.[1] | Document Number<br>Number-Kind Code[2] *(if known)* | Publication Date MM-DD-YYYY | Name of Patentee or Applicant of Cited Document | Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear |
|---|---|---|---|---|---|
| | 1 | US- 1,688,126 | 10/16/1928 | Metcalfe | Fig 1; Page 3: 70–79 |
| | 2 | US- 2,112,736 | 03/29/1938 | Cockrell | Page 1:41– Page 2:15 |
| | 3 | US- 2,136,256 | 11/08/1938 | Sweet | Page 1:4–Page 2:2 |
| | 4 | US- 3,301,307 | 01/31/1967 | Kobayashi, et al. | Col 2: 3 -15 |
| | 5 | US- 4,082,493 | 04/04/1978 | Dahlgren | Fig 2; C3:32–42; Tbl:C3:20-30 |
| | 6 | US- 8,310,801 | 11/13/2012 | McDonald, et al. | Col 2: 10–44 |
| | 7 | US- 6,404,342 | 06/11/2002 | Planer, et al. | Col 1: 21–32 |
| | 16 | US- 4,317,487 | 03/02/1982 | Merkl | Col 2:59 – Col 3: 11 |
| | 19 | US- 307,031 | 10/21/1884 | Edison | Page 1:16–29 |
| | 20 | US- 803,684 | 11/07/1905 | Fleming | Page 1:11–37 |
| | 23 | US- 1,077,628 | 11/04/1913 | Mershon | Page 1:40-50 |
| | 27 | US- 3,956,080 | 05/11/1976 | Hradcovsky, et al. | Col 2: 10–48 |
| | 33 | US- 2,709,799 | 05/31/1955 | Norton | |
| | 34 | US- 2,804,608 | 08/27/1957 | Carbauh | |
| | | US- | | | |
| | | US- | | | |
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| | | US- | | | |

**FOREIGN PATENT DOCUMENTS**

| Examiner Initials* | Cite No.[1] | Foreign Patent Document<br>Country Code[3] -Number [4] -Kind Code[5] *(if known)* | Publication Date MM-DD-YYYY | Name of Patentee or Applicant of Cited Document | Pages, Columns, Lines, Where Relevant Passages Or Relevant Figures Appear | T[6] |
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| Examiner Signature | | Date Considered | |
|---|---|---|---|

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant. [1] Applicant's unique citation designation number (optional). [2] See Kinds Codes of USPTO Patent Documents at www.uspto.gov or MPEP 901.04. [3] Enter Office that issued the document, by the two-letter code (WIPO Standard ST.3). [4] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [5] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [6] Applicant is to place a check mark here if English language Translation is attached.

Substitute for form 1449/PTO

# INFORMATION DISCLOSURE STATEMENT BY APPLICANT

*(Use as many sheets as necessary)*

| Complete if Known | |
|---|---|
| **Application Number** | |
| **Filing Date** | |
| **First Named Inventor** | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |



**NON PATENT LITERATURE DOCUMENTS**

| Examiner Initials* | Cite No.[1] | Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published. | T[2] |
|---|---|---|---|
| | 8 | Prediction and Measurement of Electron Density and Collision Frequency in a Weakly Ionised Pine Fire; by MPHALE, MOHAN, and HERON; Int J Infrared Milli Waves (2007) 28:251-262; DOI 10.1007/s10762-007-9199-7; http://eprints.jcu.edu.au/2655/1/17300_Mphale_et_al_2007 | |
| | 9 | Conduction of Electricity Through Gases by J. J. THOMSON; Cambridge Cambridge University Press; 1903,1906; Chapter IX Ionization in Gases from Flames; page 228, PDF page 8; http://trove.nla.gov.au/goto?i=book&w=808233&d=http%3A%2F%2Fopenlibrary.org%2Fbooks%2FOL7102511M | |
| | 10 | About Plasmas from the Coalition For Plasma Science; Plasma and Flames - The Burning Question; http://www.plasmacoalition.org/plasma_writeups/flame.pdf | |
| | 11 | Plasma Fundamentals and Applications; by Dr. I.J. VAN DER WALT, Senior Scientist Necsa contains a chart (PDF page 8) http://www.nstf.org.za/ShowProperty?nodePath=/NSTF%20Repository/NSTF/files/ScienceCouncils/2012/PlasmaFundamentals.pdf | |
| | 12 | Introduction to Combustion; by Stephen R. Turns, McGraw Hill Education (India); Page 108, PDF page 3; page 159, bottom of PDF page 5. | |
| | 13 | Burning Sulfur Compounds; Banks Engineering - Tulsa; http://www.banksengineering.com/Burning%20Sulfur%20Compounds.pdf | |

| Examiner Signature | | Date Considered | |
|---|---|---|---|

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

1 Applicant's unique citation designation number (optional). 2 Applicant is to place a check mark here if English language Translation is attached.

Substitute for form 1449/PTO

# INFORMATION DISCLOSURE STATEMENT BY APPLICANT

*(Use as many sheets as necessary)*

| Complete if Known | |
|---|---|
| **Application Number** | |
| **Filing Date** | |
| **First Named Inventor** | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |



## NON PATENT LITERATURE DOCUMENTS

| Examiner Initials* | Cite No.[1] | Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published. | T[2] |
|---|---|---|---|
| | 14 | Alkali metal halide, Wikipedia January 19, 2014; http://en.wikipedia.org/wiki/Alkali_metal_halide | |
| | 15 | Alkali Metal, Wikipedia January 19, 2014; http://en.wikipedia.org/wiki/Alkali_metal | |
| | 17 | Grades of Propane - Gas Purity and Quality http://www.propane101.com/propanegradesandquality.htm | |
| | 18 | The Truth About Propane http://www.thriftypropane.com/truthaboutpropane.aspx | |
| | 21 | Definition of "Electrolyte" retrieved from Wikipedia 1/31/2014 http://en.wikipedia.org/wiki/Electrolyte | |
| | 22 | Dissertation Counter Electromotive Force in the Aluminum Rectifier; ALBERT LEWIS FITCH; Press of the New Era Printing Co.; Lancaster, Pa; 1917; Pages 15-17). | |
| | 24 | General Descriptions of Aluminum Electrolytic Capacitors, 1-1 Principles of Aluminum Electrolytic Capacitors' Nichicon; Page 1. http://www.nichicon.co.jp/english/products/pdf/aluminum.pdf | |

| Examiner Signature | | Date Considered | |
|---|---|---|---|

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

1 Applicant's unique citation designation number (optional). 2 Applicant is to place a check mark here if English language Translation is attached.

PTO/SB/08b (07-09)
Approved for use through 07/31/2012. OMB 0651-0031
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Substitute for form 1449/PTO

# INFORMATION DISCLOSURE STATEMENT BY APPLICANT

*(Use as many sheets as necessary)*

| Complete if Known | |
|---|---|
| **Application Number** | |
| **Filing Date** | |
| **First Named Inventor** | Jed Margolin |
| Art Unit | |
| Examiner Name | |
| Attorney Docket Number | |



## NON PATENT LITERATURE DOCUMENTS

| Examiner Initials* | Cite No.[1] | Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published. | T[2] |
|---|---|---|---|
| | 25 | Batteries and electrochemical capacitors; HECTOR D. ABRUNA, YASUKUKI KIYA, and JAY C. HENDERSON; Physics Today Physics Today December 2008, page 43-47 | |
| | 26 | Electroplating; from Wikipedia, retrieved 2/1/2014. http://en.wikipedia.org/wiki/Electroplating | |
| | 28 | Front pages from datasheets for 5U4GT, 5Y3GT, and 6X4/12X4 vacuum tube rectifiers. | |
| | 29 | Visual Analyzer 2011 XE Beta 0.3.2 - Visual Analyzer is a real time software program that contains a comprehensive set of measurement instruments, including an FFT Analyzer. It runs on a PC running Windows. http://www.sillanumsoft.org/ | |
| | 30 | The Art of Electronics, PAUL HOROWITZ and WINFIELD HILL, Cambridge University Press, 1991, pages 885-886. | |
| | 31 | Sine-Wave Oscillator, RON MANCINI and RICHARD PALMER, Texas Instruments, Application Note SLOA060 - March 2001; http://www.ti.com/litv/pdf/sloa060 | |
| | 32 | Datasheet for LM13700, Texas Instruments, Figure 37 Sinusoidal VCO. http://www.ti.com/cn/lit/gpn/lm13700 | |

| Examiner Signature | | Date Considered | |
|---|---|---|---|

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

1 Applicant's unique citation designation number (optional). 2 Applicant is to place a check mark here if English language Translation is attached.

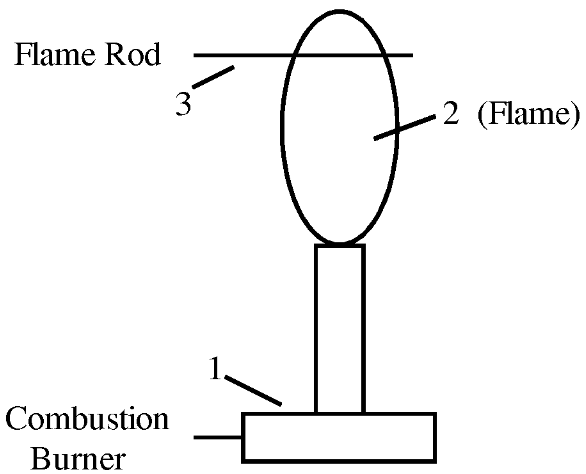



Figure 1

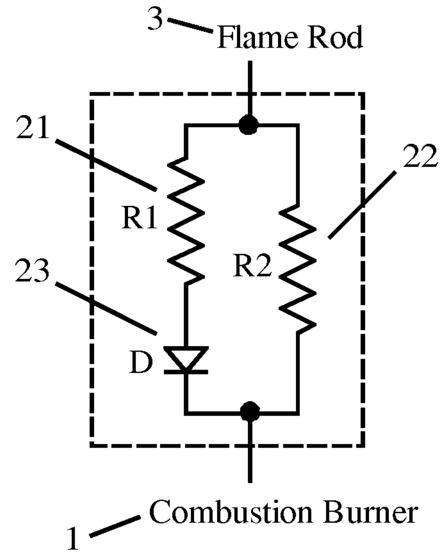



Figure 2

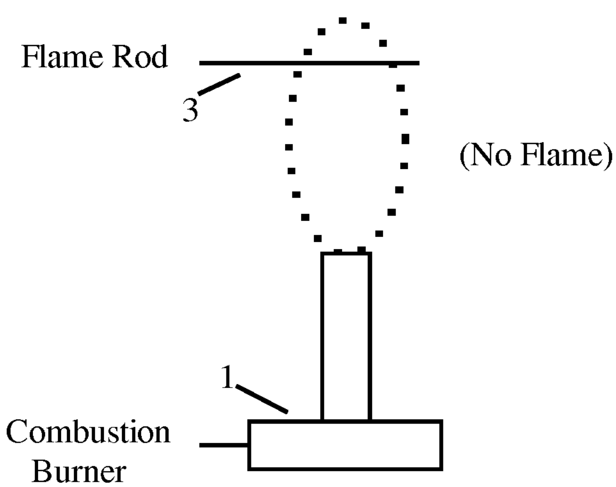



Figure 3

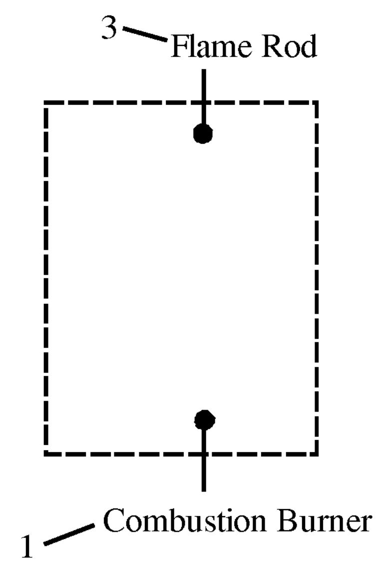



Figure 4

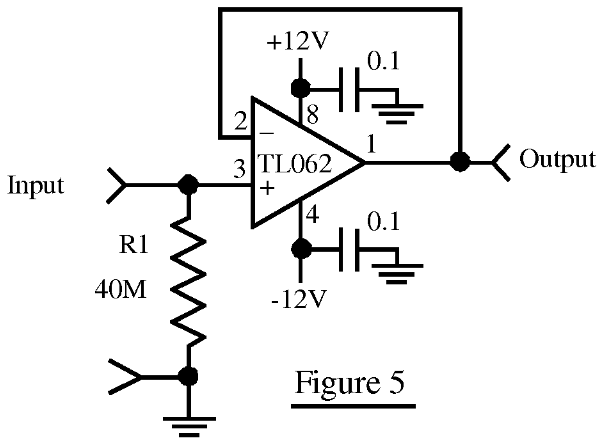



Figure 5

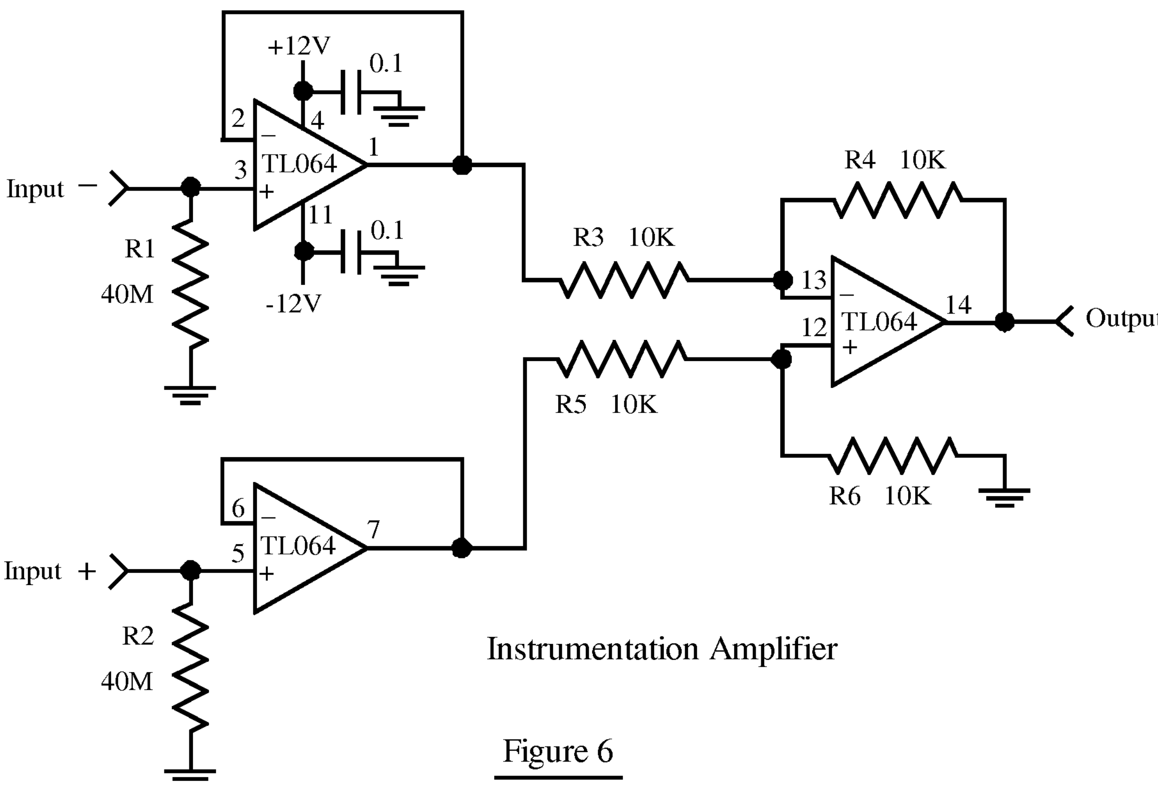



Figure 6

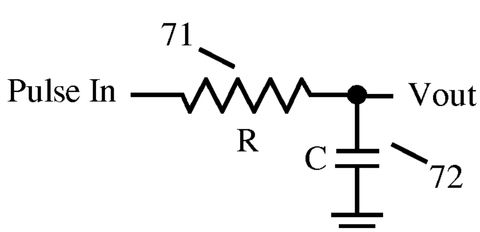



Figure 7

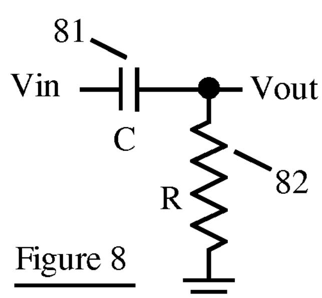



Figure 8

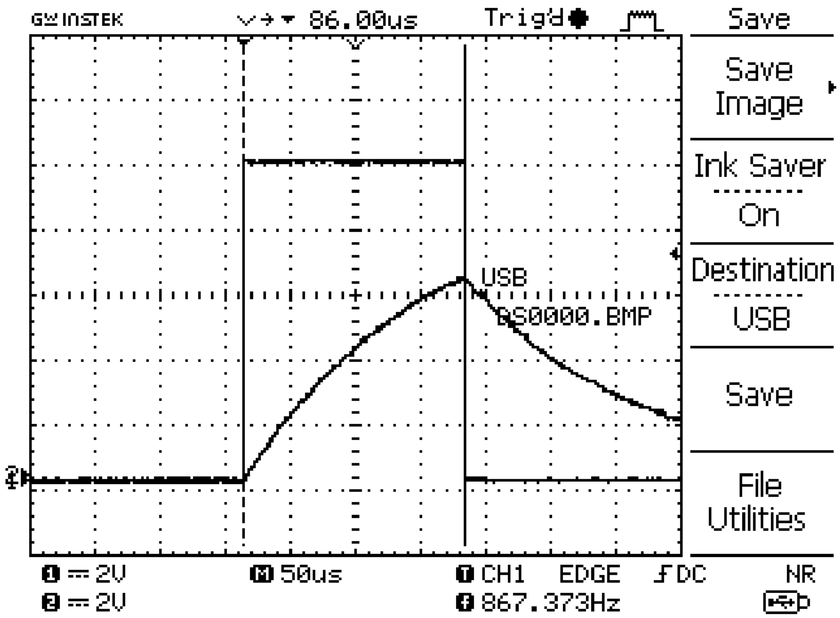



Figure 9

**Table 2**

$$\frac{Vout}{Vin} = \frac{R}{R + 1/(s*C)} \qquad H(s) = \frac{s}{s + 1/(R*C)}$$

Substitute $s = j\omega$

$$H(j\omega) = \frac{j\omega}{j\omega + 1/(R*C)}$$

The magnitude response $|H(j\omega)| = \dfrac{\omega}{Sqrt(\omega^2 + 1/(R*C)^2\,)}$

The Phase Response $\theta(j\omega) = 90^o - \tan^{-1}(\omega*R*C)$

Where $\omega = 2 * pi * Frequency$

Therefore, for

| | |
|---|---|
| Vin = 120 VAC | (120) |
| R = 1 megohm | $(1*10^6)$ |
| C = 160 pF/10*2.5 | $(40*10^{-12})$ |
| Frequency = 60 Hz | (60) |

The magnitude of Vout is approximately 1.81 VAC
The phase response is a phase lead of approximately 8.9 degrees.

Figure 10

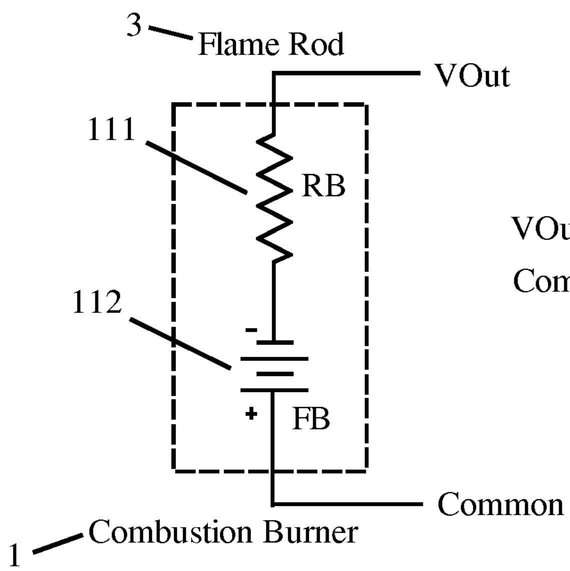



Figure 11

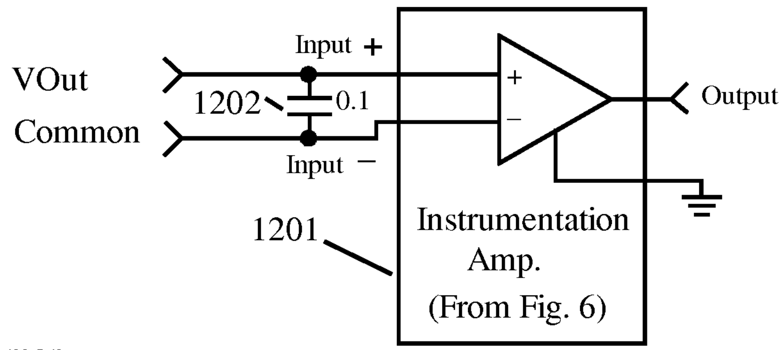



Figure 12

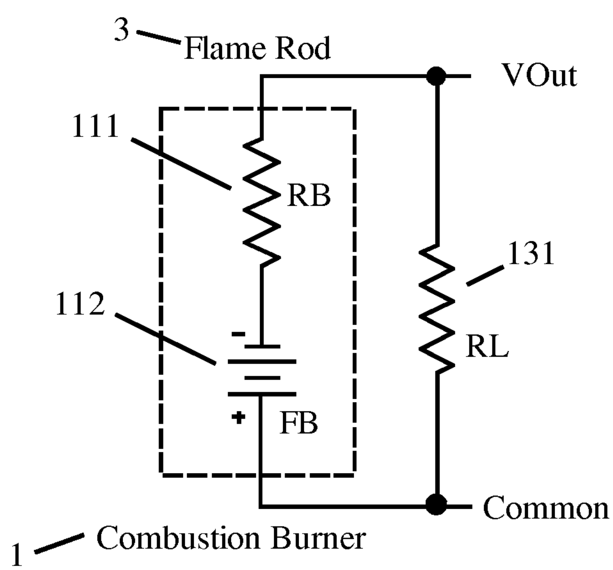



Figure 13

**Table 5.4** (continued)

| No. | Reaction | Forward Rate Coefficient[a] A | b | E |
|---|---|---|---|---|
| ***N-Containing Reactions (continued)*** | | | | |
| 201 | $NH_2 + O \rightarrow H + HNO$ | 3.9E + 13 | 0.0 | 0.0 |
| 202 | $NH_2 + H \rightarrow NH + H_2$ | 4.00E + 13 | 0.0 | 3,650 |
| 203 | $NH_2 + OH \rightarrow NH + H_2O$ | 9.00E + 07 | 1.5 | −460 |
| 204 | $NNH \rightarrow N_2 + H$ | 3.30E + 08 | 0.0 | 0.0 |
| 205 | $NNH + M \rightarrow N_2 + H + M$ | 1.30E + 14 | −0.1 | 4,980 |
| 206 | $NNH + O_2 \rightarrow HO_2 + N_2$ | 5.00E + 12 | 0.0 | 0.0 |
| 207 | $NNH + O \rightarrow OH + N_2$ | 2.50E + 13 | 0.0 | 0.0 |
| 208 | $NNH + O \rightarrow NH + NO$ | 7.00E + 13 | 0.0 | 0.0 |
| 209 | $NNH + H \rightarrow H_2 + N_2$ | 5.00E + 13 | 0.0 | 0.0 |
| 210 | $NNH + OH \rightarrow H_2O + N_2$ | 2.00E + 13 | 0.0 | 0.0 |
| 211 | $NNH + CH_3 \rightarrow CH_4 + N_2$ | 2.50E + 13 | 0.0 | 0.0 |
| 212 | $H + NO + M \rightarrow HNO + M$ | 4.48E + 19 | −1.3 | 740 |
| 213 | $HNO + O \rightarrow NO + OH$ | 2.50E + 13 | 0.0 | 0.0 |
| 214 | $HNO + H \rightarrow H_2 + NO$ | 9.00E + 11 | 0.7 | 660 |
| 215 | $HNO + OH \rightarrow NO + H_2O$ | 1.30E + 07 | 1.9 | −950 |
| 216 | $HNO + O_2 \rightarrow HO_2 + NO$ | 1.00E + 13 | 0.0 | 13,000 |
| 217 | $CN + O \rightarrow CO + N$ | 7.70E + 13 | 0.0 | 0.0 |
| 218 | $CN + OH \rightarrow NCO + H$ | 4.00E + 13 | 0.0 | 0.0 |
| 219 | $CN + H_2O \rightarrow HCN + OH$ | 8.00E + 12 | 0.0 | 7,460 |
| 220 | $CN + O_2 \rightarrow NCO + O$ | 6.14E + 12 | 0.0 | −440 |
| 221 | $CN + H_2 \rightarrow HCN + H$ | 2.95E + 05 | 2.5 | 2,240 |
| 222 | $NCO + O \rightarrow NO + CO$ | 2.35E + 13 | 0.0 | 0.0 |
| 223 | $NCO + H \rightarrow NH + CO$ | 5.40E + 13 | 0.0 | 0.0 |
| 224 | $NCO + OH \rightarrow NO + H + CO$ | 2.50E + 12 | 0.0 | 0.0 |
| 225 | $NCO + N \rightarrow N_2 + CO$ | 2.00E + 13 | 0.0 | 0.0 |
| 226 | $NCO + O_2 \rightarrow NO + CO_2$ | 2.00E + 12 | 0.0 | 20,000 |
| 227 | $NCO + M \rightarrow N + CO + M$ | 3.10E + 14 | 0.0 | 54,050 |
| 228 | $NCO + NO \rightarrow N_2O + CO$ | 1.90E + 17 | −1.5 | 740 |
| 229 | $NCO + NO \rightarrow N_2 + CO_2$ | 3.80E + 18 | −2.0 | 800 |
| 230 | $HCN + M \rightarrow H + CN + M$ | 1.04E + 29 | −3.3 | 126,600 |
| 231 | $HCN + O \rightarrow NCO + H$ | 2.03E + 04 | 2.6 | 4,980 |
| 232 | $HCN + O \rightarrow NH + CO$ | 5.07E + 03 | 2.6 | 4,980 |
| 233 | $HCN + O \rightarrow CN + OH$ | 3.91E + 09 | 1.6 | 26,600 |
| 234 | $HCN + OH \rightarrow HOCN + H$ | 1.10E + 06 | 2.0 | 13,370 |
| 235 | $HCN + OH \rightarrow HNCO + H$ | 4.40E + 03 | 2.3 | 6,400 |
| 236 | $HCN + OH \rightarrow NH_2 + CO$ | 1.60E + 02 | 2.6 | 9,000 |
| 237 | $H + HCN + M \rightarrow H_2CN + M$ | | pressure dependent | |
| 238 | $H_2CN + N \rightarrow N_2 + CH_2$ | 6.00E + 13 | 0.0 | 400 |
| 239 | $C + N_2 \rightarrow CN + N$ | 6.30E + 13 | 0.0 | 46,020 |
| 240 | $CH + N_2 \rightarrow HCN + N$ | 3.12E + 09 | 0.9 | 20,130 |
| 241 | $CH + N_2 (+M) \rightarrow HCNN (+M)$ | | pressure dependent | |
| 242 | $CH_2 + N_2 \rightarrow HCN + NH$ | 1.00E + 13 | 0.0 | 74,000 |
| 243[b] | $CH_2(S) + N_2 \rightarrow NH + HCN$ | 1.00E + 11 | 0.0 | 65,000 |

Figure 14 (from Turns)

# Table 1

**Table 17.12** Composition (mol%) and properties of natural gas from sources in the United States [28][a]

| **Location** | **$CH_4$** | **$C_2H_6$** | **$C_3H_8$** | **$C_4H_{10}$** | **$CO_2$** | **$N_2$** | **Density[c] (kg/m³)** | **HHV[d] (kJ/M³)** | **HHV[d] (kJ/hg)** |
|---|---|---|---|---|---|---|---|---|---|
| Alaska | 99.6 | — | — | — | — | 0.4 | 0.686 | 37,590 | 54,800 |
| Birmingham, | 90.0 | 5.0 | — | — | — | 5.0 | 0.735 | 37,260 | 50,690 |
| East Ohio[b] | 94.1 | 3.01 | 0.42 | 0.28 | 0.71 | 1.41 | 0.723 | 38,260 | 52,940 |
| Kansas City, | 84.1 | 6.7 | — | — | 0.8 | 8.4 | 0.772 | 36,140 | 46,830 |
| Pittsburgh, | 83.4 | 15.8 | — | — | — | 0.8 | 0.772 | 41,840 | 54,215 |

[a] Although not explicitly stated in Ref. [28], these gases appear to be pipeline gases.
[b] Also contains 0.01 % $H_2$ and 0.01% $O_2$.
[c] At 1 atm and 15.6°C (60 F).
[d] Higher heating values for 1 atm and 15.6°C (60 F) [28].

Figure 15 (Turns Table 17.12)

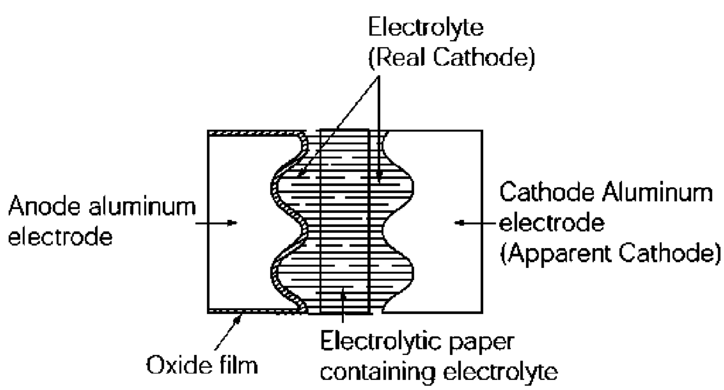



**Fig. 1 - 1**

Figure 16 (Nichicon Figure 1-1)

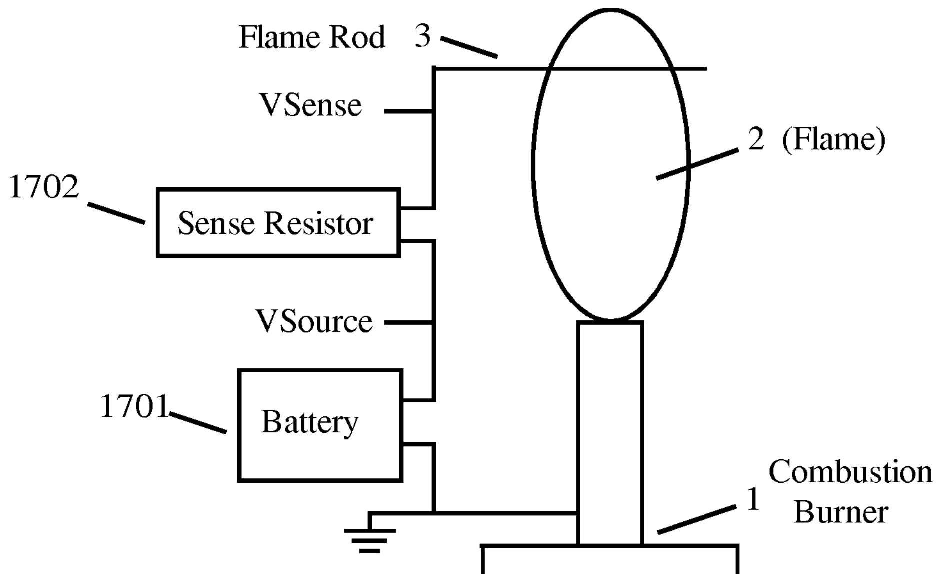



Figure 17

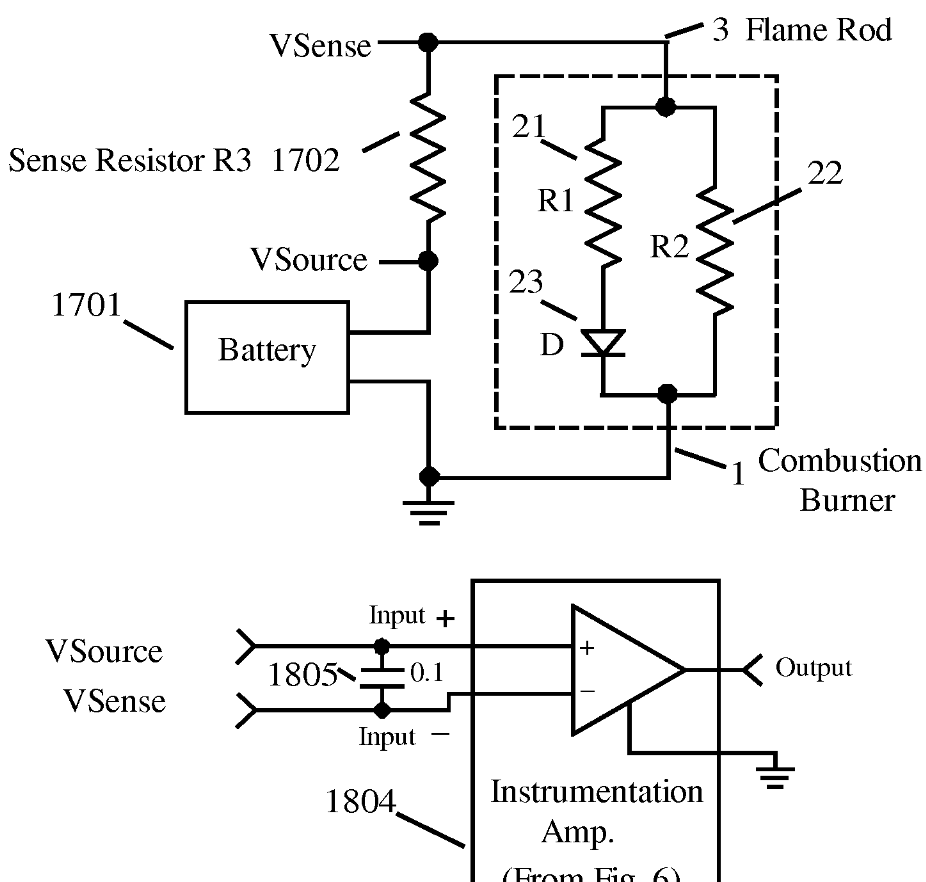



Figure 18

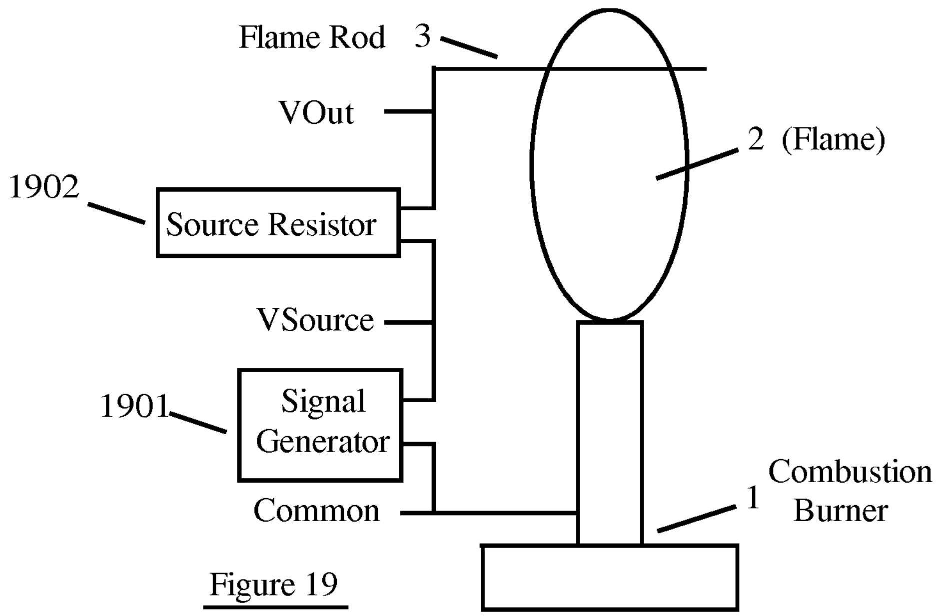



Figure 19

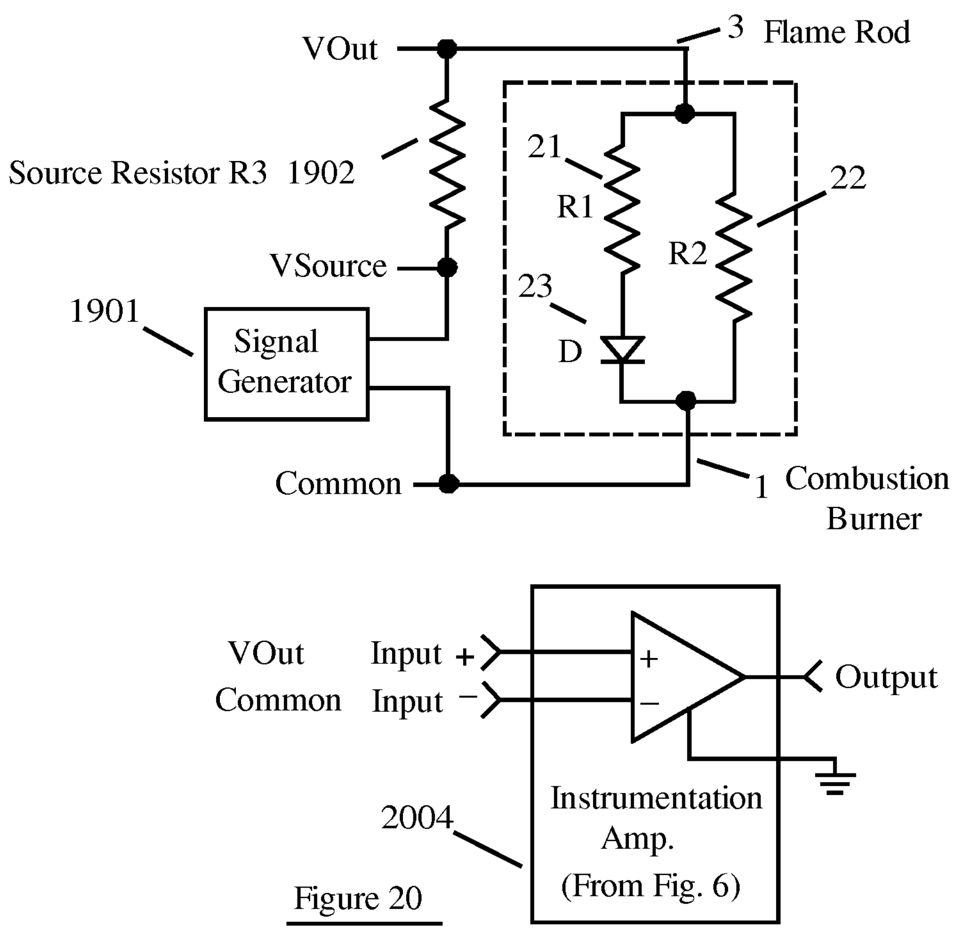



Figure 20

Experiment 2 -1.27V open circuit

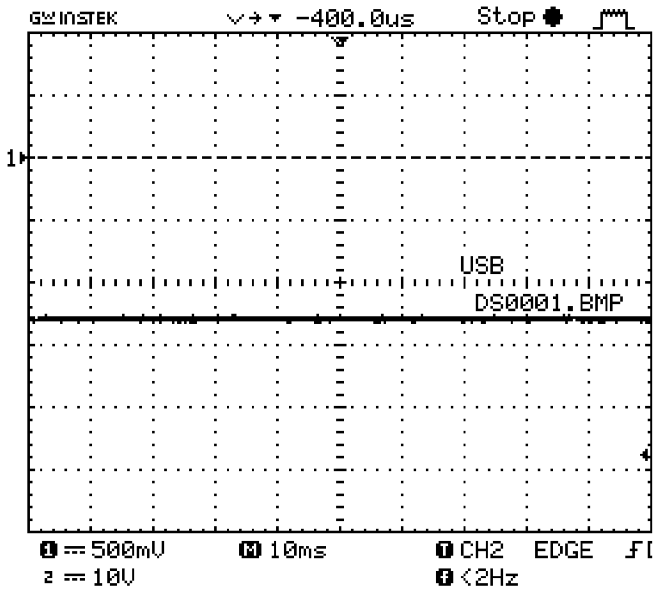



Figure 21a

Experiment 2 0.68 V (4.3 megohm load)

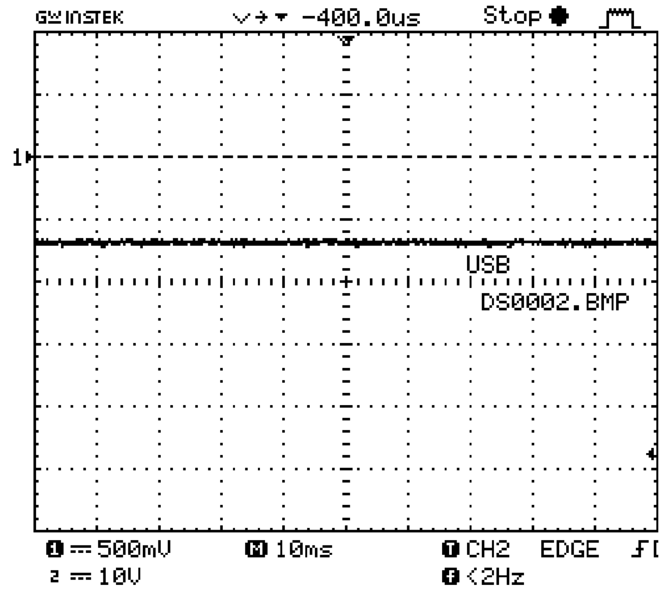



Figure 21b

Experiment 3 -40 mV

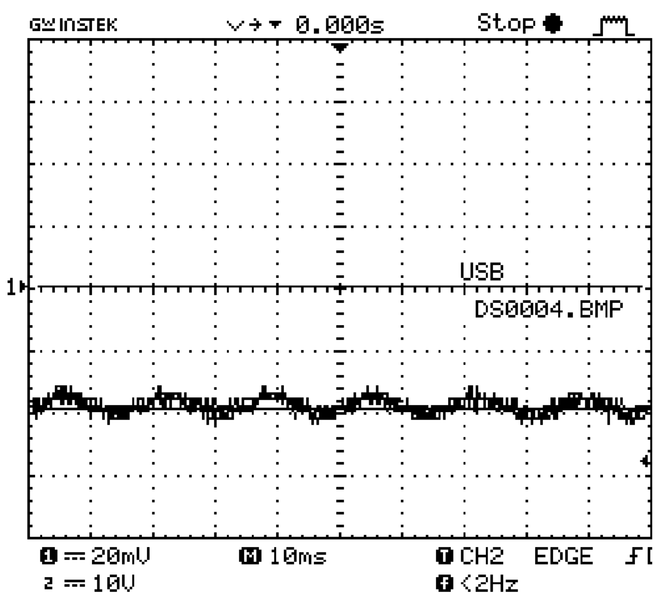



Figure 22a

Experiment 3 +1.39 V

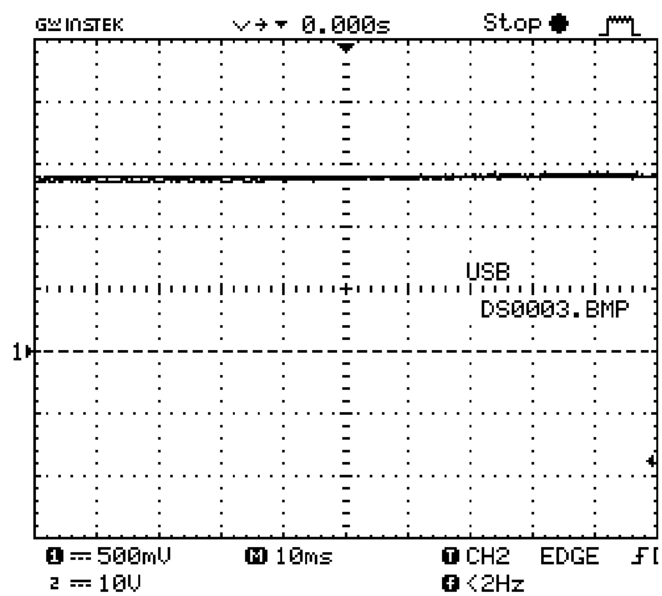



Figure 22b

Experiment 4 100 Hz +2.79 V to -7.2 V

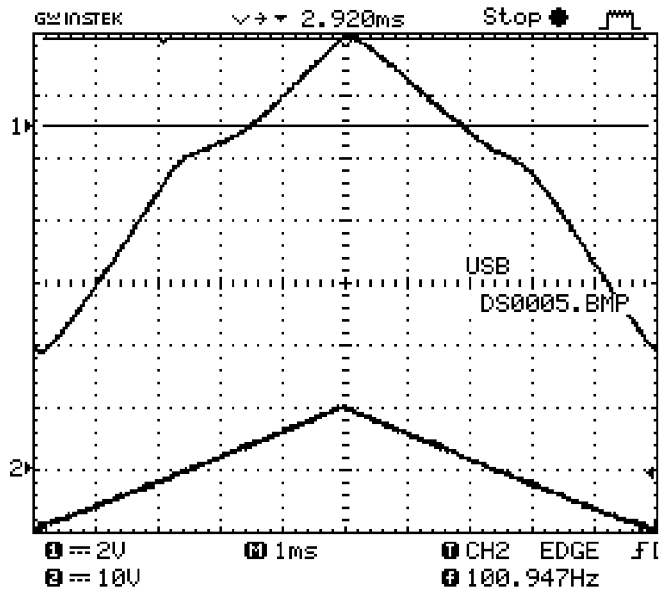



Figure 23a

Experiment 4 Leading Edge -960 mV to 0 V

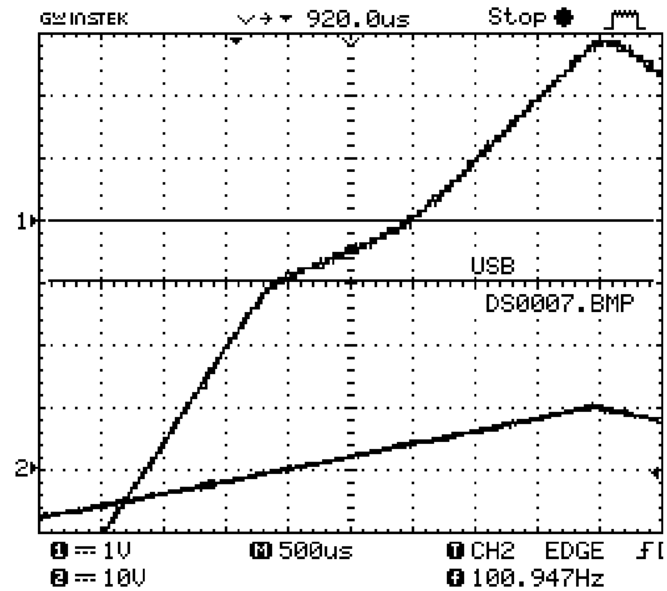



Figure 23b

Experiment 4 Trailing Edge -640 mV to -1.20 V

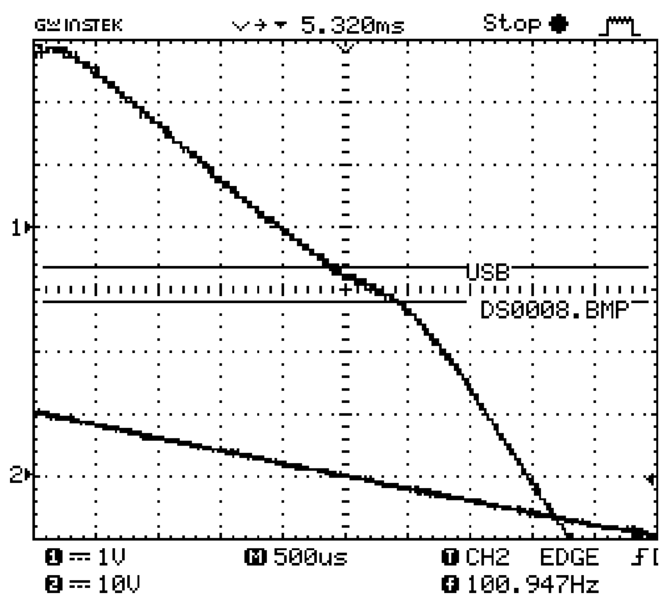



Figure 23c

Experiment 4 200 Hz +2.24 V to -6.88 V

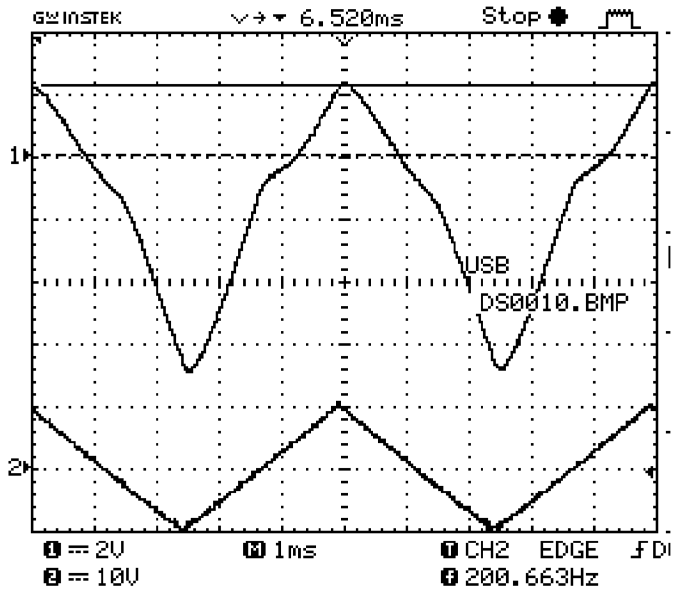



Figure 24a

Experiment 4 Leading Edge -760 mV to -120 mV

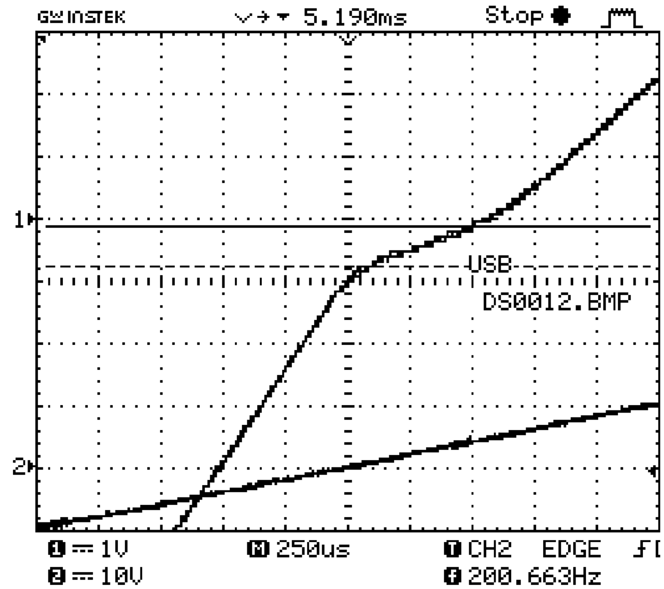



Figure 24b

Experiment 4 Trailing Edge -680 mV to -1.39 mV

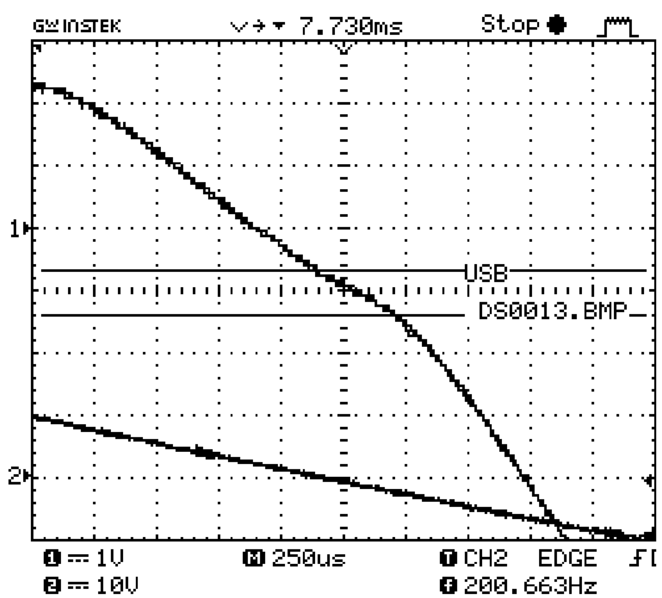



Figure 24c

Experiment 4 400 Hz +1.84 V to -6.32 V

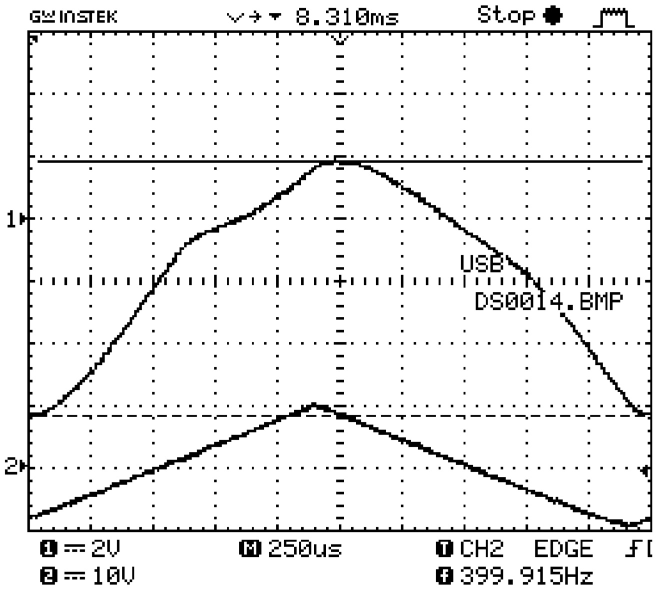



Figure 25a

Experiment 4 Leading Edge -440 mV to +200 mV

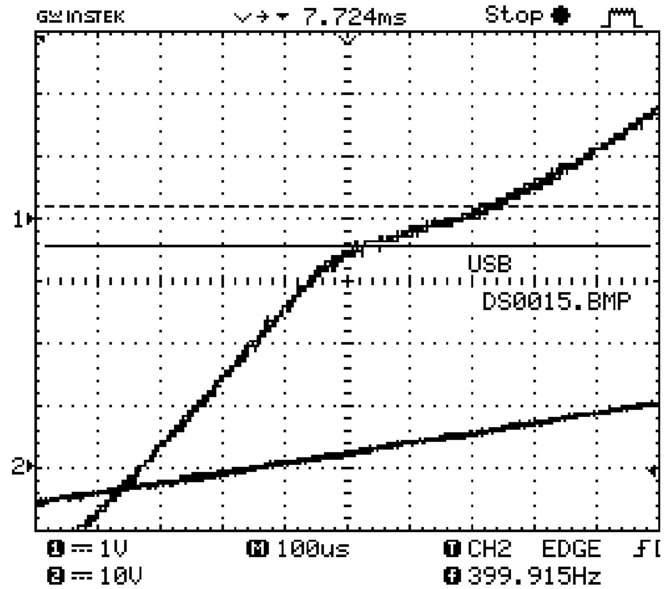



Figure 25b

Experiment 4 Trailing Edge -1.63 V to -2.0 V

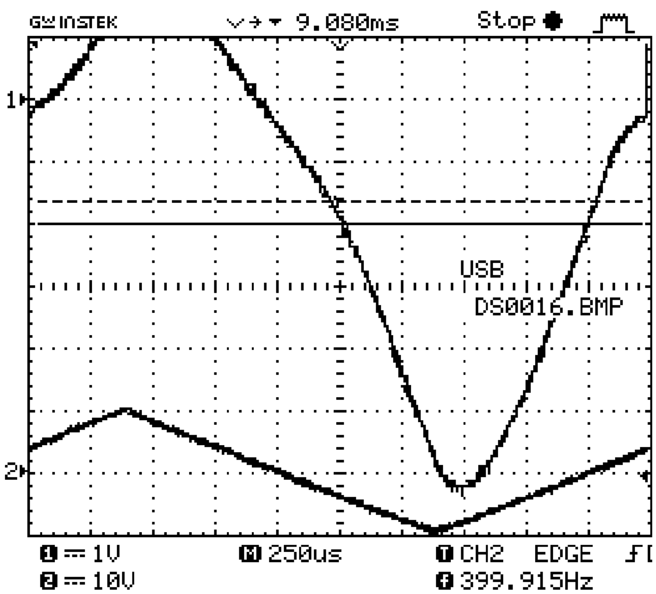



Figure 25c

Experiment 4 1KHz +0.920 V to -4.88 V

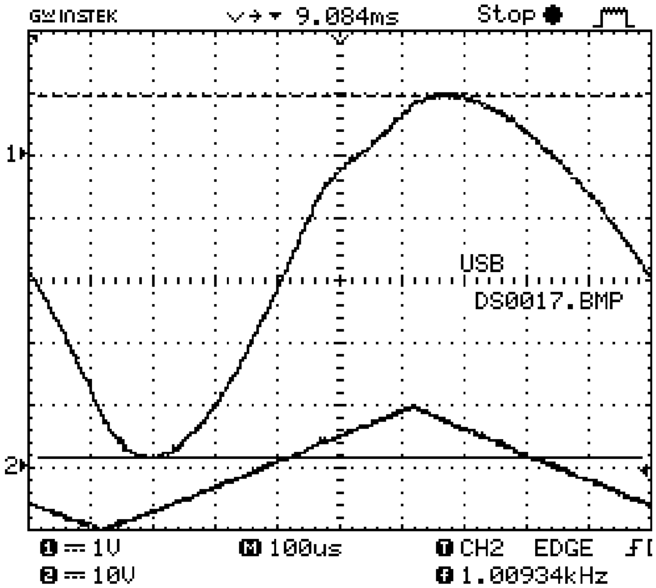



Figure 26a

Experiment 4 Leading Edge -340 mV to +440 mV

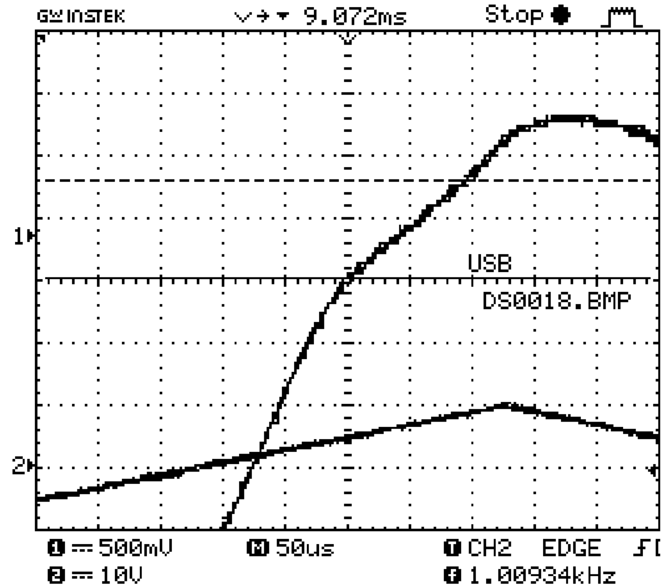



Figure 26b

Experiment 4 Trailing Edge – Indistinct

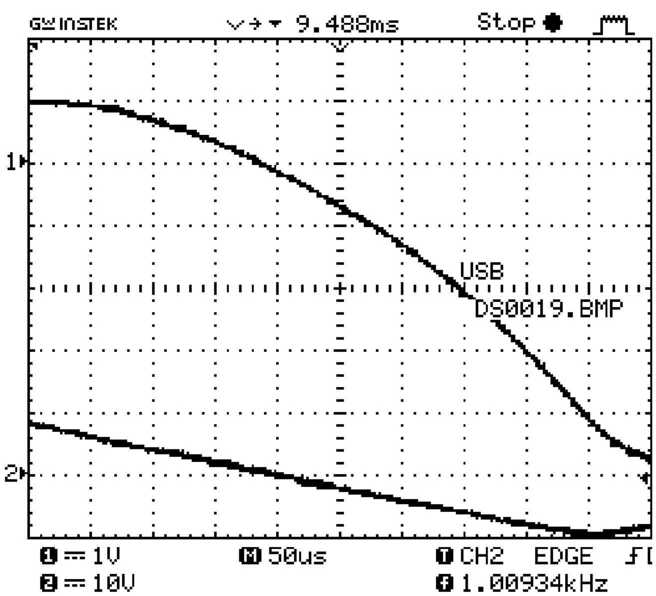



Figure 26c

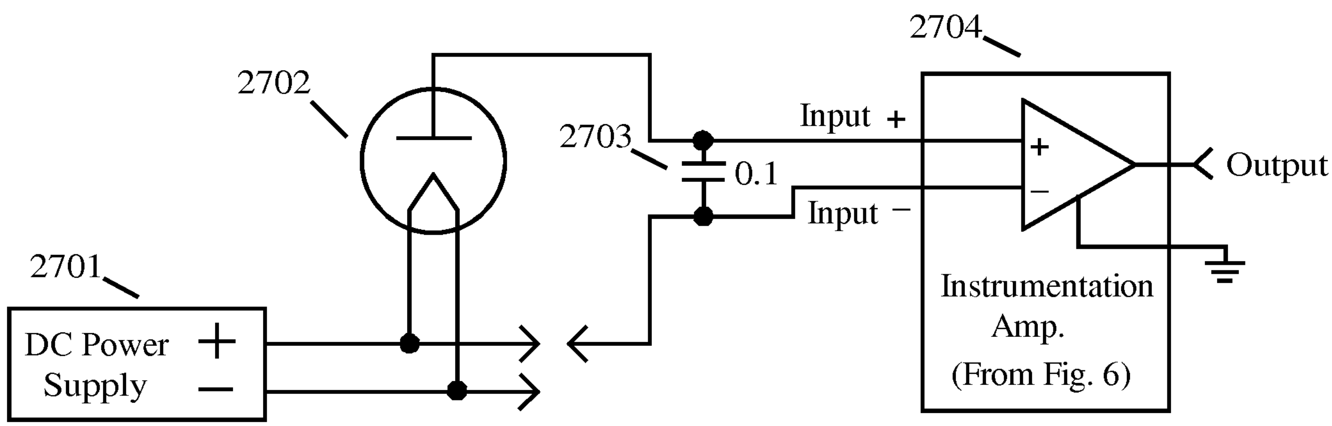



Figure 27

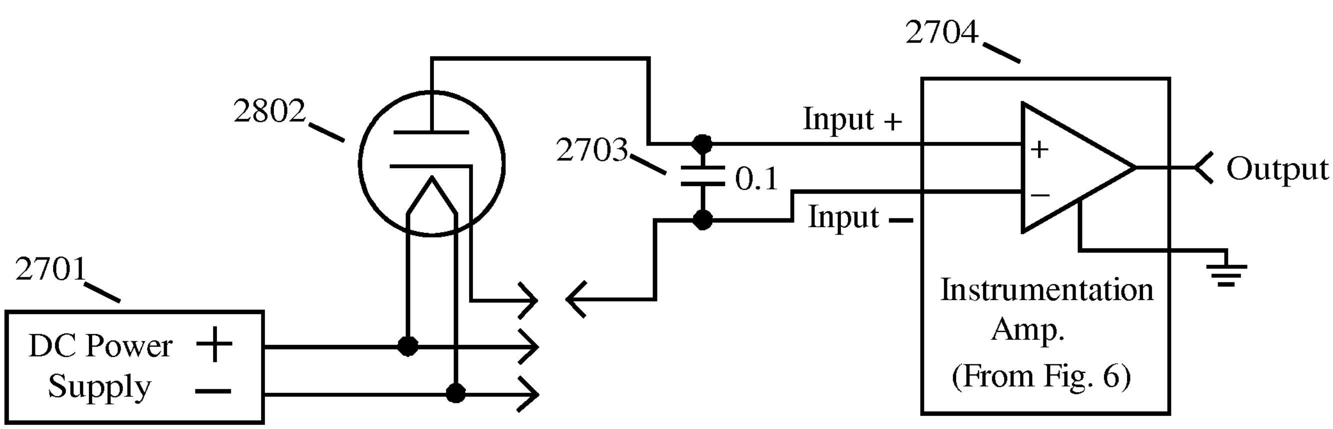



Figure 28

**Table 4 - Thermionic Emission Test – 5U4GB Vacuum Tube**

| 5U4GB | #1 Westinghouse | | 1/12/14 | | jm |
|---|---|---|---|---|---|
| | | | | | |
| 2 | Filament(2) | | 0V | | +5 VDC 2.94A |
| 8 | Filament(8) | | +5 VDC 2.93A | | 0V |
| | | | | | |
| 2 | Filament(2) | | Ref | | Ref |
| 4 | Plate 1 | | -0.93V | | -3.46V |
| 6 | Plate 2 | | -0.01V | | -5.59V |
| | | | | | |
| 8 | Filament(8) | | Ref | | Ref |
| 4 | Plate 1 | | -5.68V | | -0.09V |
| 6 | Plate 2 | | -3.30V | | -0.84V |

Figure 29

**Table 5 - Thermionic Emission Test – 5Y3 Vacuum Tube**

| 5Y3 | #1 RCA | | 1/12/2014 | | jm |
|---|---|---|---|---|---|
| | | | | | |
| 2 | Filament(2) | | 0V | | +5 VDC 2.00A |
| 8 | Filament(8) | | +5 VDC 1.98A | | 0V |
| | | | | | |
| 2 | Filament(2) | | Ref | | Ref |
| 4 | Plate 1 | | -0.61V | | -3.04V |
| 6 | Plate 2 | | 0.0V | | -5.25V |
| | | | | | |
| 8 | Filament(8) | | Ref | | Ref |
| 4 | Plate 1 | | -5.37V | | 0.0V |
| 6 | Plate 2 | | -3.00V | | -0.51V |

Figure 30

**Table 6 - Thermionic Emission Test – 6X4 Vacuum Tube**

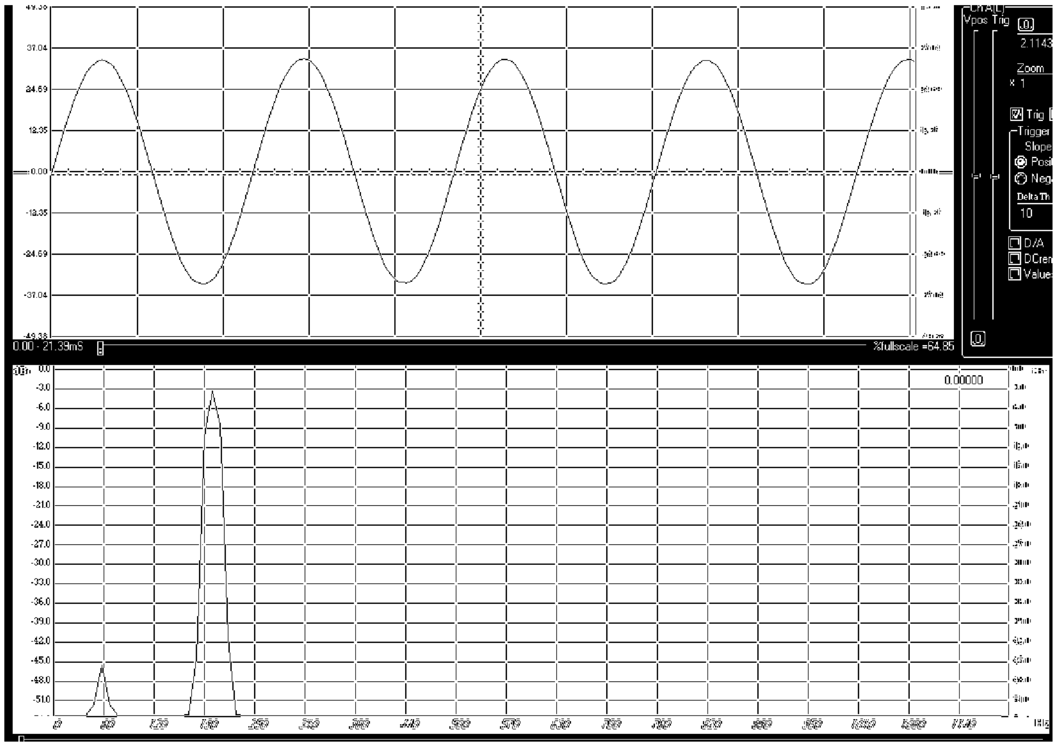
| 6X4 #1 Raytheon | 1/13/14 jm | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| 3 | Filament(3) | 0V | | 3 | Filament(3) | +6.3DC 0.60A |
| 4 | Filament(4) | +6.3VDC 0.59A | | 4 | Filament(4) | 0V |
| | | | | | | |
| 7 | Cathode | Ref | | 7 | Cathode | Ref |
| 6 | Plate 1 | -0.91V | | 6 | Plate 1 | -0.92V |
| 1 | Plate 2 | -1.14V | | 1 | Plate 2 | -1.17V |
| | | | | | | |
| 7,3 | Cathode, Filament(3) | Ref | | 7,3 | Cathode, Filament(3) | Ref |
| 6 | Plate 1 | -0.91V | | 6 | Plate 1 | -0.93V |
| 1 | Plate 2 | -1.16V | | 1 | Plate 2 | -1.18V |
| | | | | | | |
| 7,4 | Cathode, Filament(4) | Ref | | 7,4 | Cathode, Filament(4) | Ref |
| 6 | Plate 1 | -0.91V | | 6 | Plate 1 | -0.93V |
| 1 | Plate 2 | -1.16V | | 1 | Plate 2 | -1.19V |
| | | | | | | |
| 3 | Filament(3) | Ref | | 3 | Filament(3) | Ref |
| 7 | Cathode | +2.50V | | 7 | Cathode | -3.67V |
| | | | | | | |
| 4 | Filament(4) | Ref | | 4 | Filament(4) | Ref |
| 7 | Cathode | -3.66V | | 7 | Cathode | +2.52V |

Figure 31

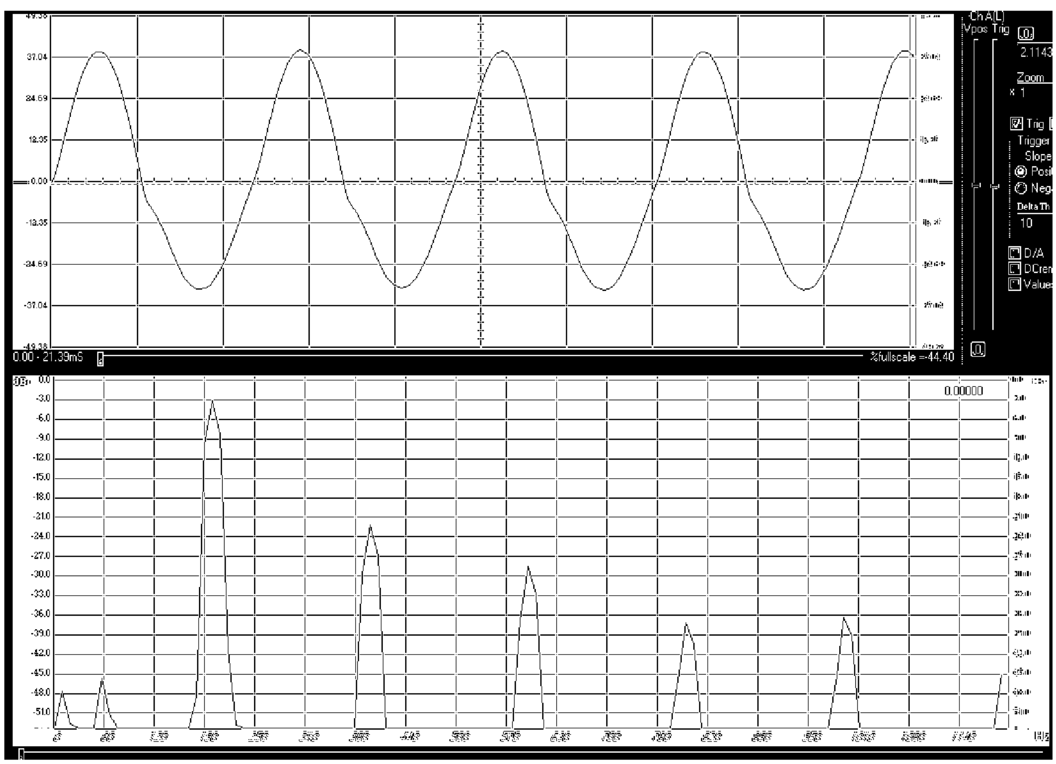
**Table 7 - Thermionic Emission Test – 12X4 Vacuum Tube**

| 12X4 #1 RCA | 01/13/2014 jm | | | | |
|---|---|---|---|---|---|
| | | | | | |
| 3 | Filament | 0V | 3 | Filament | +12.6 VDC 0.32A |
| 4 | Filament | +12.6 VDC 0.32A | 4 | Filament | 0V |
| | | | | | |
| 7 | Cathode | Ref | 7 | Cathode | Ref |
| 6 | Plate 1 | -1.17V | 6 | Plate 1 | -1.17V |
| 1 | Plate 2 | -1.04V | 1 | Plate 2 | -1.05V |
| | | | | | |
| 7,3 | Cathode, Filament(3) | Ref | 7,3 | Cathode, Filament(3) | Ref |
| 6 | Plate 1 | -1.17V | 6 | Plate 1 | -1.17V |
| 1 | Plate 2 | -1.04V | 1 | Plate 2 | -1.05V |
| | | | | | |
| 7,4 | Cathode, Filament(4) | Ref | 7,4 | Cathode, Filament(4) | Ref |
| 6 | Plate 1 | -1.17V | 6 | Plate 1 | -1.17V |
| 1 | Plate 2 | -1.05V | 1 | Plate 2 | -1.05V |
| | | | | | |
| 3 | Filament(3) | Ref | 3 | Filament(3) | Ref |
| 7 | Cathode | +1.66V | 7 | Cathode | -4.70V |
| | | | | | |
| 4 | Filament(4) | Ref | 4 | Filament(4) | Ref |
| 7 | Cathode | -4.70V | 7 | Cathode | +1.83V |

Figure 32



<u>Figure 33a</u> 200 Hz; 10 Megohm Source; Sine Wave; No Flame



<u>Figure 33b</u> 200 Hz; 10 Megohm Source; Sine Wave; Flame

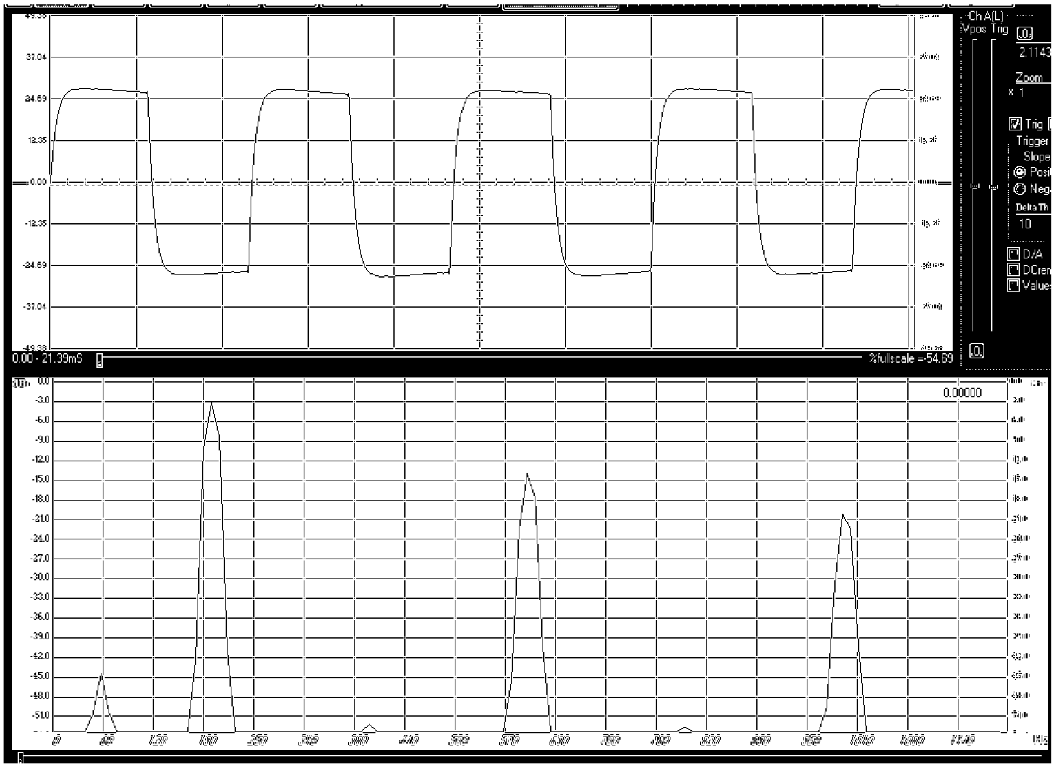


Figure 34a 200 Hz; 10 Megohm Source; Square Wave; No Flame

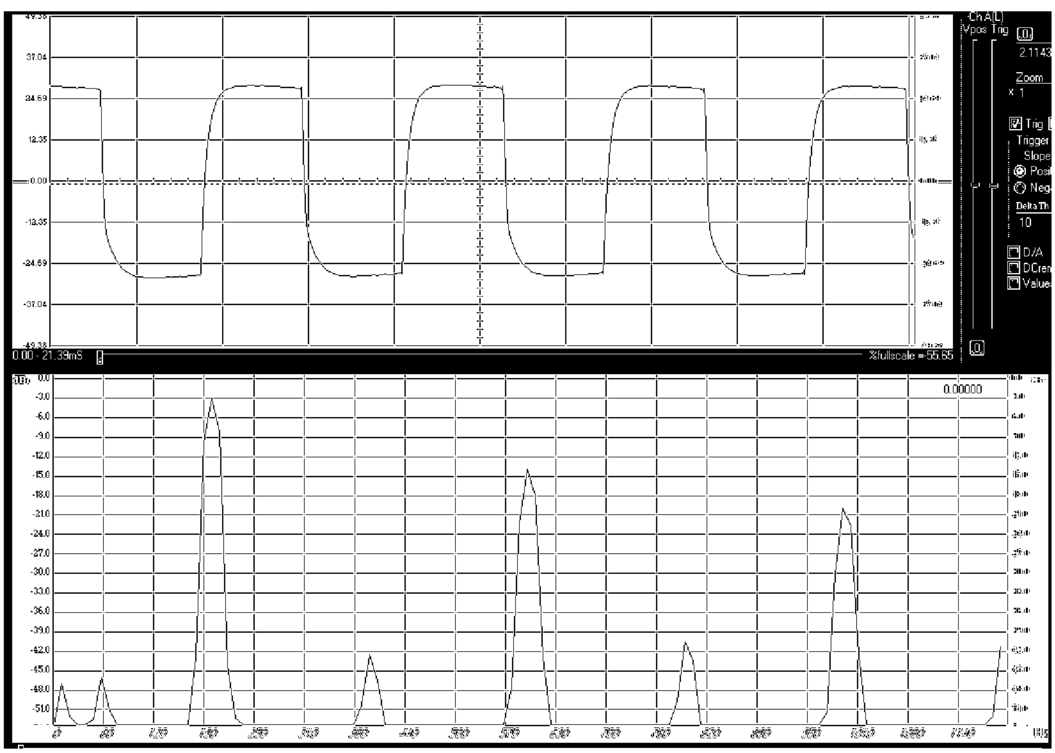


Figure 34b 200 Hz; 10 Megohm Source; Square Wave; Flame

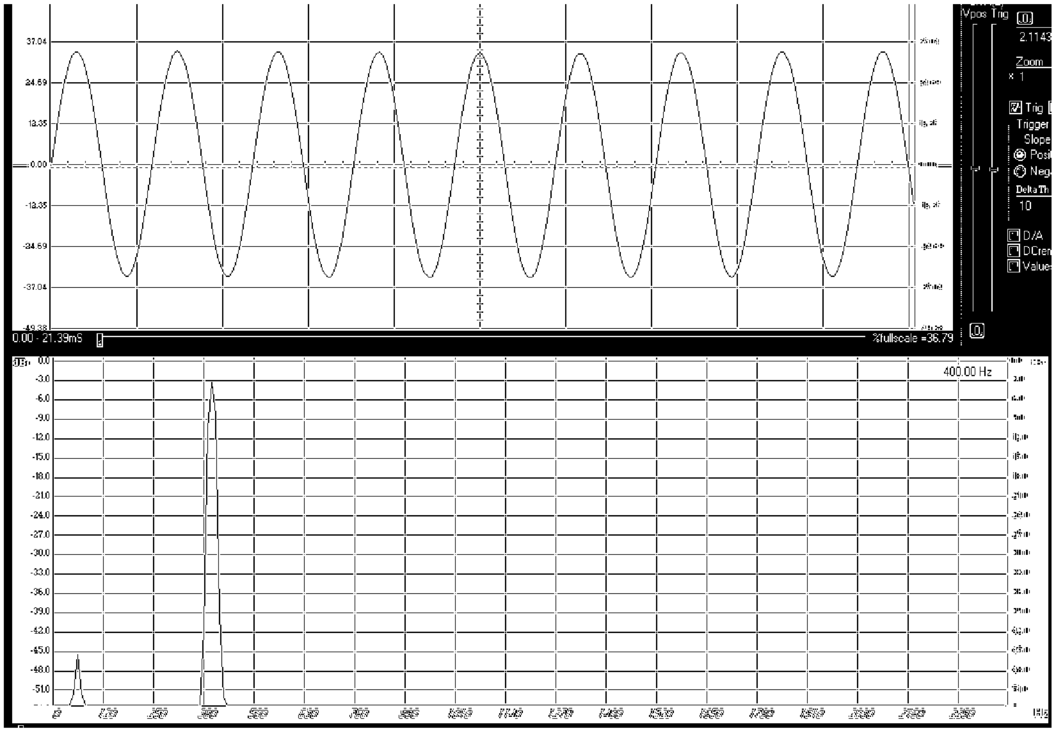


Figure 35a 400 Hz; 10 Megohm Source; Sine Wave; No Flame

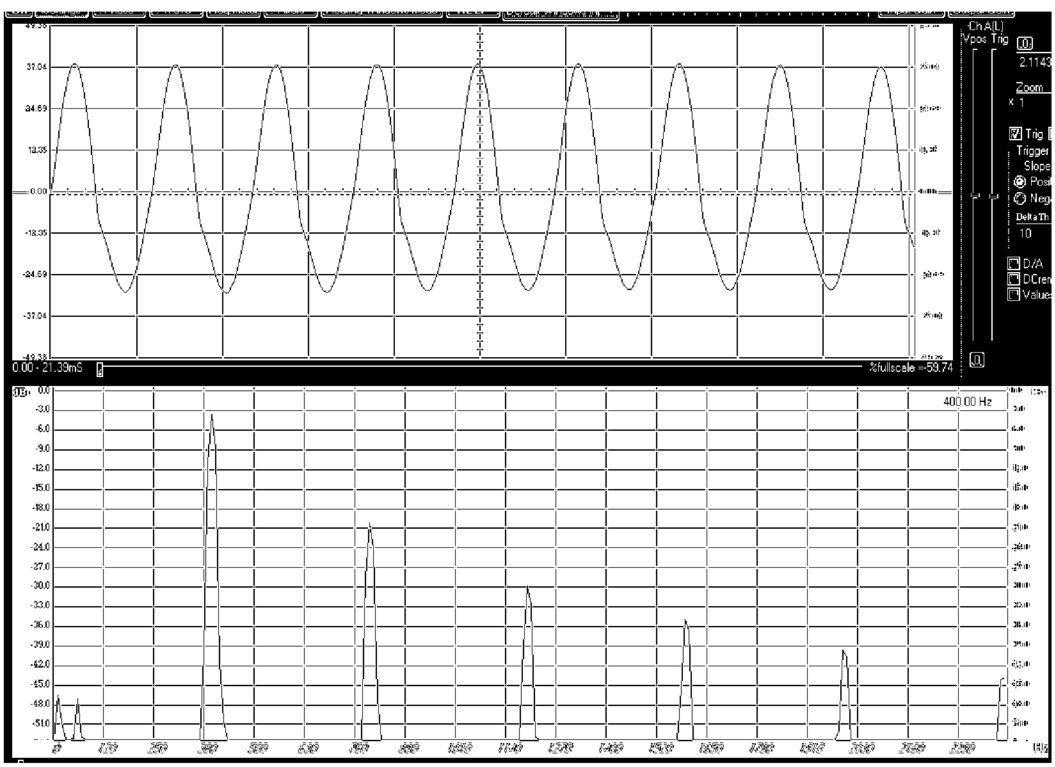


Figure 35b 400 Hz; 10 Megohm Source; Sine Wave; Flame

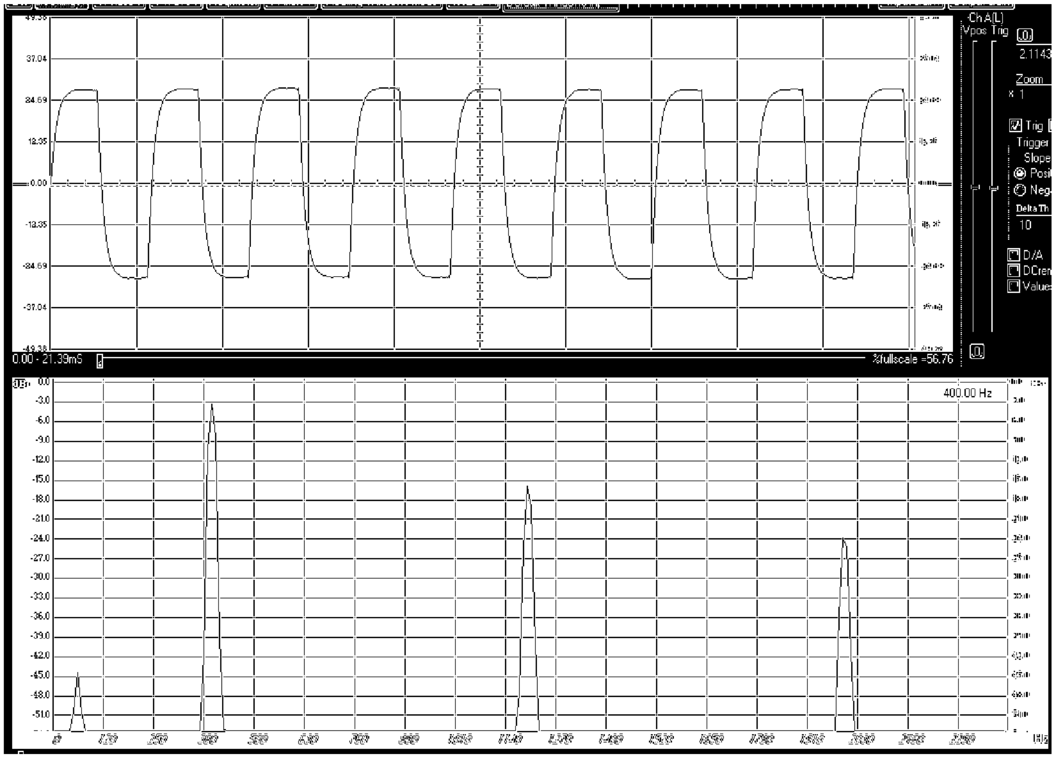


Figure 36a 400 Hz; 10 Megohm Source; Square Wave; No Flame

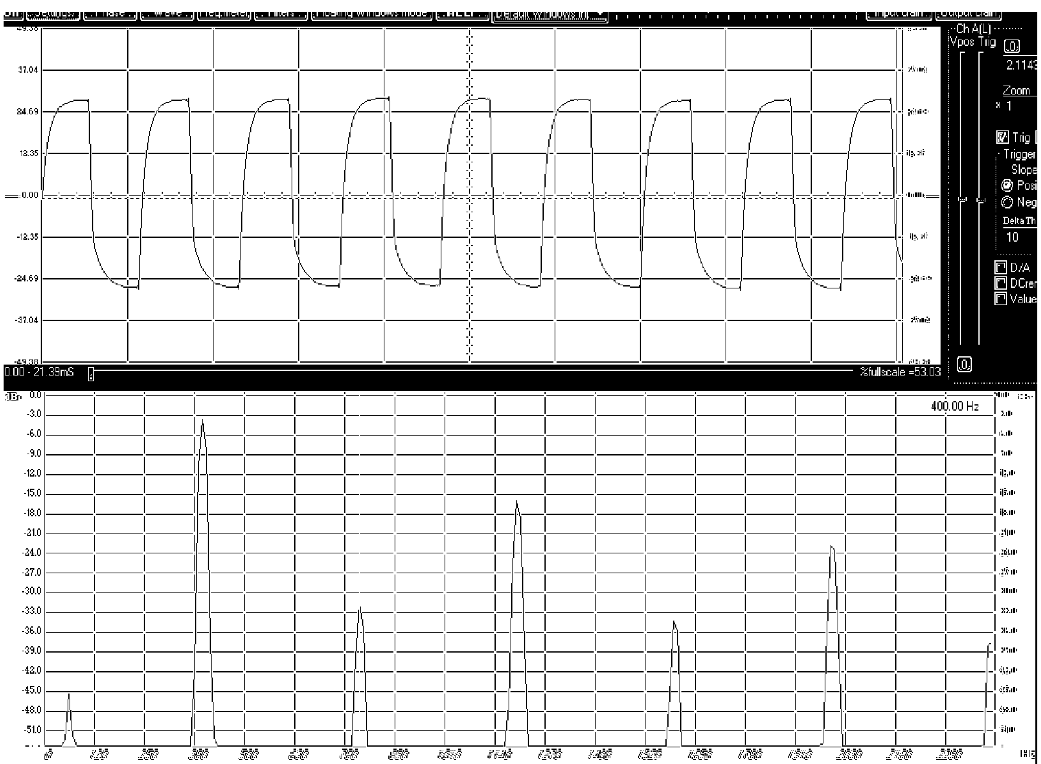


Figure 36b 400 Hz; 10 Megohm Source; Square Wave; Flame

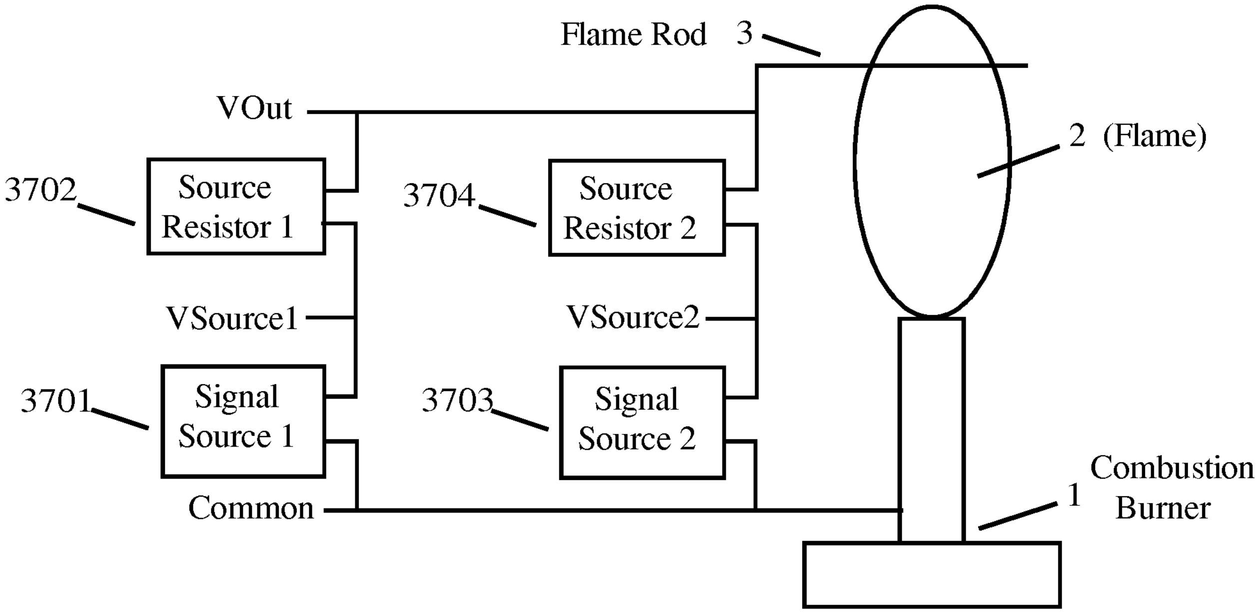



Figure 37

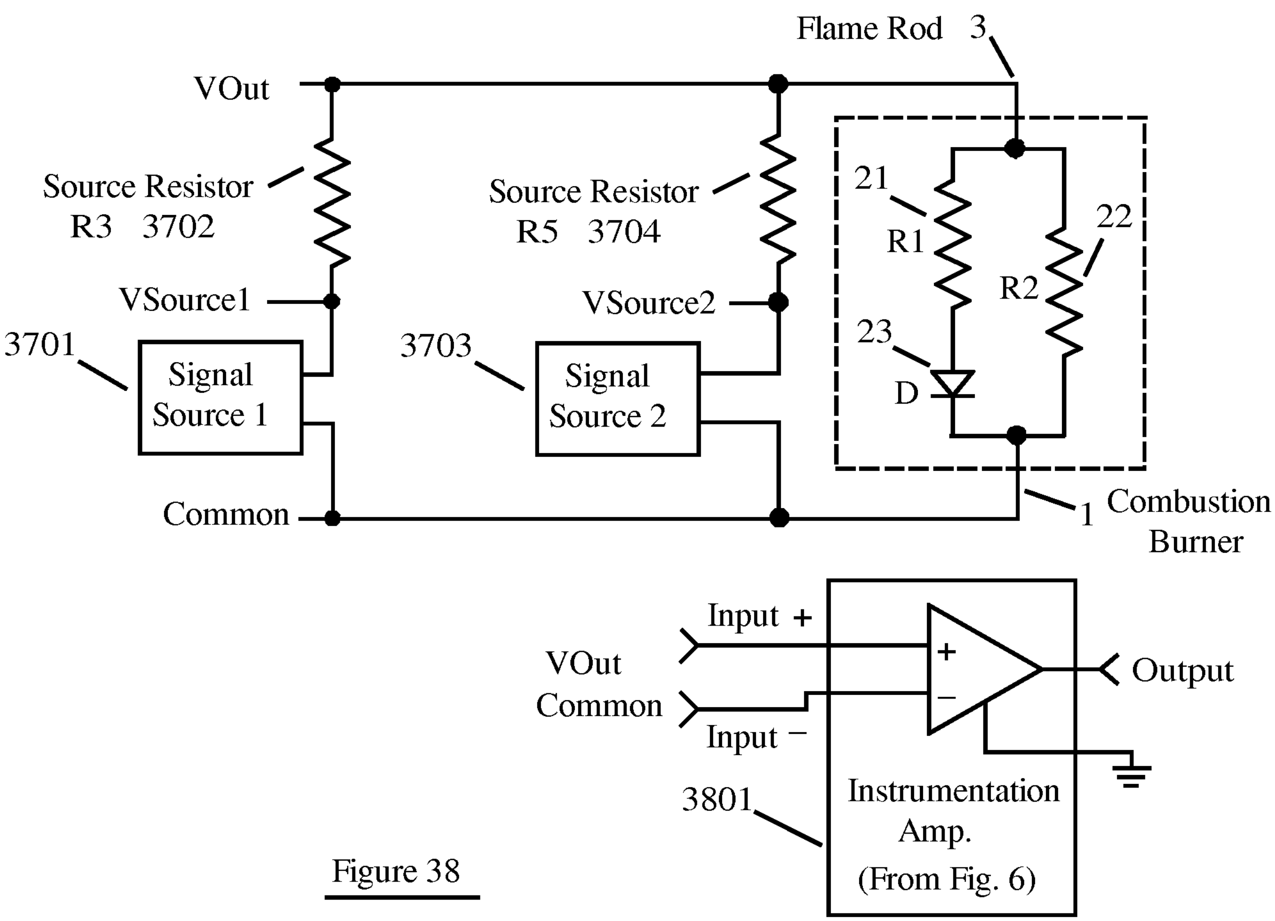



Figure 38

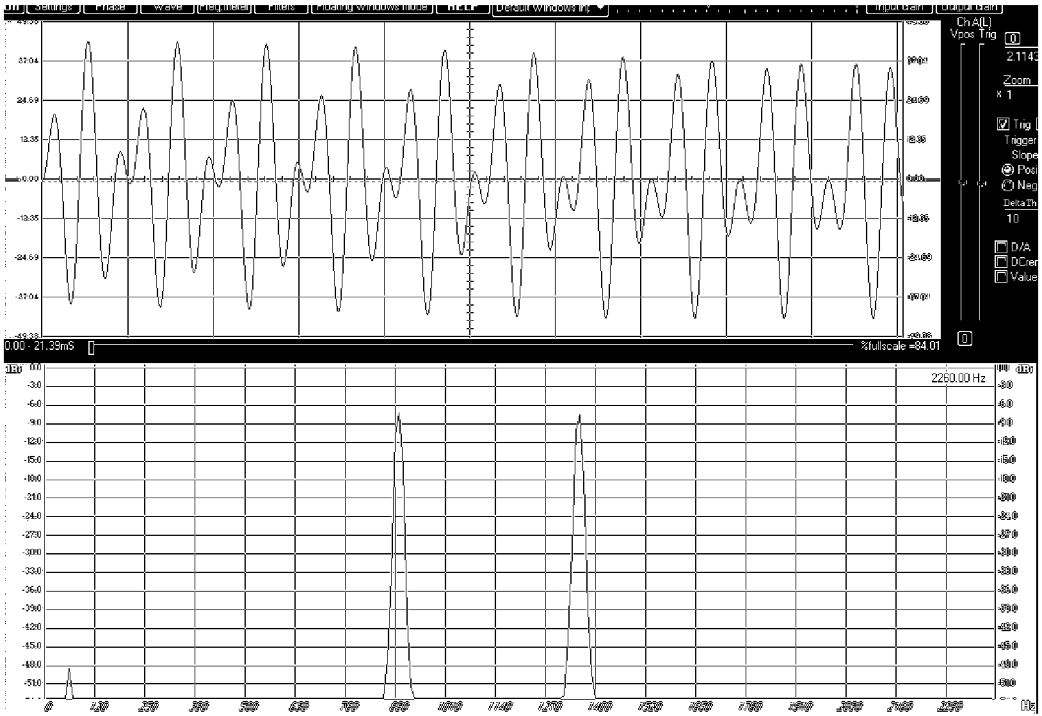
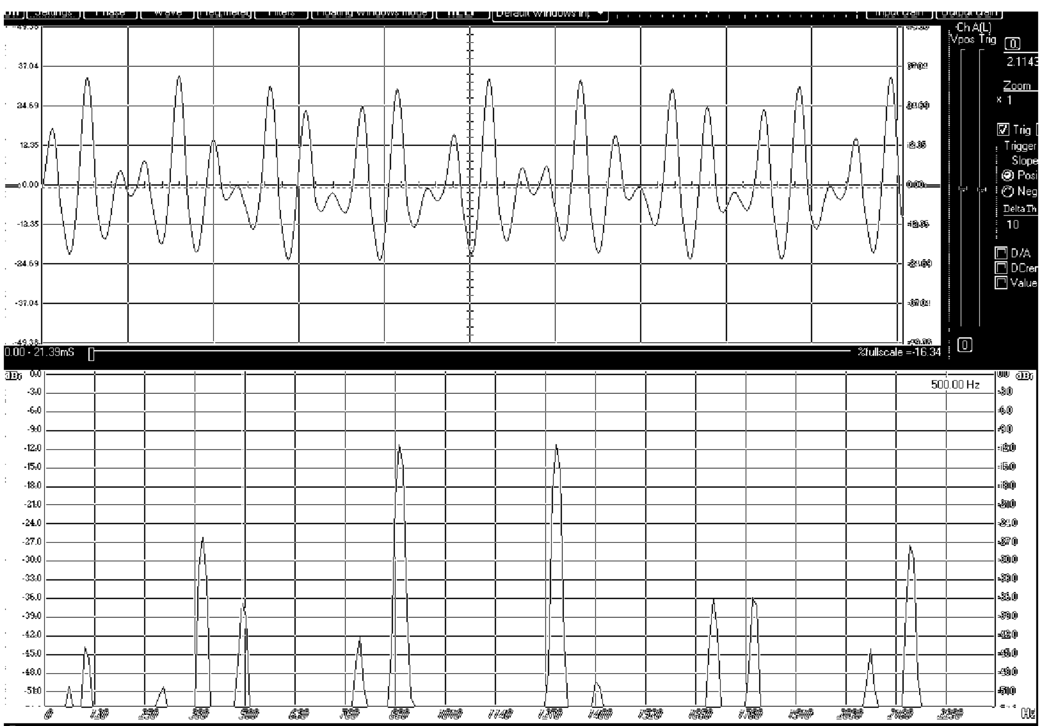
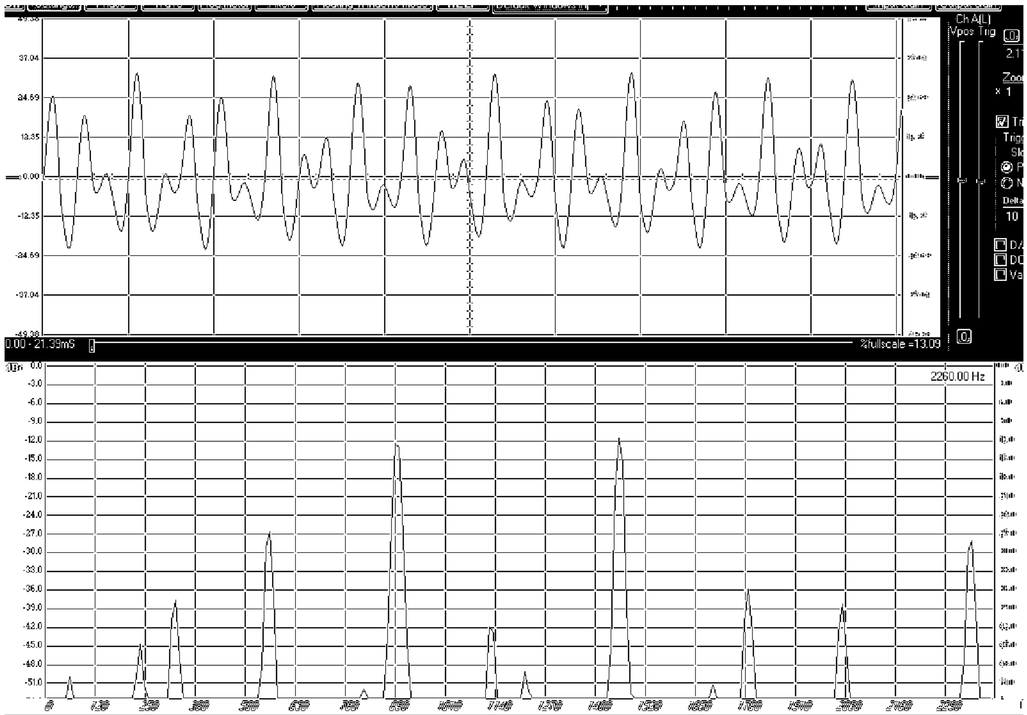



Figure 39a Mixer Test; Sine Waves (No Flame): 900 Hz (-7 dB); 1,300 Hz (-7 dB)



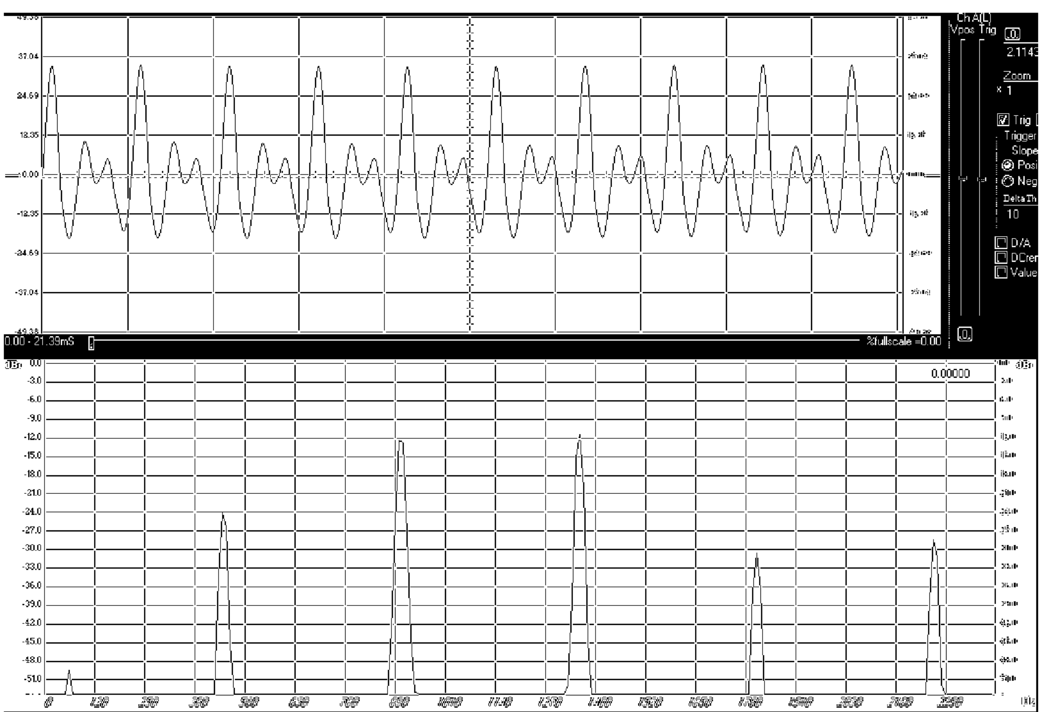

900 Hz (-12 dB); 1,300 Hz (-12 dB); 400 Hz (-27 dB); 2,200 Hz (-27 dB); 500 Hz (-39 dB)

Figure 39b Mixer Test; Sine Waves (Flame):



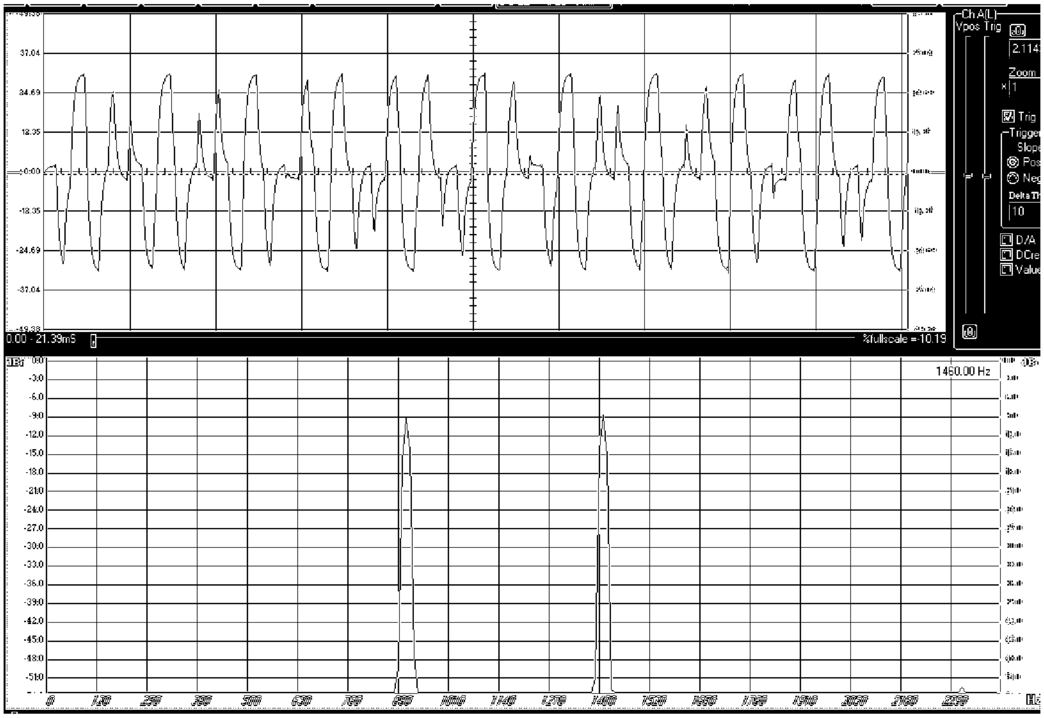
900 Hz (-12dB); 1,460 Hz (-12 dB); 560 Hz (-27 dB); 2,360 Hz (-28 dB); 340 Hz (-37 dB)

Figure 40 Mixer Test; Sine Waves (Flame)



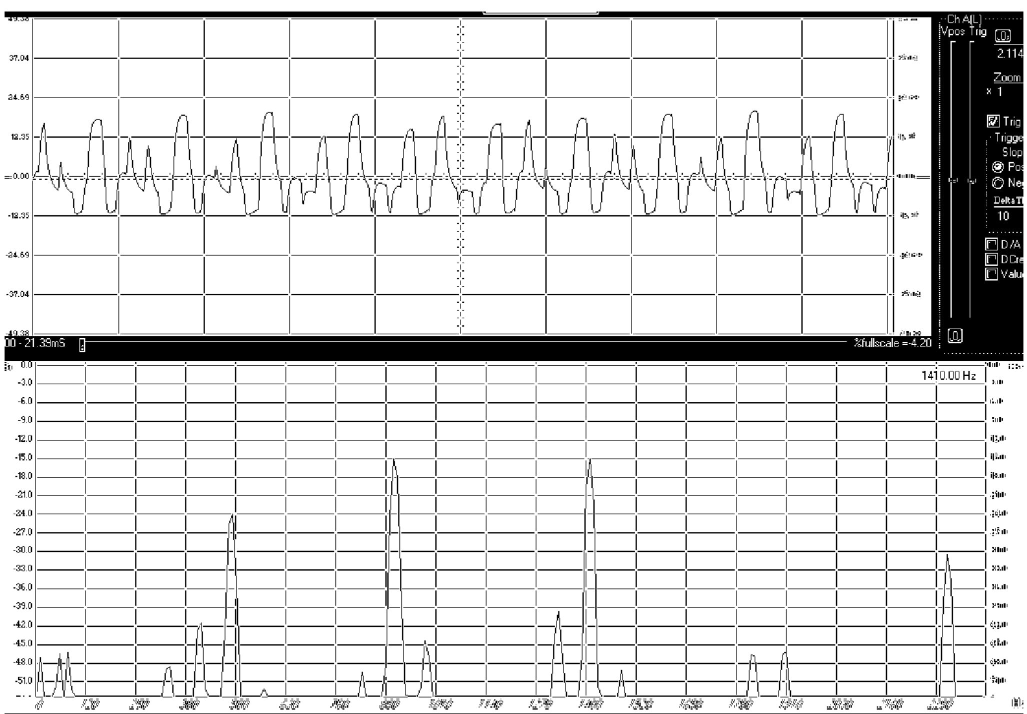
900 Hz (-12dB); 1,350 Hz (-12 dB); 450 Hz (-24 dB); 1,810 Hz (-32 dB); 2,260 Hz (-28 dB)

Figure 41 Mixer Test; Sine Waves (Flame)




910 Hz (-9 dB); 1,410 Hz (-9 dB)

<u>Figure 42a</u> Mixer Test; Square Waves (No Flame)




910 Hz (-15 dB); 1410 Hz (-15 dB); 500 Hz (-24 dB); 2,320 (-30 dB); 410 Hz (-41 dB)

<u>Figure 42b</u> Mixer Test; Square Waves (Flame)

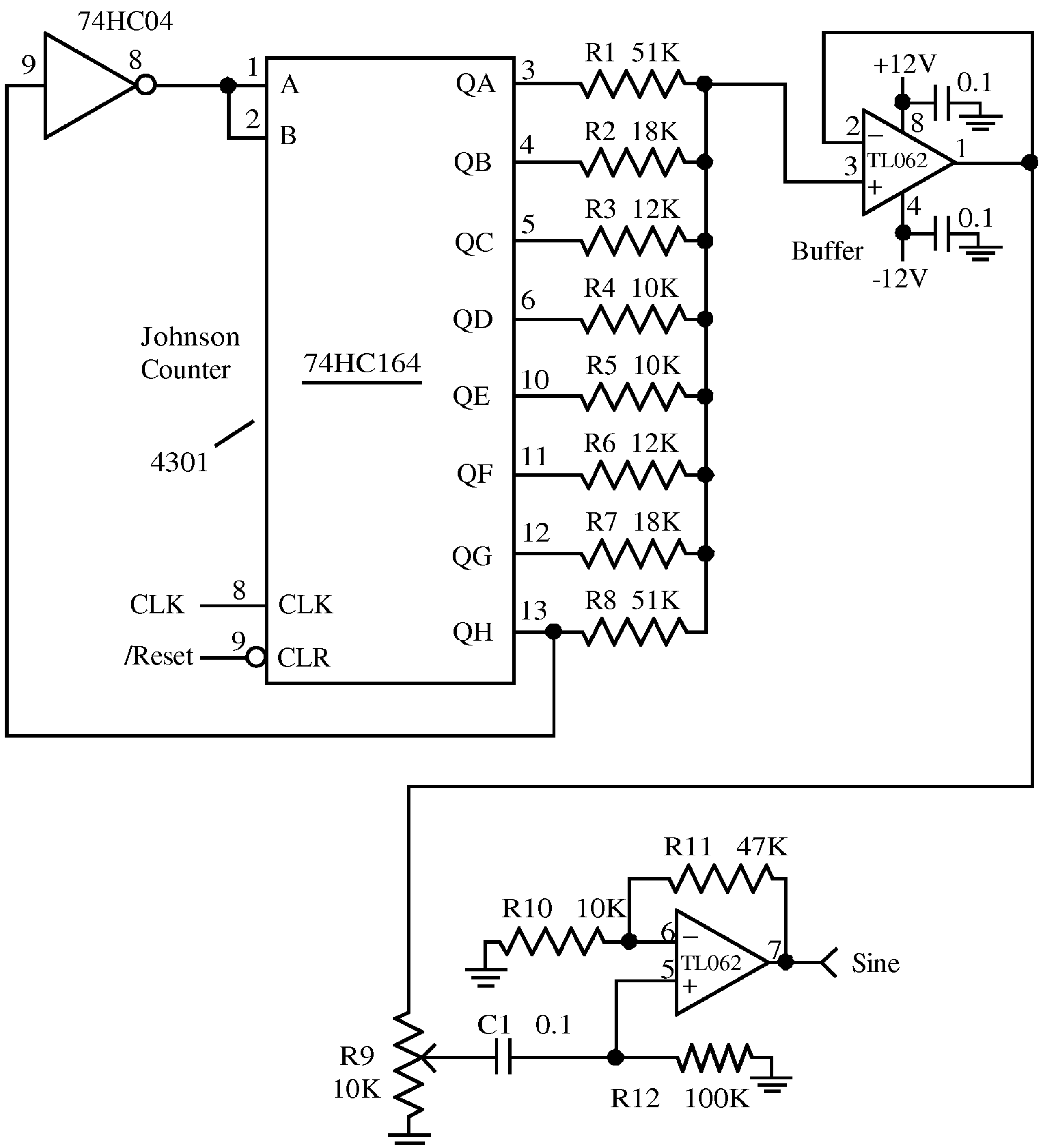



Figure 43a Sine Wave Generator

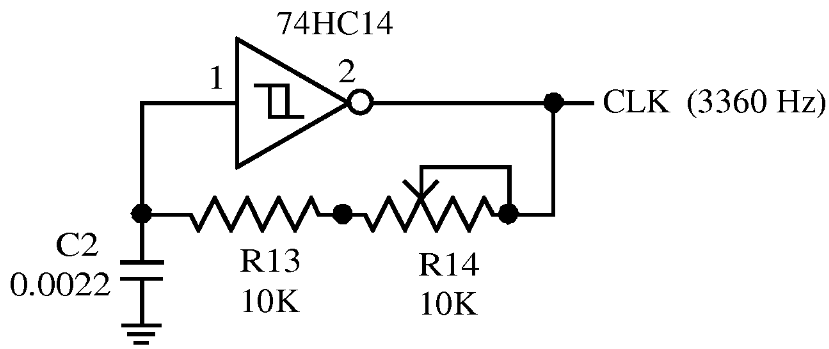



Figure 43b Oscillator

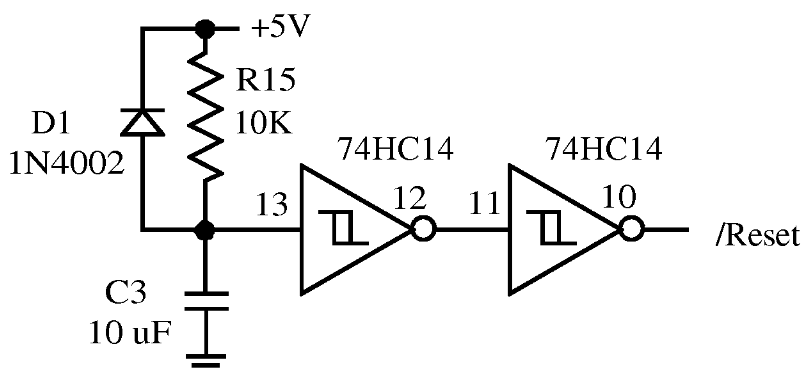
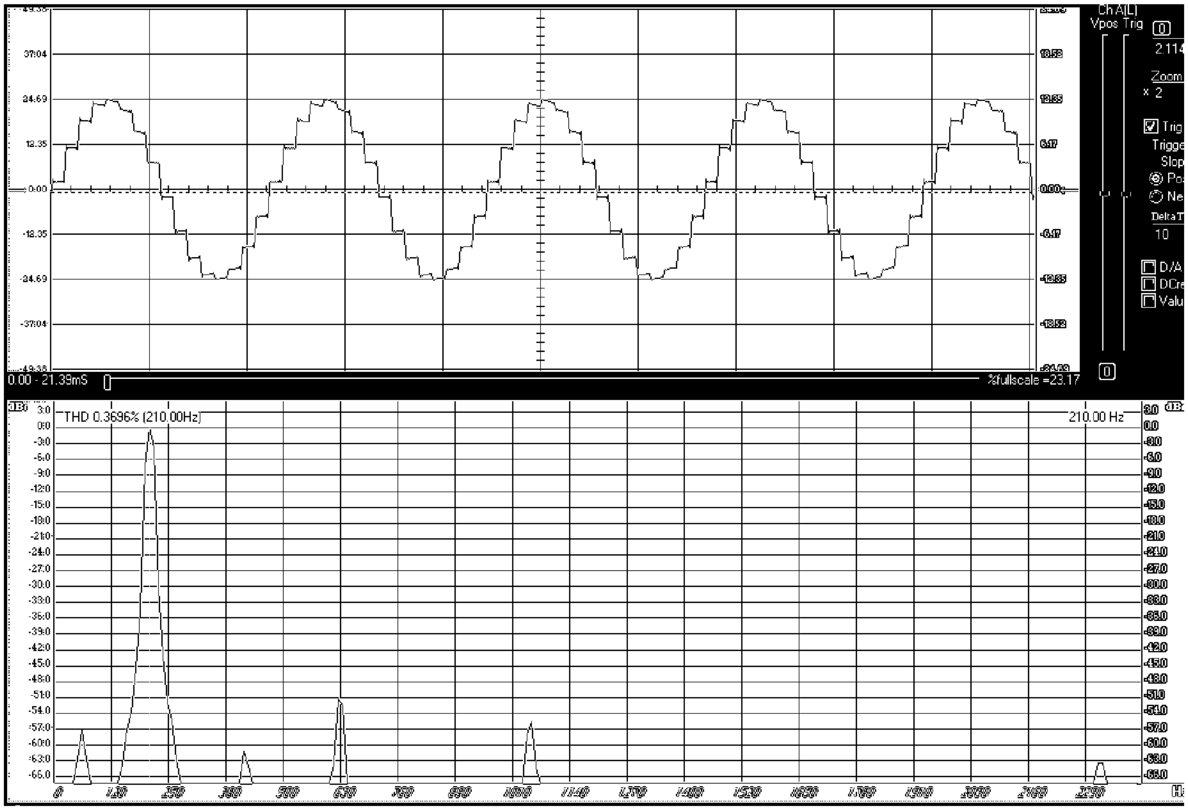



Figure 43c Reset




210 Hz Fundamental 0 dB; 2nd Harmonic -61 dB; 3rd Harmonic -51 dB;
5th Harmonic -54 dB; 60 Hz -57 dB

Figure 44 - Johnson Counter Results

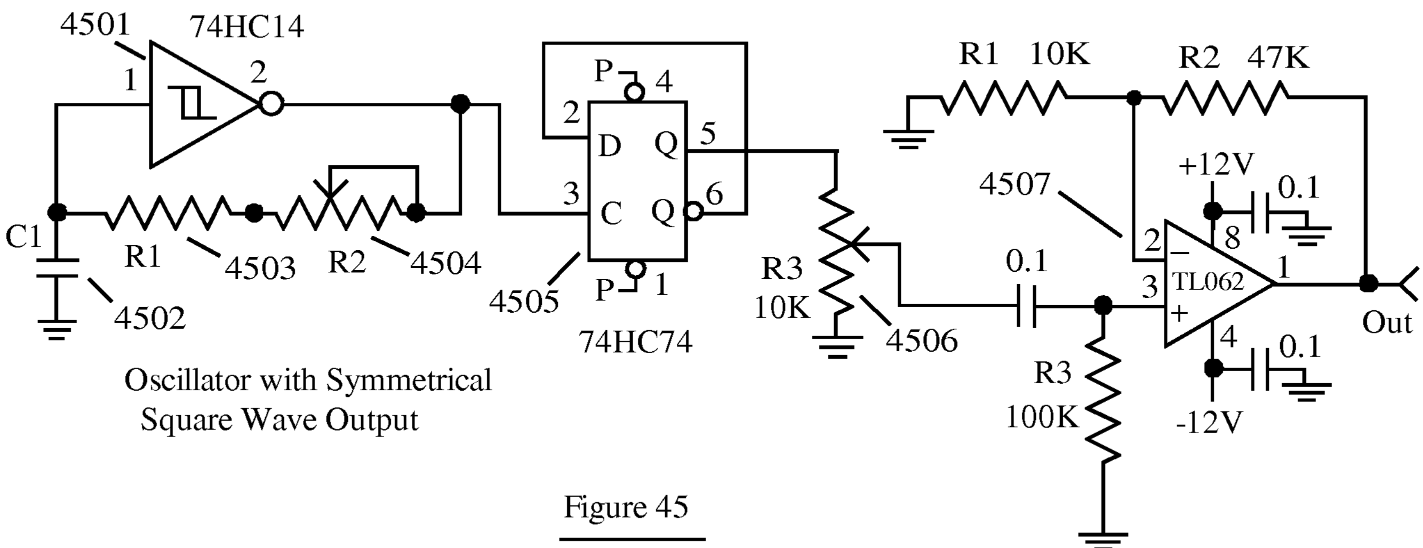



Figure 45

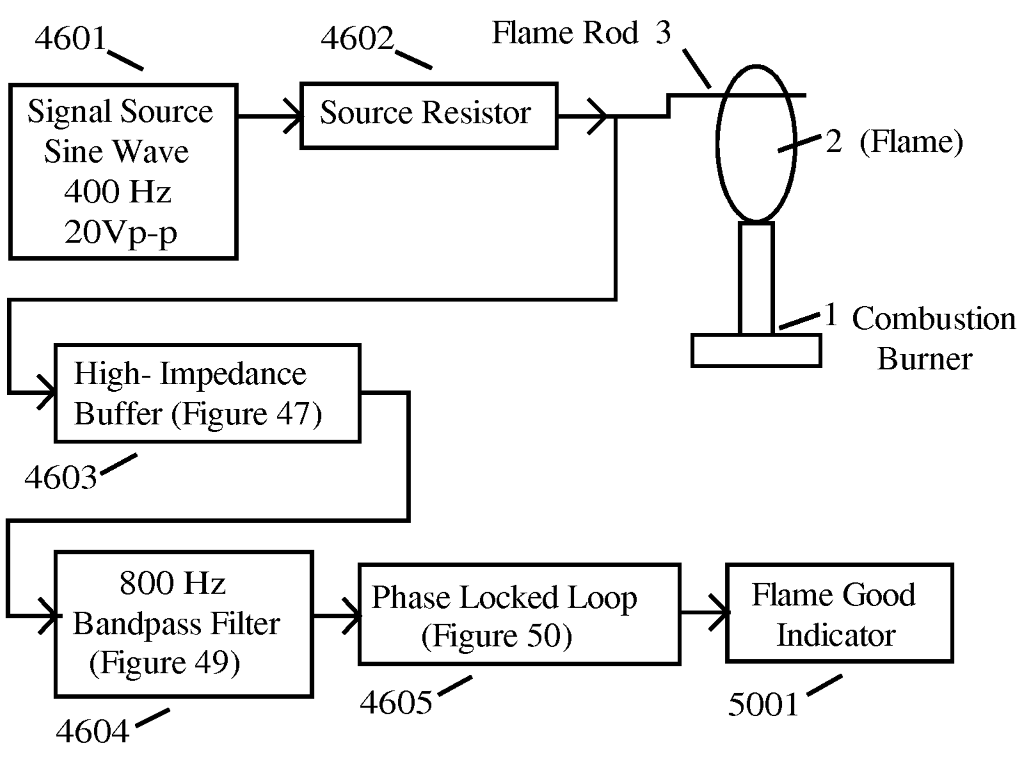



Figure 46

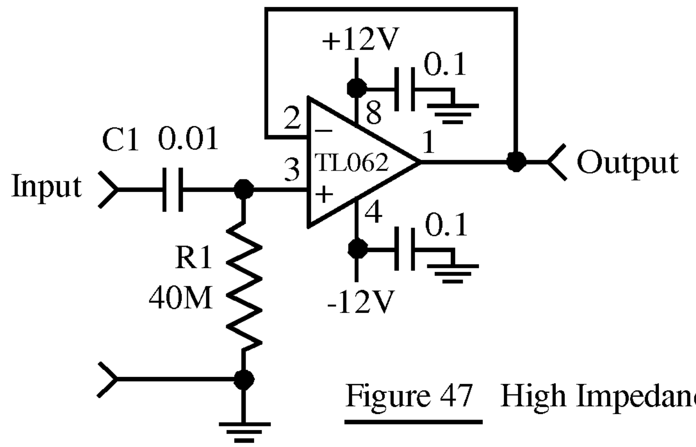



Figure 47 High Impedance Buffer

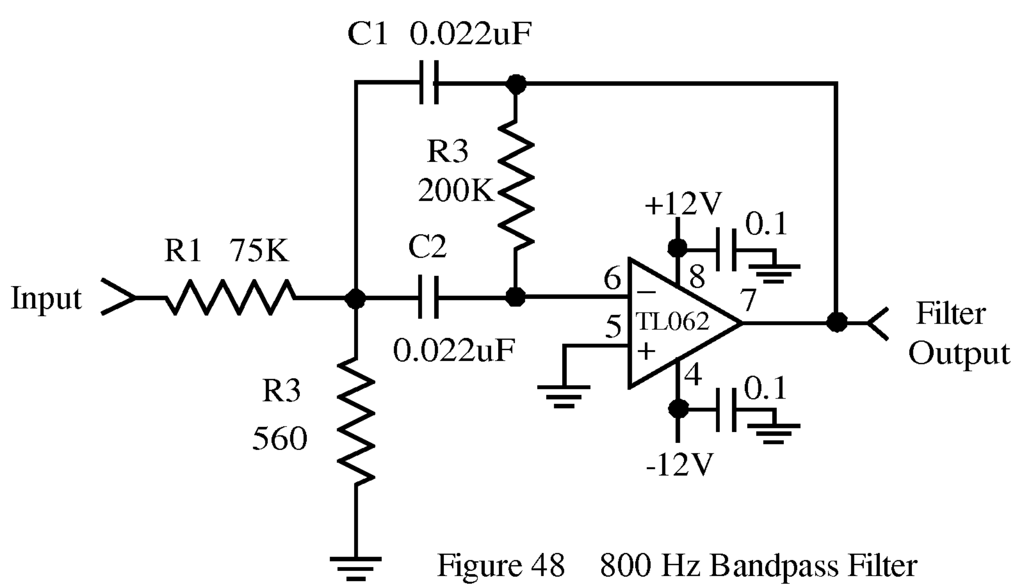



Figure 48 800 Hz Bandpass Filter

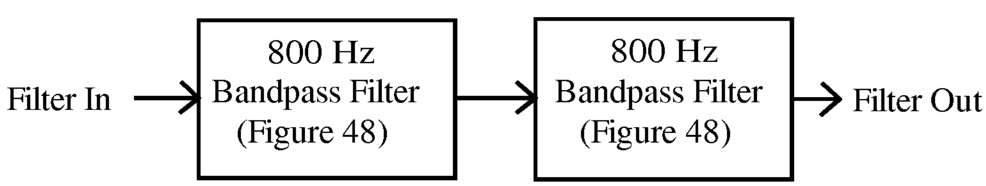



Figure 49 Two Cascaded Bandpass Filters

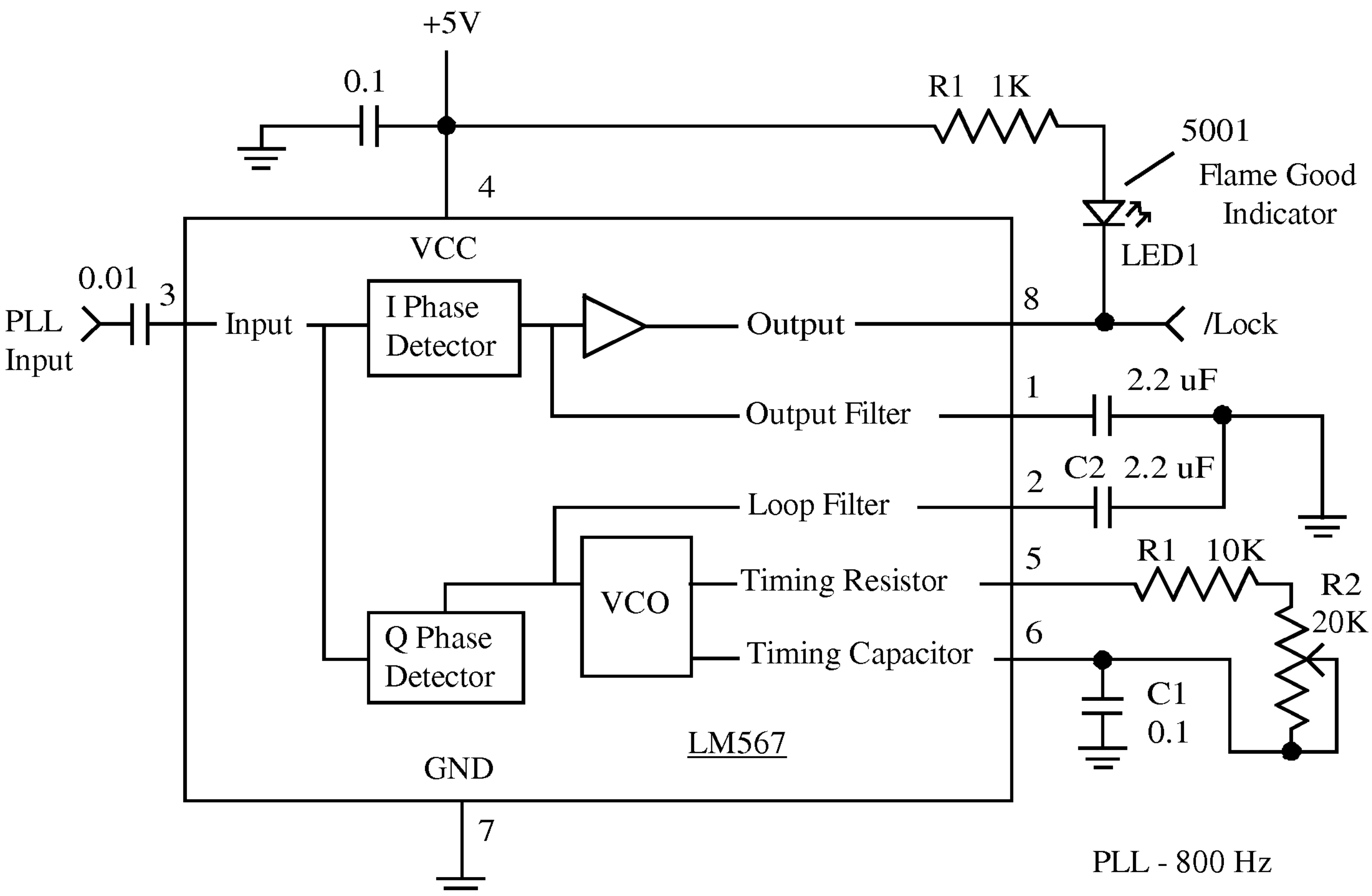

+5V
0.1
R1 1K
5001
Flame Good
Indicator
LED1
4
VCC
0.01
3
PLL
Input
Input
I Phase
Detector
Output
8
/Lock
Output Filter
1
2.2 uF
C2 2.2 uF
2
Loop Filter
VCO
Timing Resistor
5
R1 10K
R2
20K
Timing Capacitor
6
C1
0.1
Q Phase
Detector
LM567
GND
7
PLL - 800 Hz

Figure 50

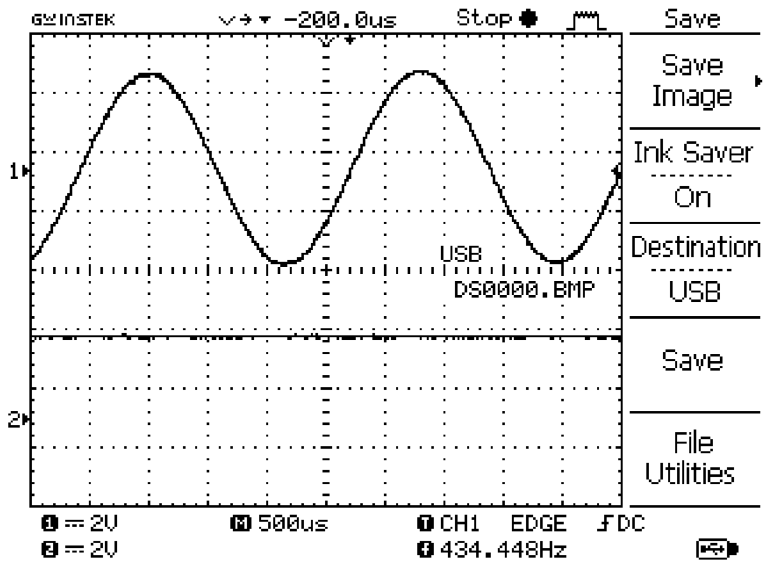



Figure 51a Sine Wave; 435 Hz; Flame Off

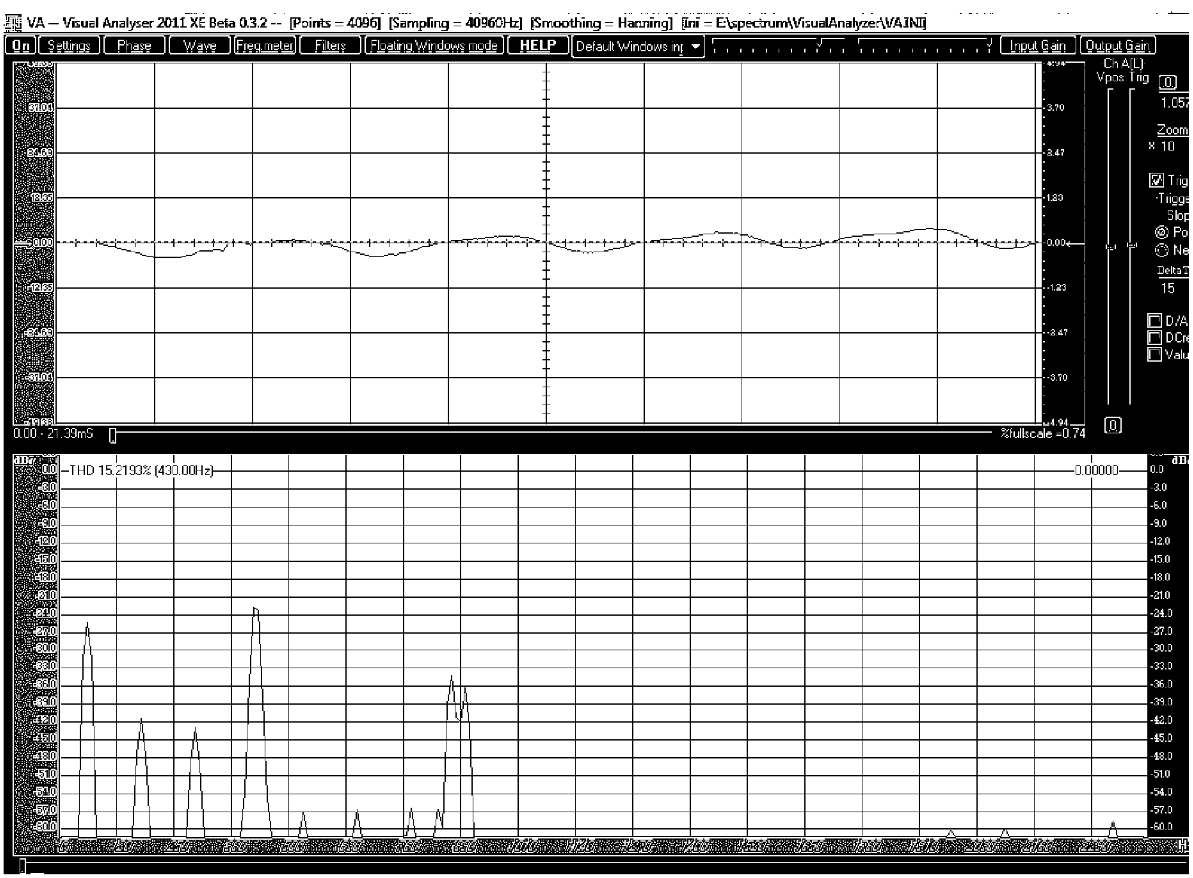



Figure 51b Sine Wave; 435 Hz; Flame Off

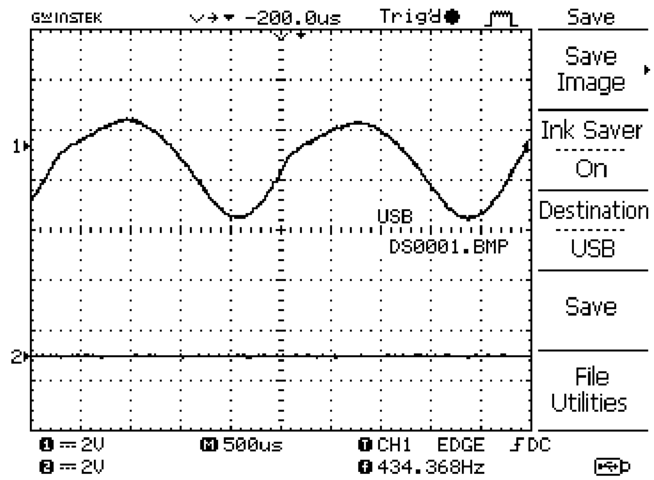



Figure 52a Sine Wave; 435 Hz; Flame On

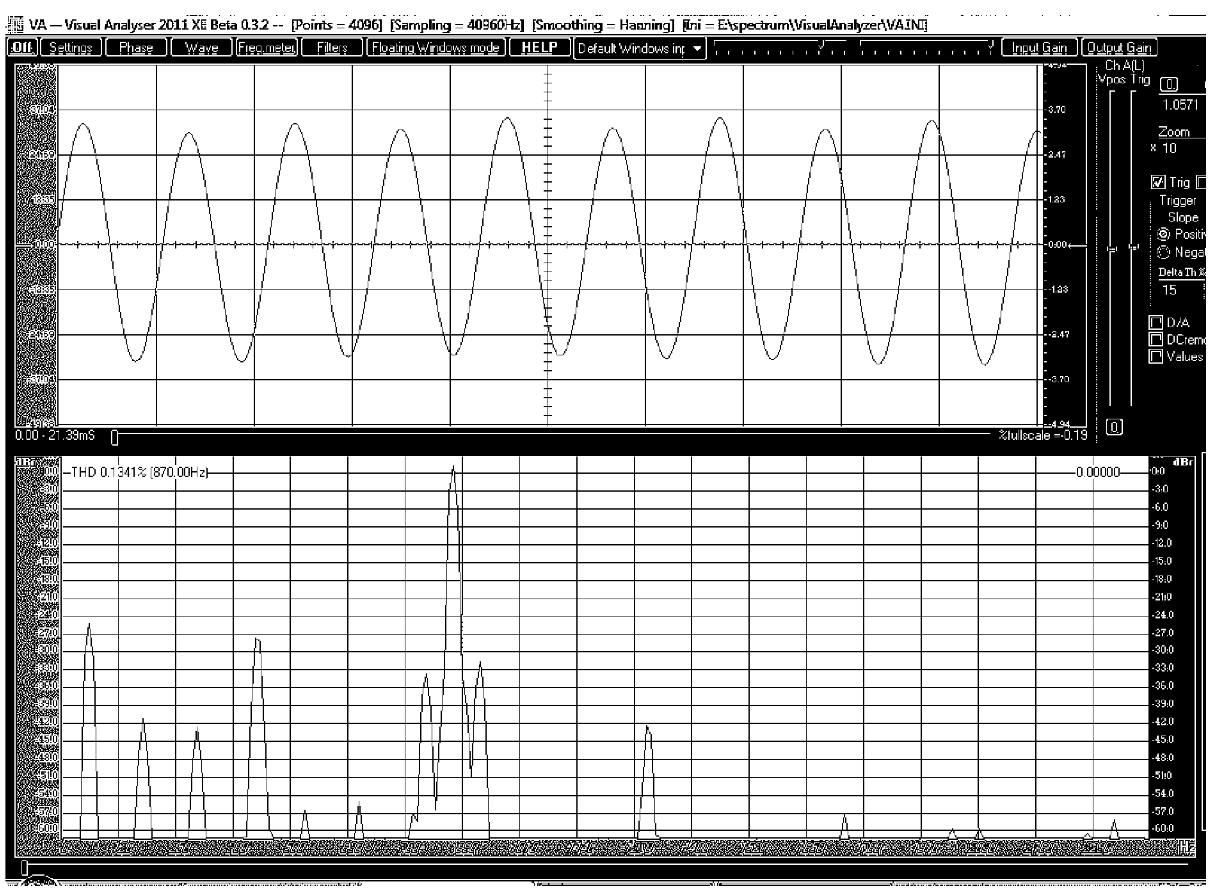



Figure 52b Sine 435 Hz; Flame On

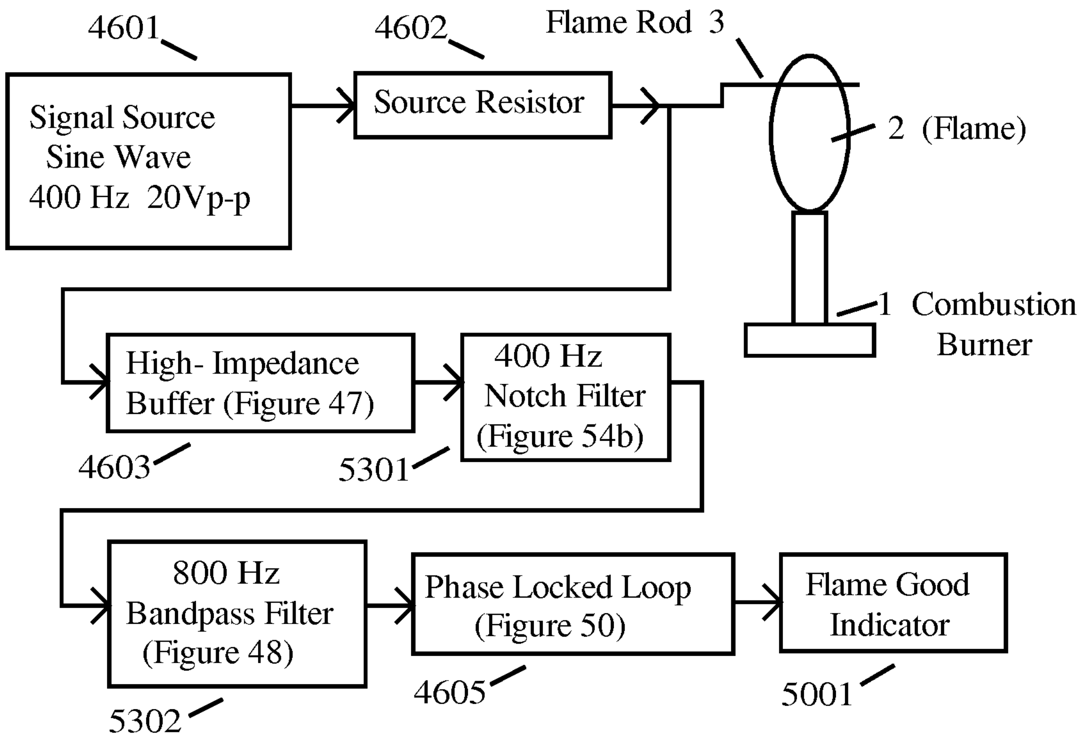
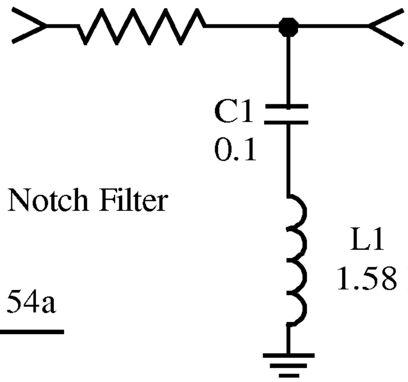
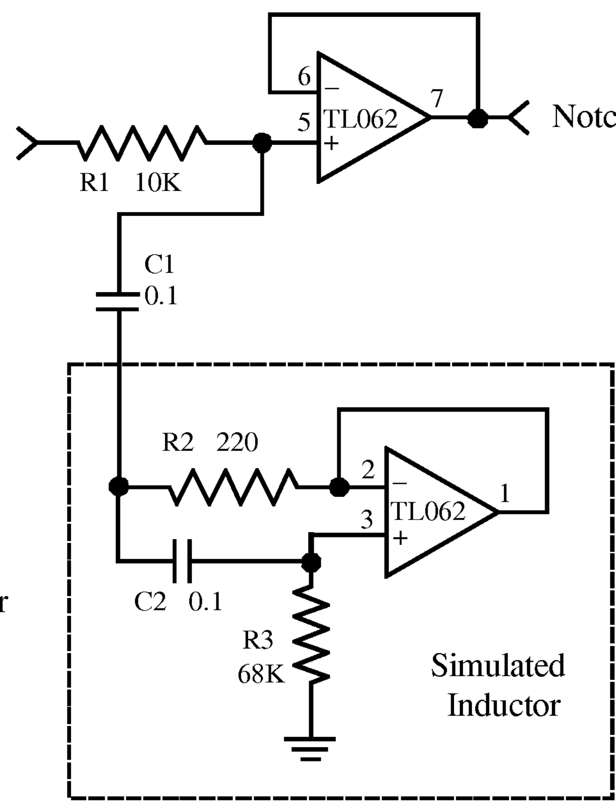

4601
4602
Flame Rod 3
Signal Source
Sine Wave
400 Hz 20Vp-p
Source Resistor
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 47)
400 Hz
Notch Filter
(Figure 54b)
4603
5301
800 Hz
Bandpass Filter
(Figure 48)
Phase Locked Loop
(Figure 50)
Flame Good
Indicator
5302
4605
5001

Figure 53




400 Hz Series LC Notch Filter

Figure 54a




400 Hz
Series LC
Notch Filter

Figure 54b

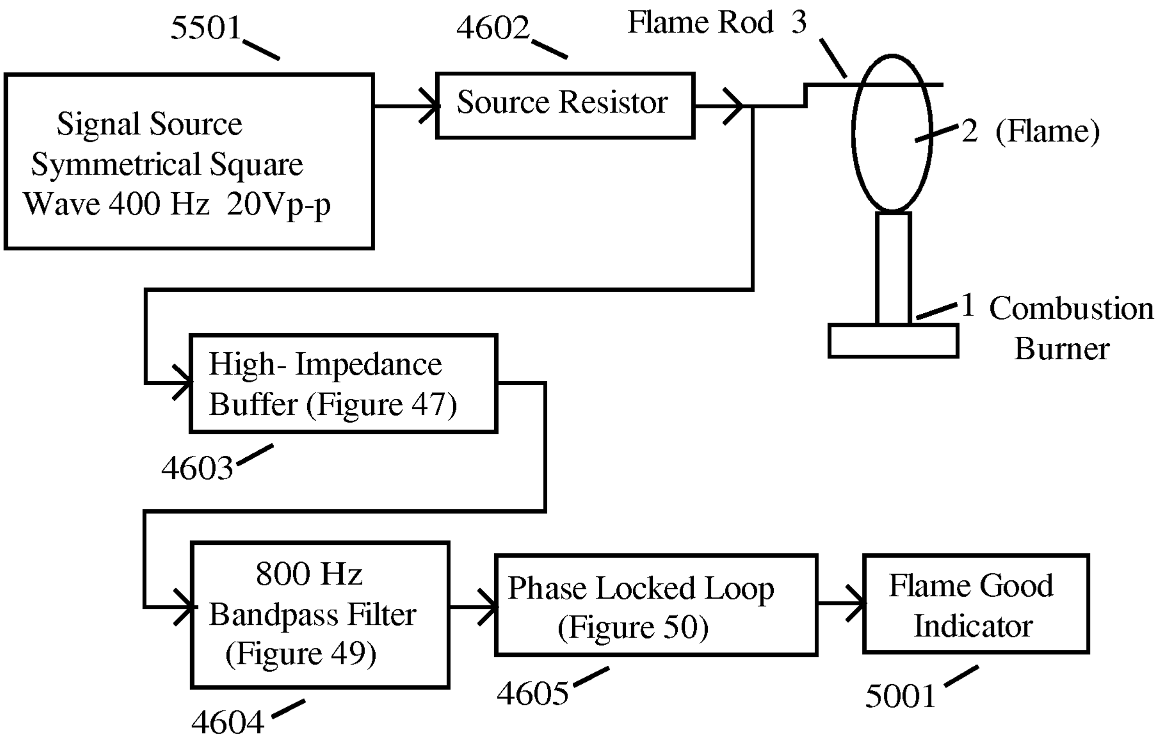

5501
Signal Source
Symmetrical Square
Wave 400 Hz 20Vp-p
4602
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 47)
4603
800 Hz
Bandpass Filter
(Figure 49)
4604
Phase Locked Loop
(Figure 50)
4605
Flame Good
Indicator
5001

Figure 55

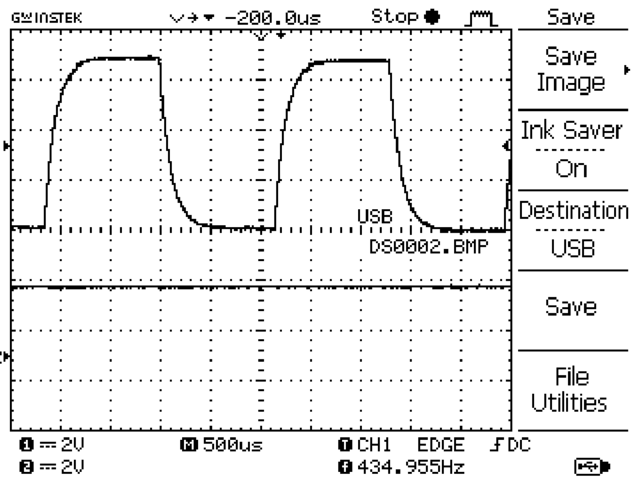



Figure 56a Square Wave; 435 Hz; Flame Off

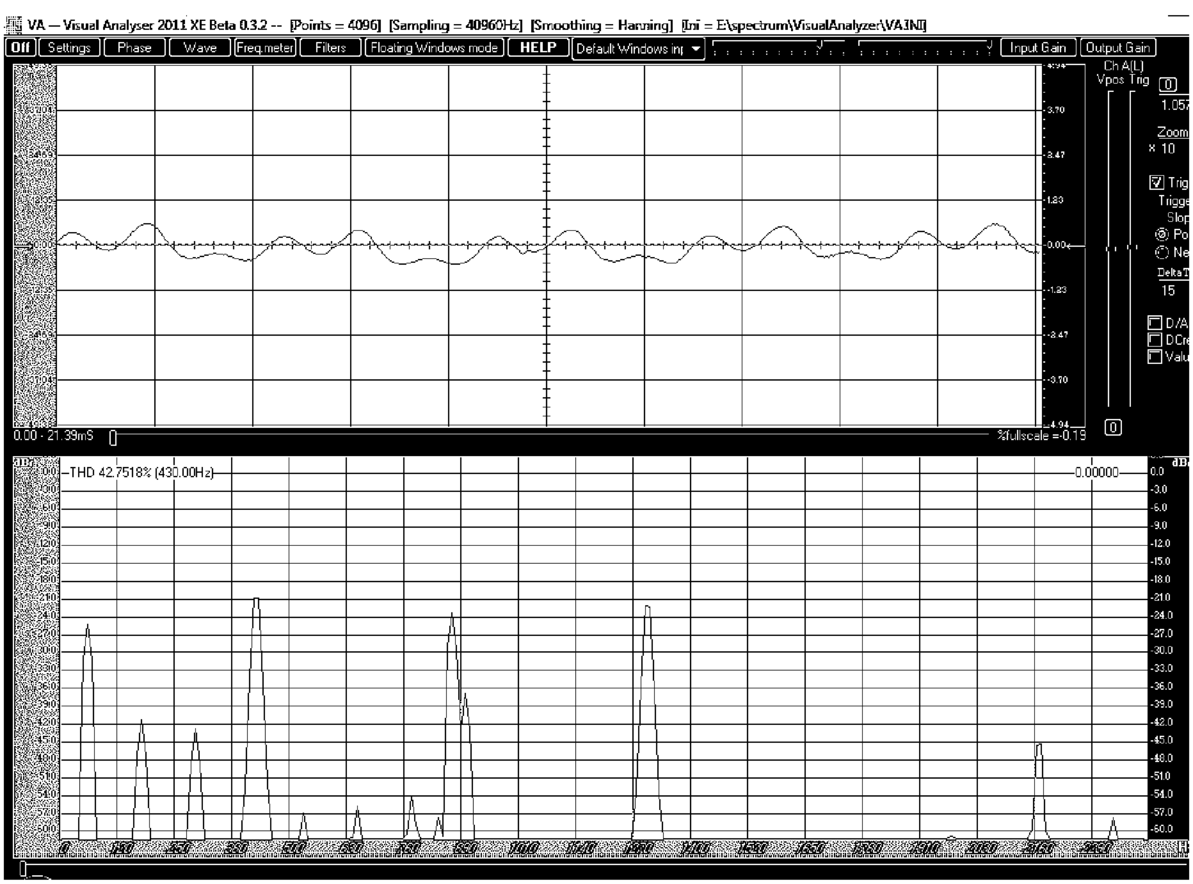



Figure 56b Square Wave; 435 Hz; Flame Off

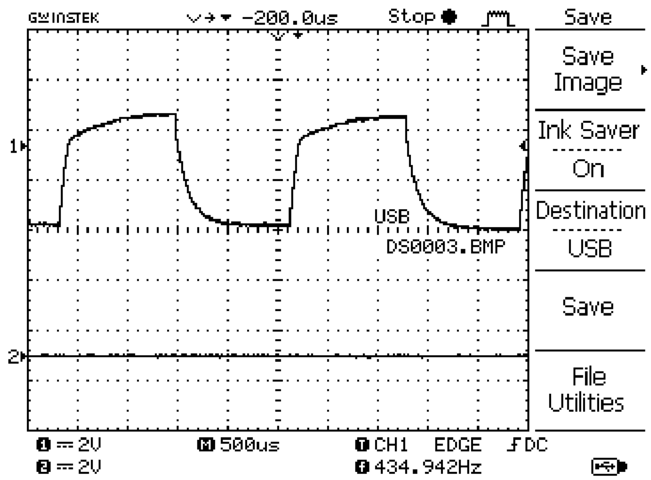



Figure 57a Square Wave; 435 Hz; Flame On

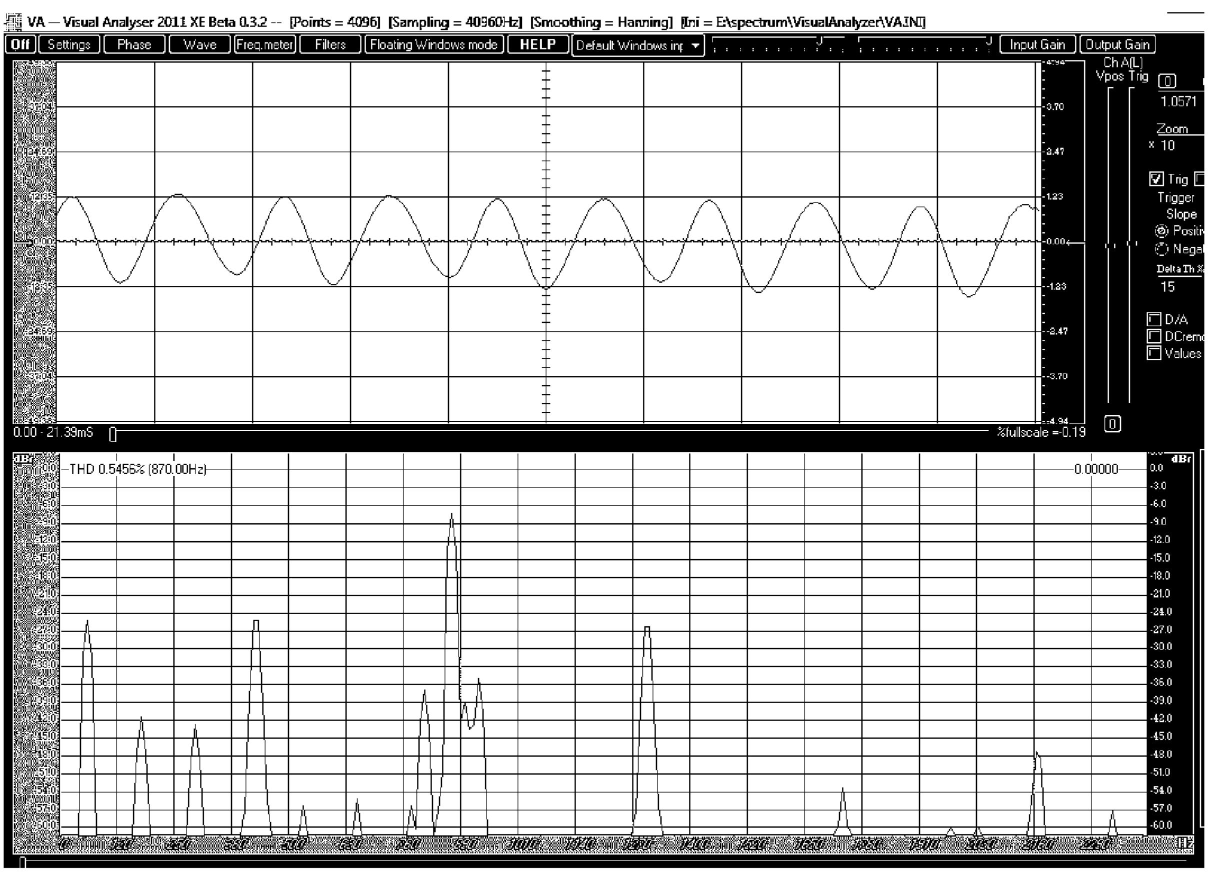



Figure 57b Square Wave; 435 Hz; Flame On

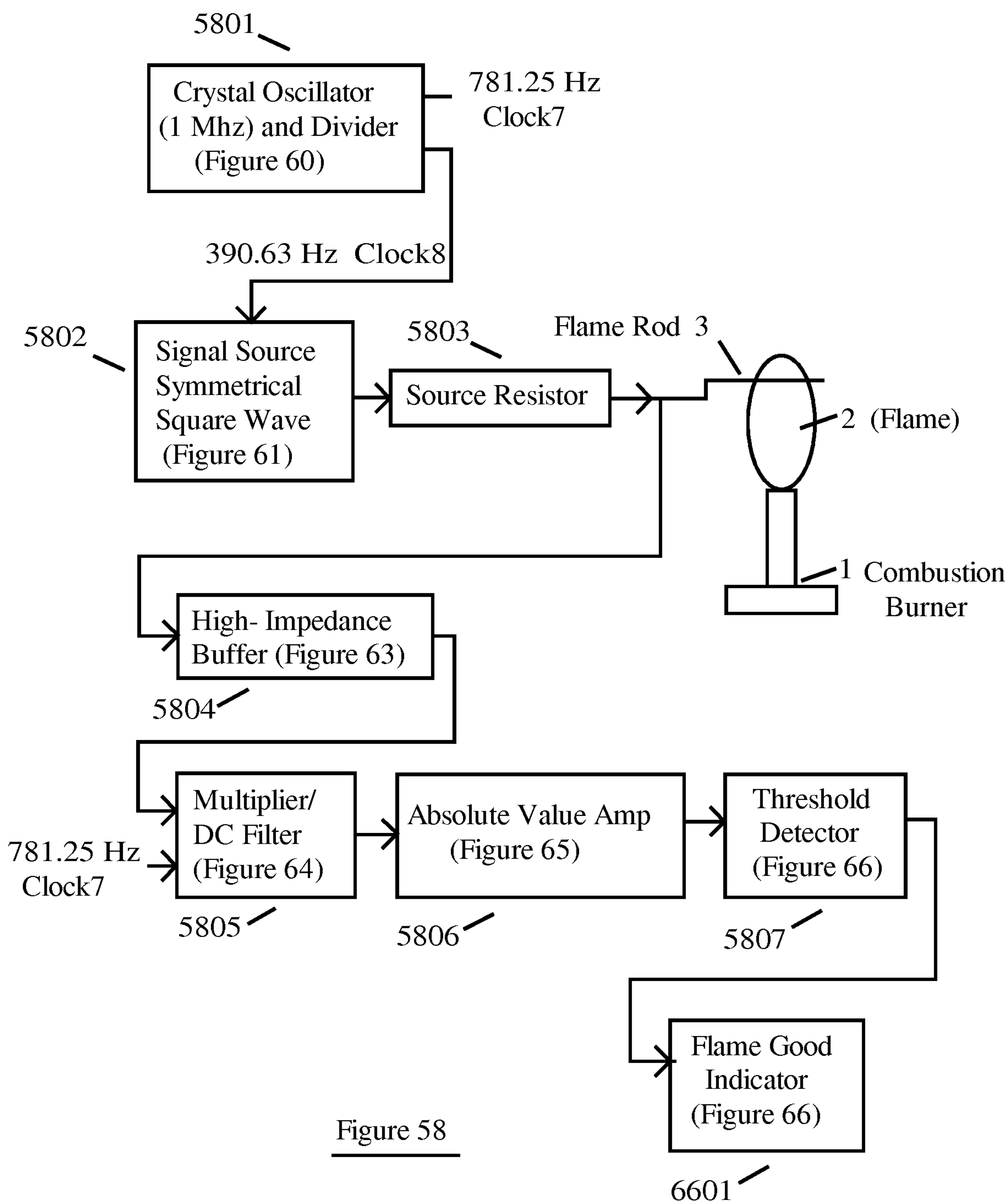

5801
Crystal Oscillator
(1 Mhz) and Divider
(Figure 60)
781.25 Hz
Clock7
390.63 Hz Clock8
5802
Signal Source
Symmetrical
Square Wave
(Figure 61)
5803
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 63)
5804
Multiplier/
DC Filter
(Figure 64)
781.25 Hz
Clock7
5805
Absolute Value Amp
(Figure 65)
5806
Threshold
Detector
(Figure 66)
5807
Flame Good
Indicator
(Figure 66)
6601

Figure 58

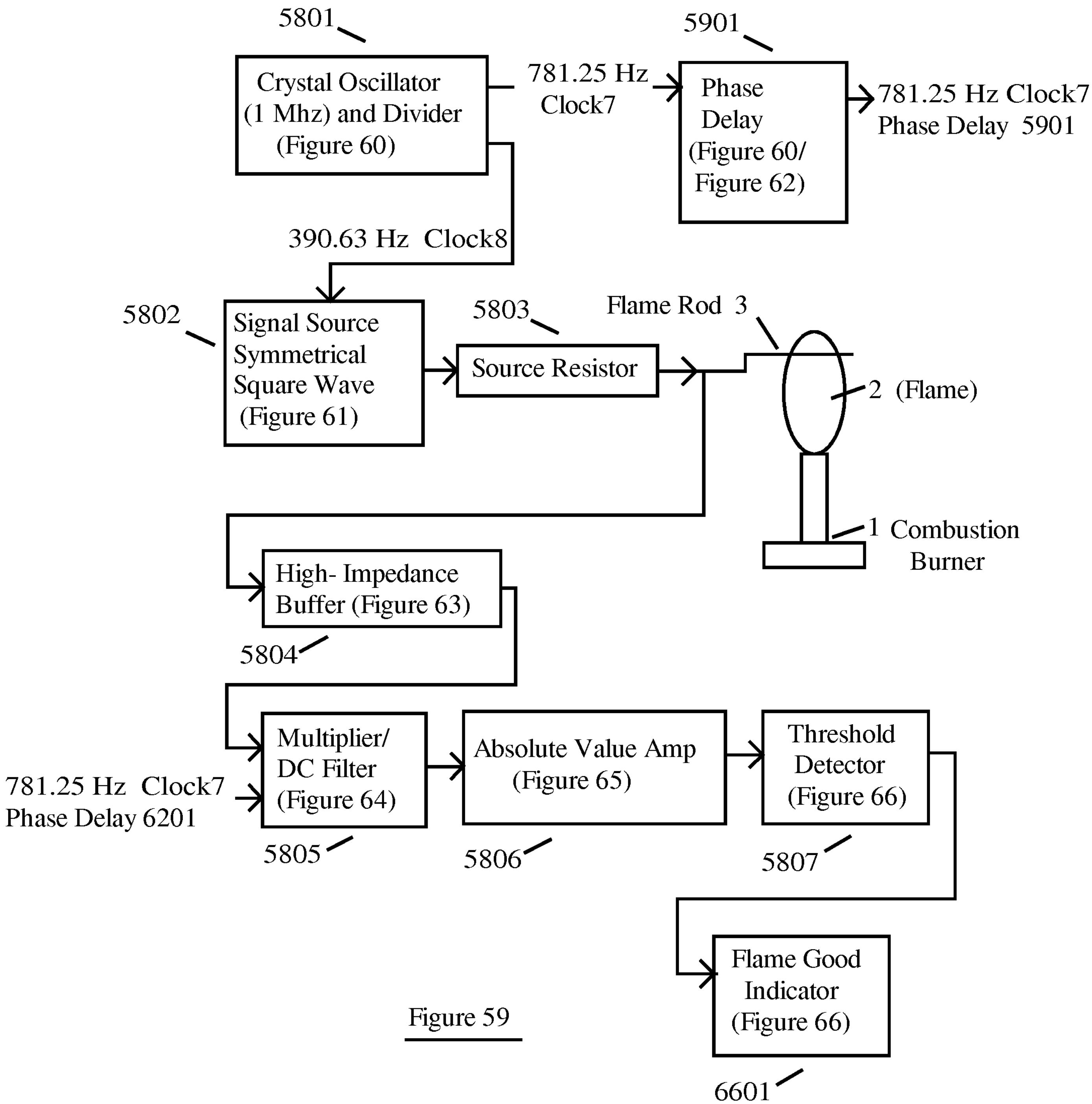
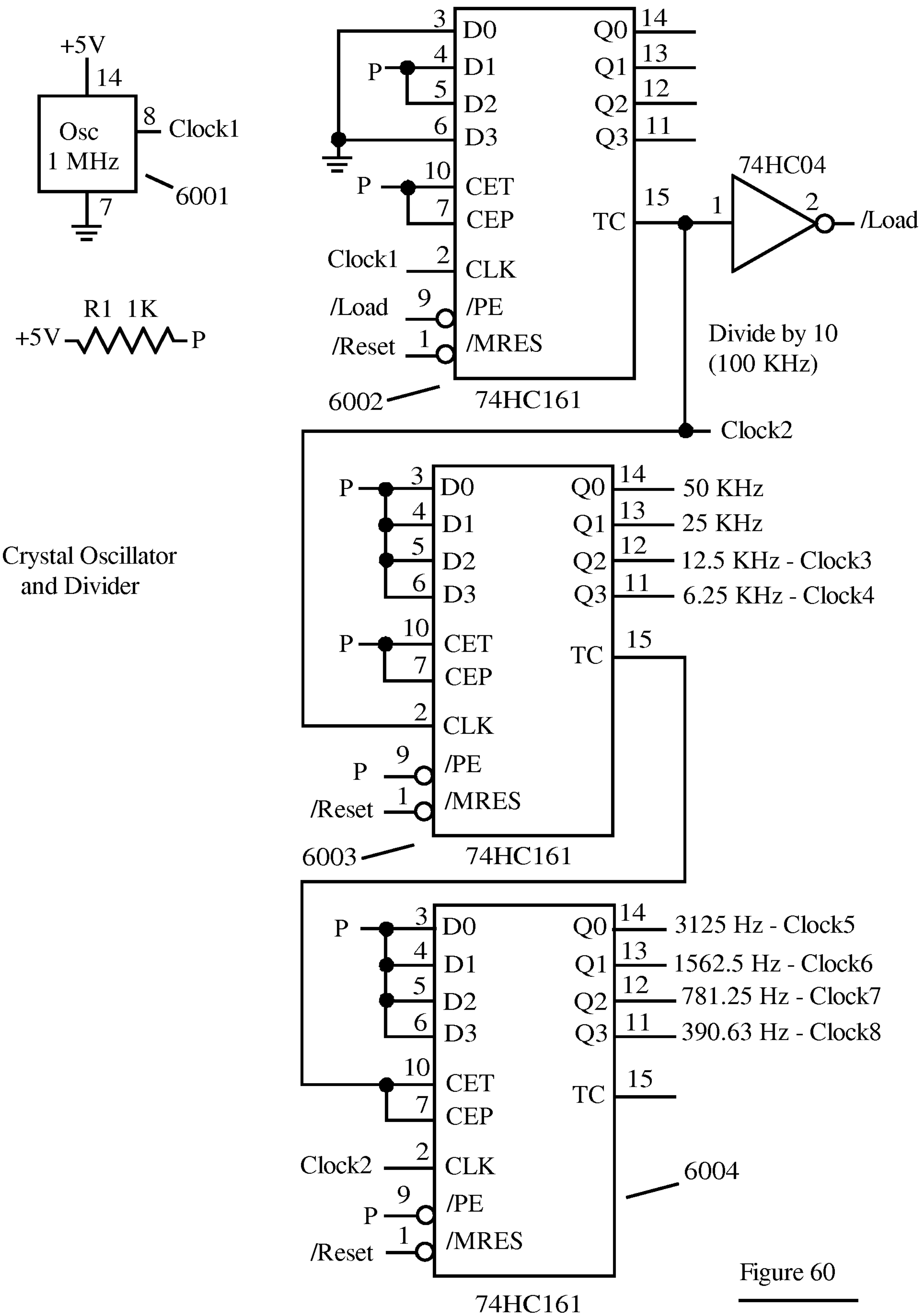

5801
Crystal Oscillator
(1 Mhz) and Divider
(Figure 60)
781.25 Hz
Clock7
5901
Phase
Delay
(Figure 60/
Figure 62)
781.25 Hz Clock7
Phase Delay 5901
390.63 Hz Clock8
5802
Signal Source
Symmetrical
Square Wave
(Figure 61)
5803
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 63)
5804
781.25 Hz Clock7
Phase Delay 6201
Multiplier/
DC Filter
(Figure 64)
5805
Absolute Value Amp
(Figure 65)
5806
Threshold
Detector
(Figure 66)
5807
Flame Good
Indicator
(Figure 66)
6601

Figure 59




Crystal Oscillator and Divider

Figure 60

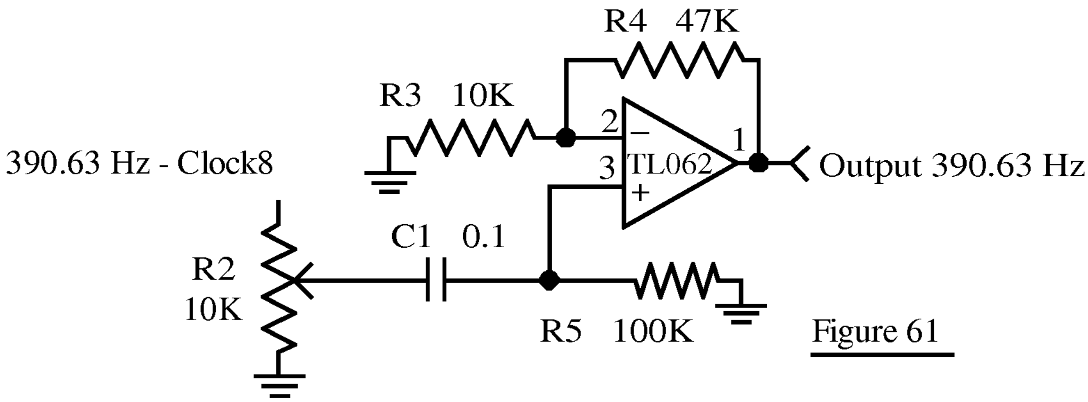



Figure 61

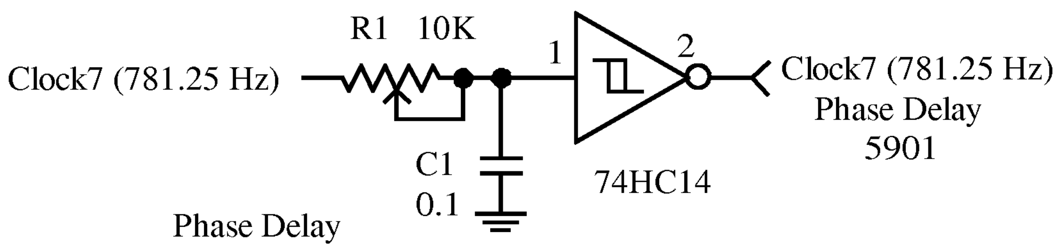



Figure 62

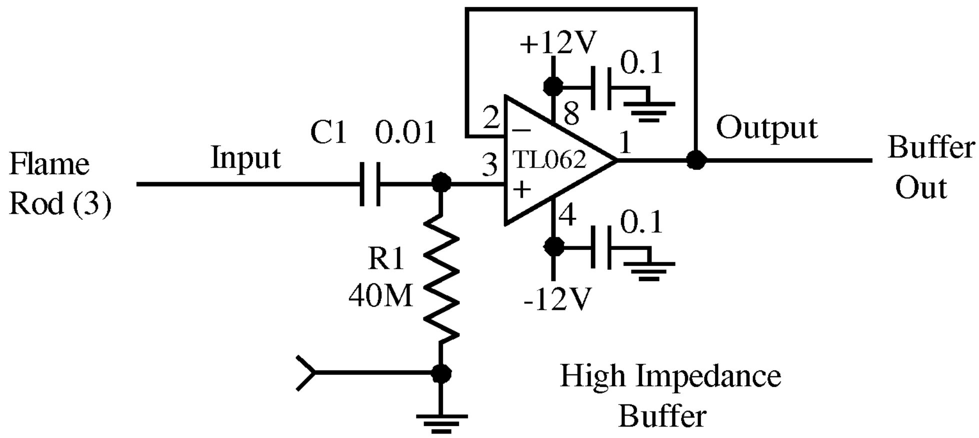



Figure 63

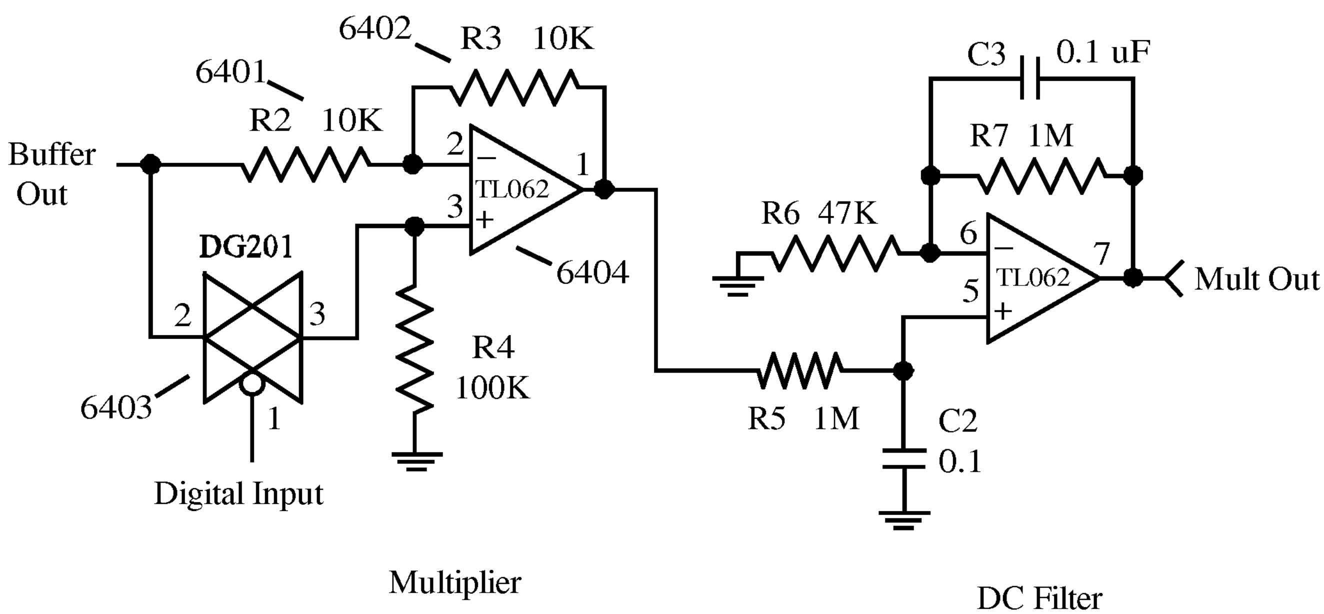



Figure 64 Multiplier and DC Filter

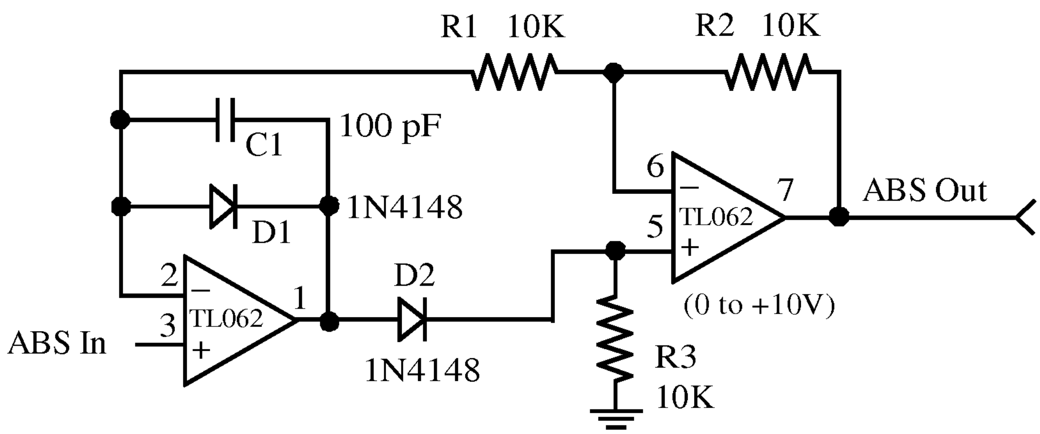



Figure 65 Absolute Value Amp

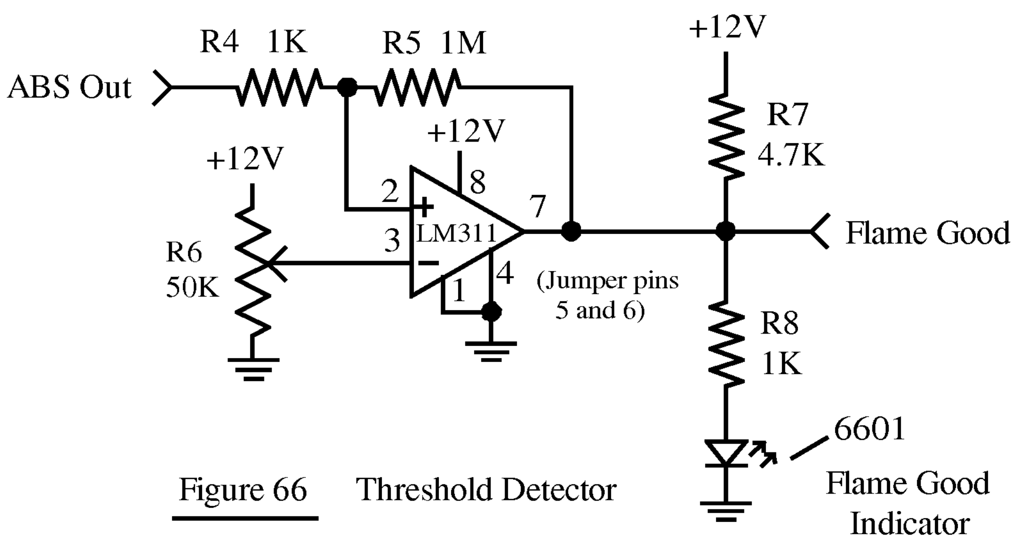



Figure 66 Threshold Detector

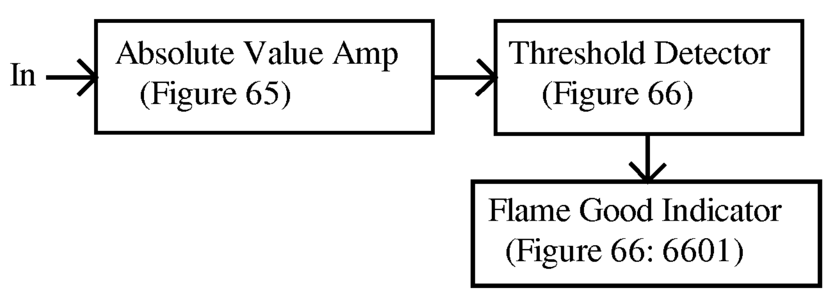
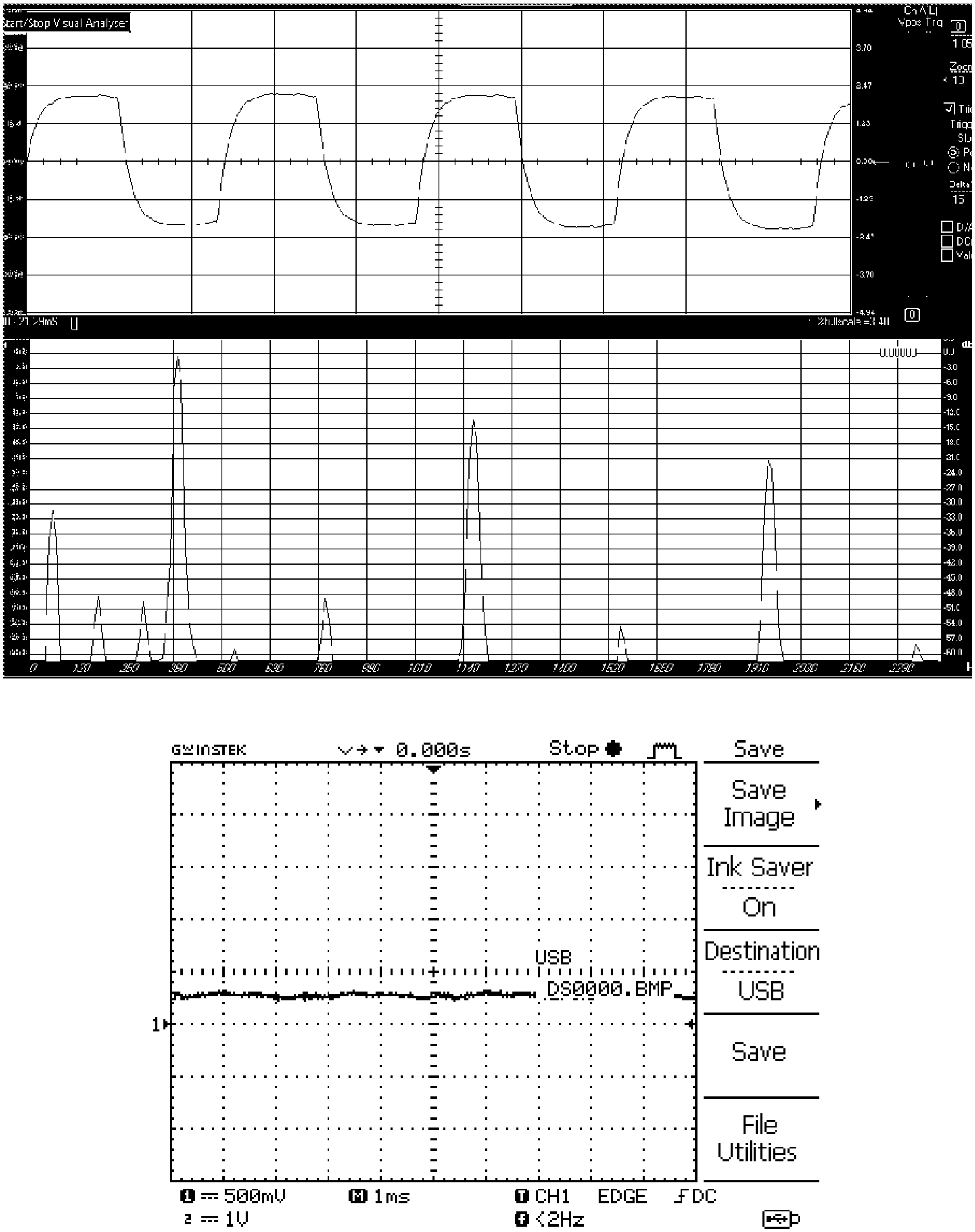
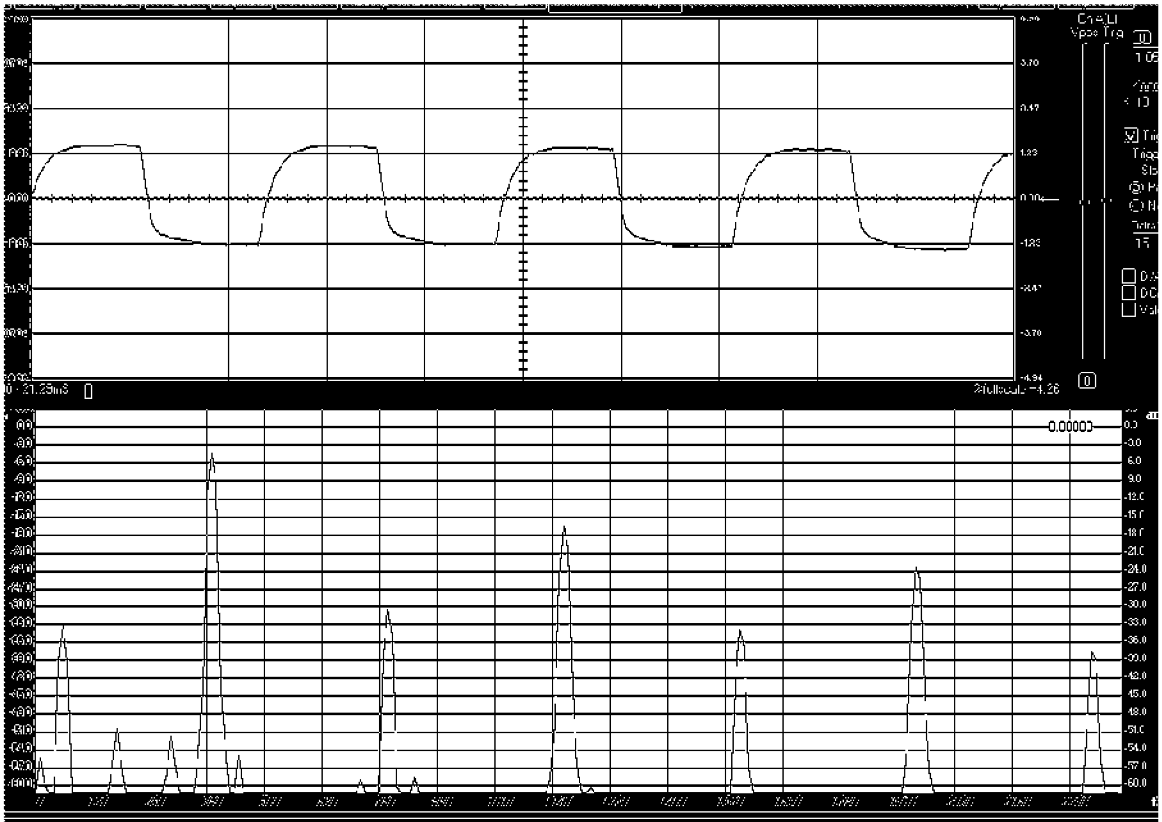


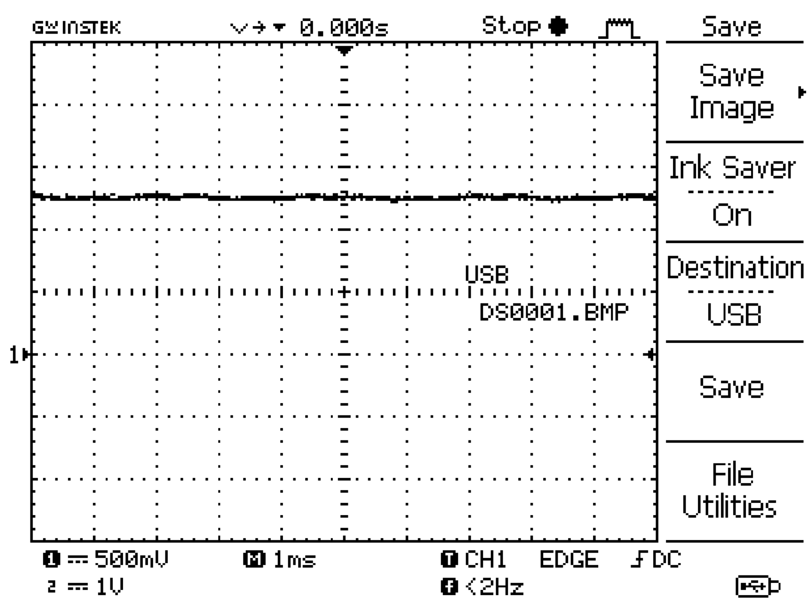

Figure 67 Threshold Detector




Experiment 14 Detecting a harmonic signal produced by flame rectification;
Signal Source: Symmetrical Square Wave
Detector: Simple Synchronous Detector
Flame: Off

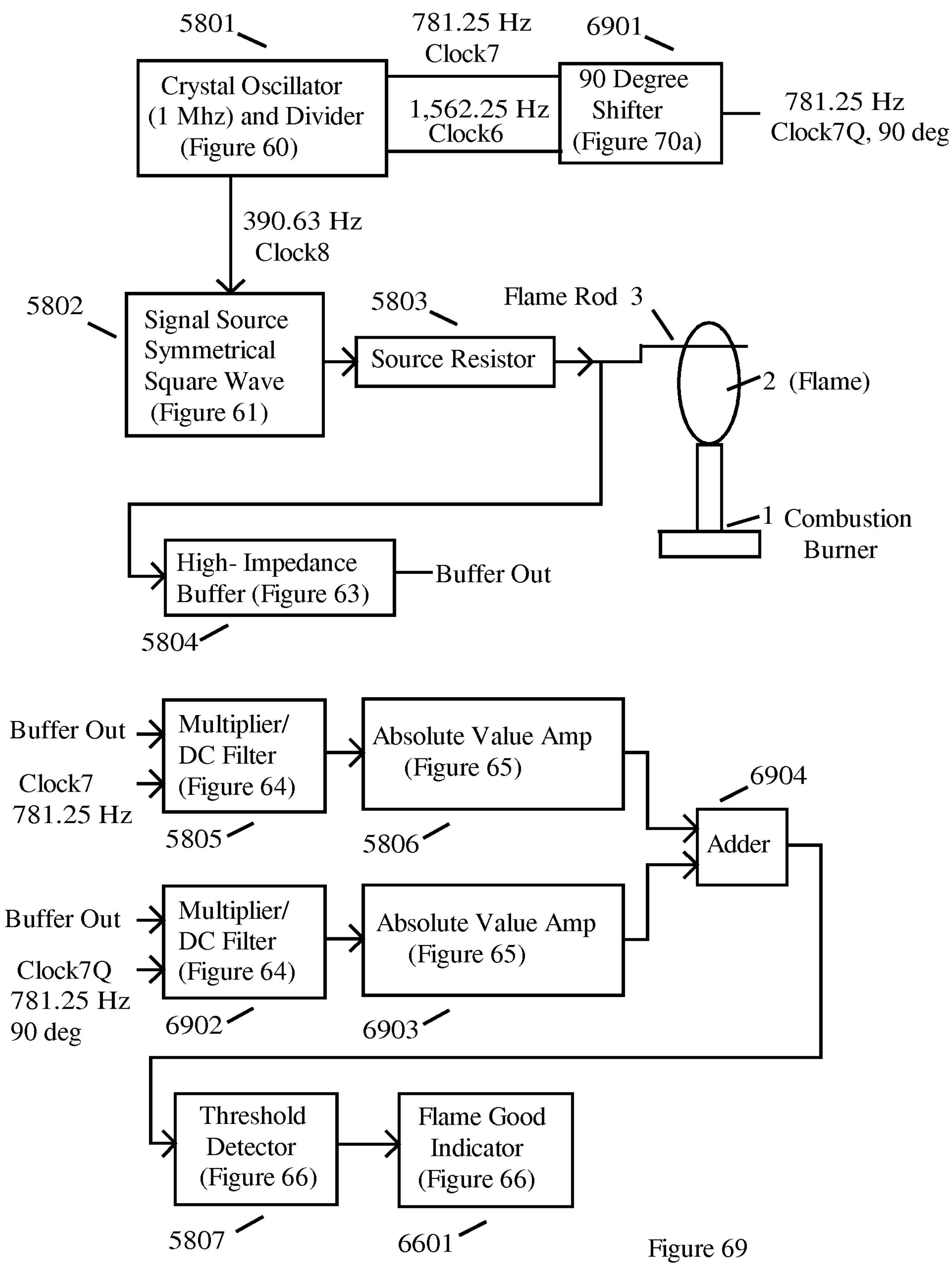
<u>Figure 68a</u>






Experiment 14 Detecting a harmonic signal produced by flame rectification;
Signal Source: Symmetrical Square Wave
Detector: Simple Synchronous Detector
Flame: On

<u>Figure 68b</u>



5801
781.25 Hz
Clock7
6901
Crystal Oscillator
(1 Mhz) and Divider
(Figure 60)
1,562.25 Hz
Clock6
90 Degree
Shifter
(Figure 70a)
781.25 Hz
Clock7Q, 90 deg
390.63 Hz
Clock8
5802
Signal Source
Symmetrical
Square Wave
(Figure 61)
5803
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 63)
Buffer Out
5804
Buffer Out
Clock7
781.25 Hz
Multiplier/
DC Filter
(Figure 64)
5805
Absolute Value Amp
(Figure 65)
5806
6904
Adder
Buffer Out
Clock7Q
781.25 Hz
90 deg
Multiplier/
DC Filter
(Figure 64)
6902
Absolute Value Amp
(Figure 65)
6903
Threshold
Detector
(Figure 66)
5807
Flame Good
Indicator
(Figure 66)
6601


Figure 69

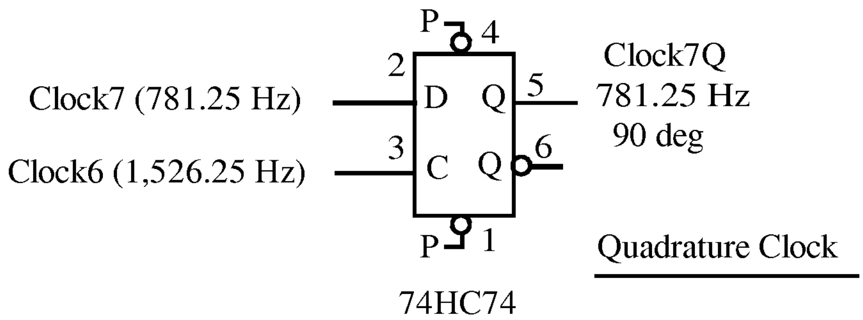



Figure 70a

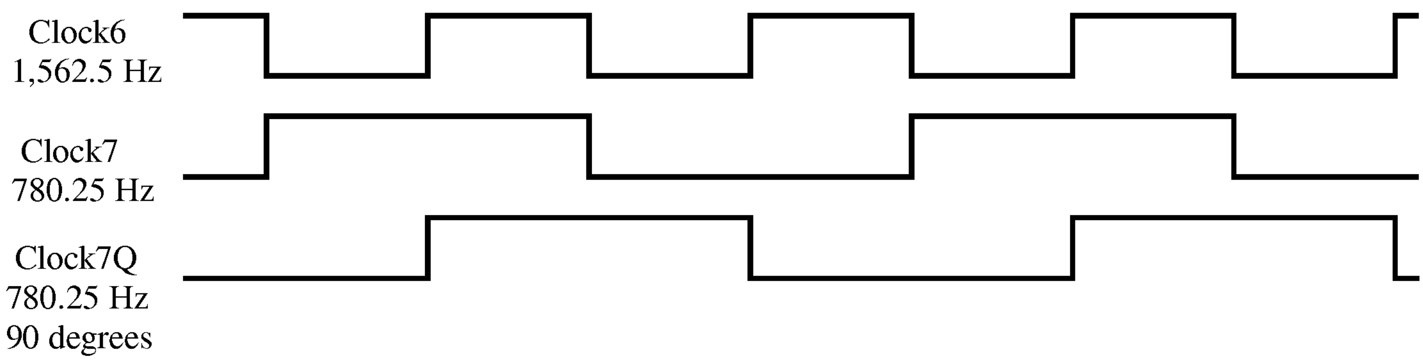



Figure 70b

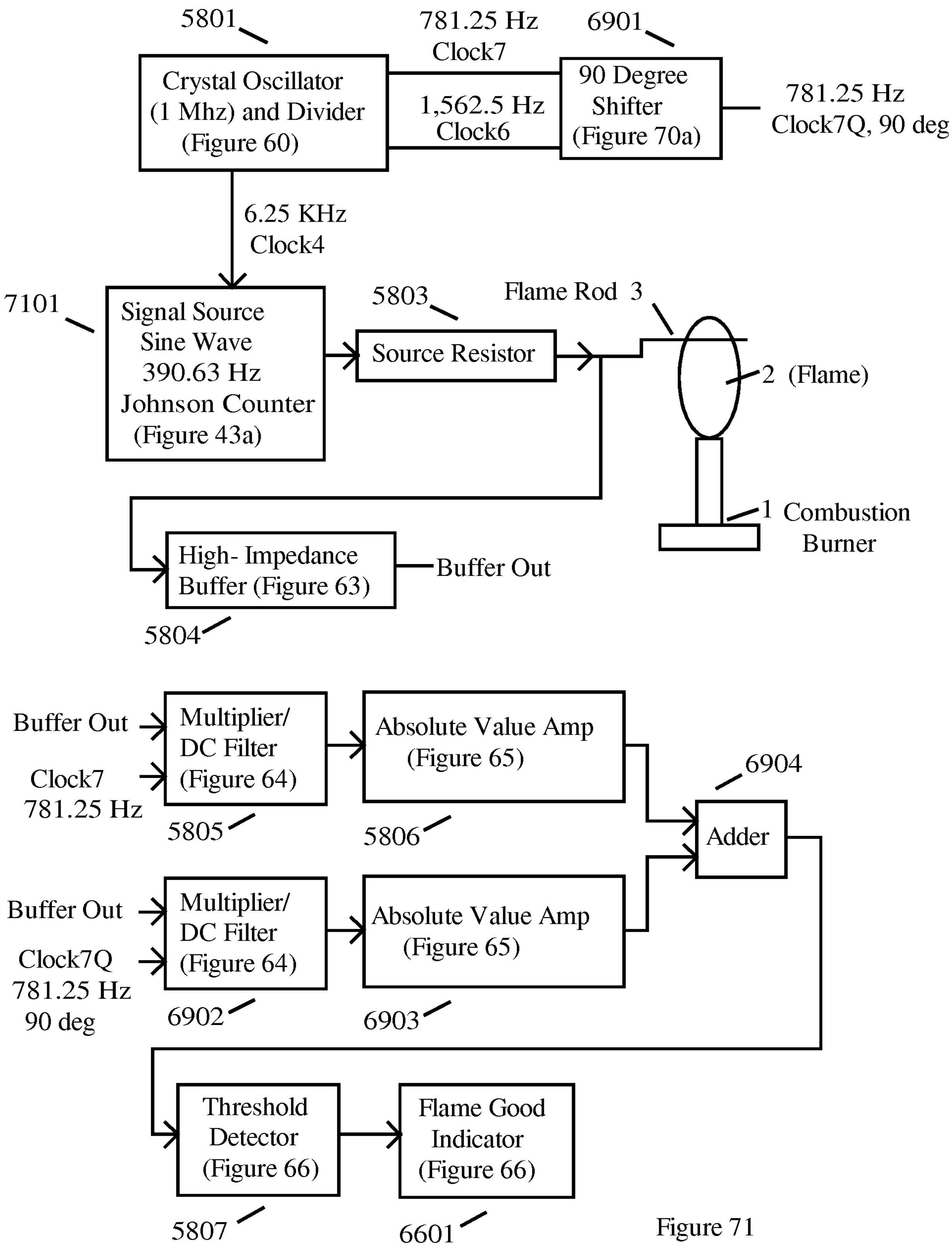

5801
781.25 Hz
Clock7
6901
Crystal Oscillator
(1 Mhz) and Divider
(Figure 60)
1,562.5 Hz
Clock6
90 Degree
Shifter
(Figure 70a)
781.25 Hz
Clock7Q, 90 deg
6.25 KHz
Clock4
7101
Signal Source
Sine Wave
390.63 Hz
Johnson Counter
(Figure 43a)
5803
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 63)
Buffer Out
5804
Buffer Out
Clock7
781.25 Hz
Multiplier/
DC Filter
(Figure 64)
Absolute Value Amp
(Figure 65)
6904
Adder
5805
5806
Buffer Out
Clock7Q
781.25 Hz
90 deg
Multiplier/
DC Filter
(Figure 64)
Absolute Value Amp
(Figure 65)
6902
6903
Threshold
Detector
(Figure 66)
Flame Good
Indicator
(Figure 66)
5807
6601

Figure 71

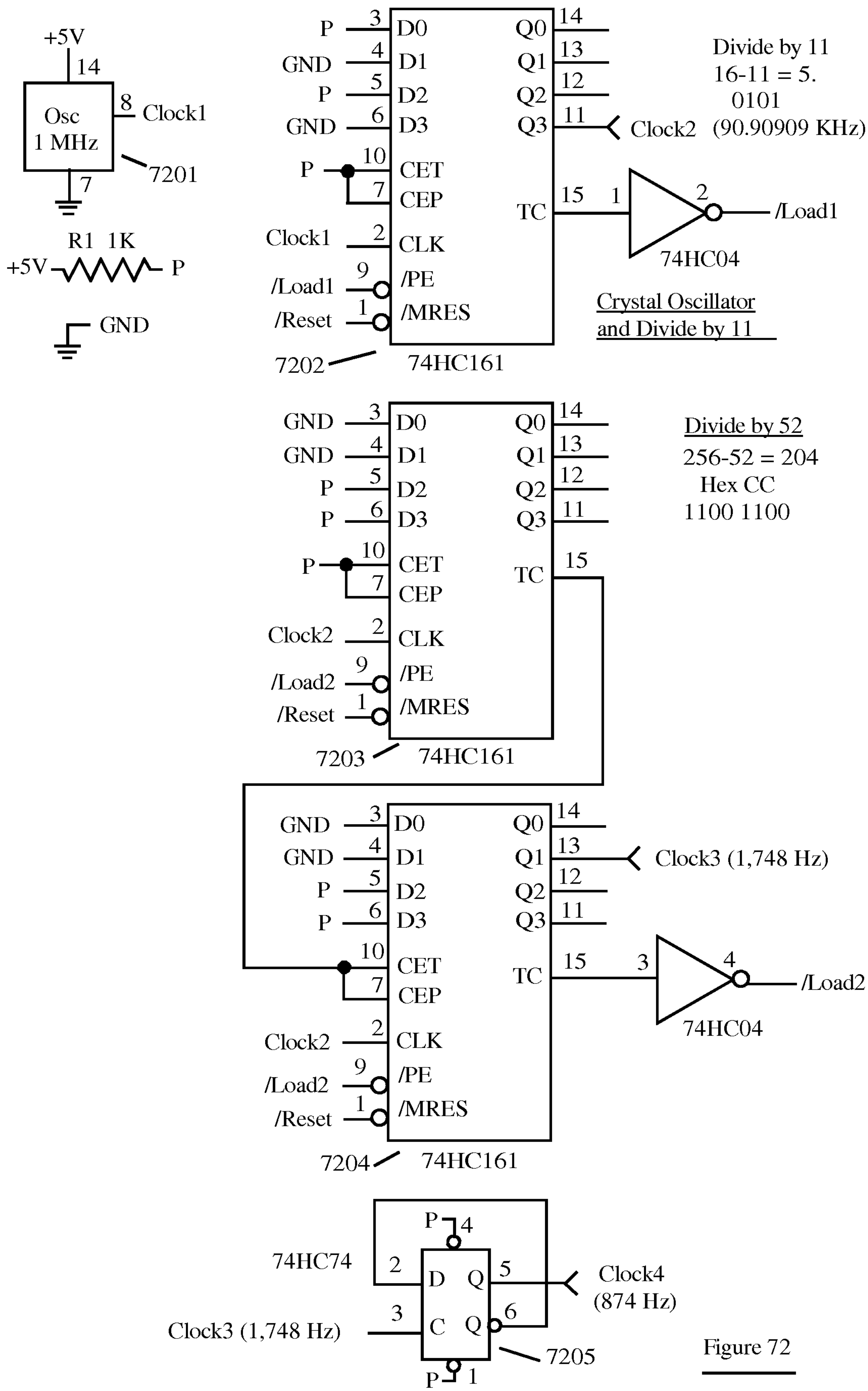

+5V
14
Osc
1 MHz
8
Clock1
7
7201
R1 1K
+5V
P
GND
P
GND
P
GND
P
Clock1
/Load1
/Reset
7202
D0
D1
D2
D3
CET
CEP
CLK
/PE
/MRES
Q0
Q1
Q2
Q3
TC
74HC161
Clock2
74HC04
/Load1
Divide by 11
16-11 = 5.
0101
(90.90909 KHz)
Crystal Oscillator
and Divide by 11
Divide by 52
256-52 = 204
Hex CC
1100 1100
Clock2
/Load2
/Reset
7203
74HC161
Clock3 (1,748 Hz)
74HC04
/Load2
7204
74HC161
74HC74
Clock4
(874 Hz)
Clock3 (1,748 Hz)
7205

Figure 72

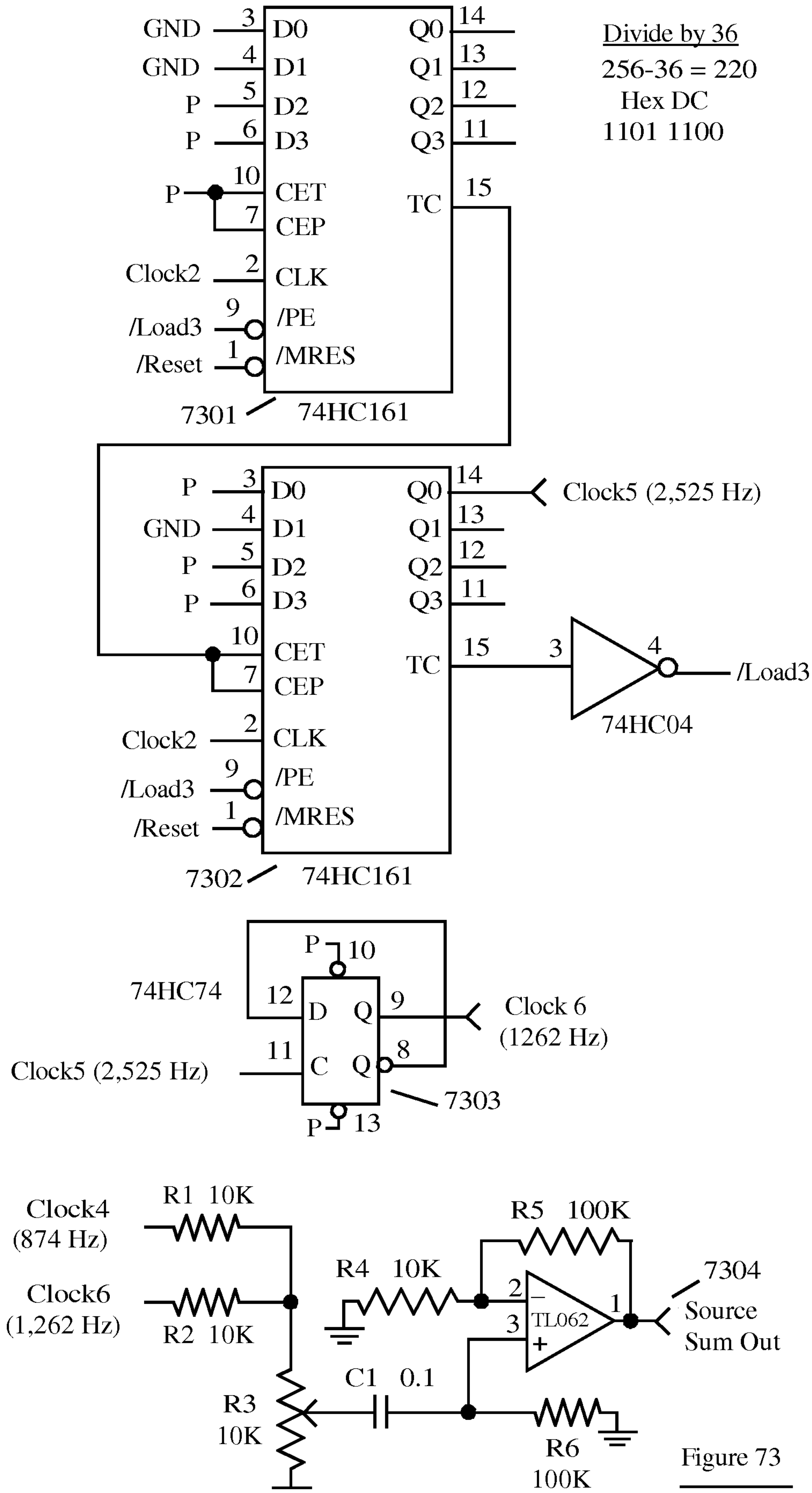

GND
GND
P
P
P
Clock2
/Load3
/Reset
D0
D1
D2
D3
CET
CEP
CLK
/PE
/MRES
Q0
Q1
Q2
Q3
TC
7301
74HC161
Divide by 36
256-36 = 220
Hex DC
1101 1100
P
GND
P
P
Clock2
/Load3
/Reset
D0
D1
D2
D3
CET
CEP
CLK
/PE
/MRES
Q0
Q1
Q2
Q3
TC
Clock5 (2,525 Hz)
/Load3
74HC04
7302
74HC161
74HC74
P
D
Q
C
Q
Clock5 (2,525 Hz)
Clock 6
(1262 Hz)
7303
Clock4
(874 Hz)
Clock6
(1,262 Hz)
R1 10K
R2 10K
R3
10K
R4 10K
R5 100K
C1 0.1
R6
100K
TL062
7304
Source
Sum Out

Figure 73

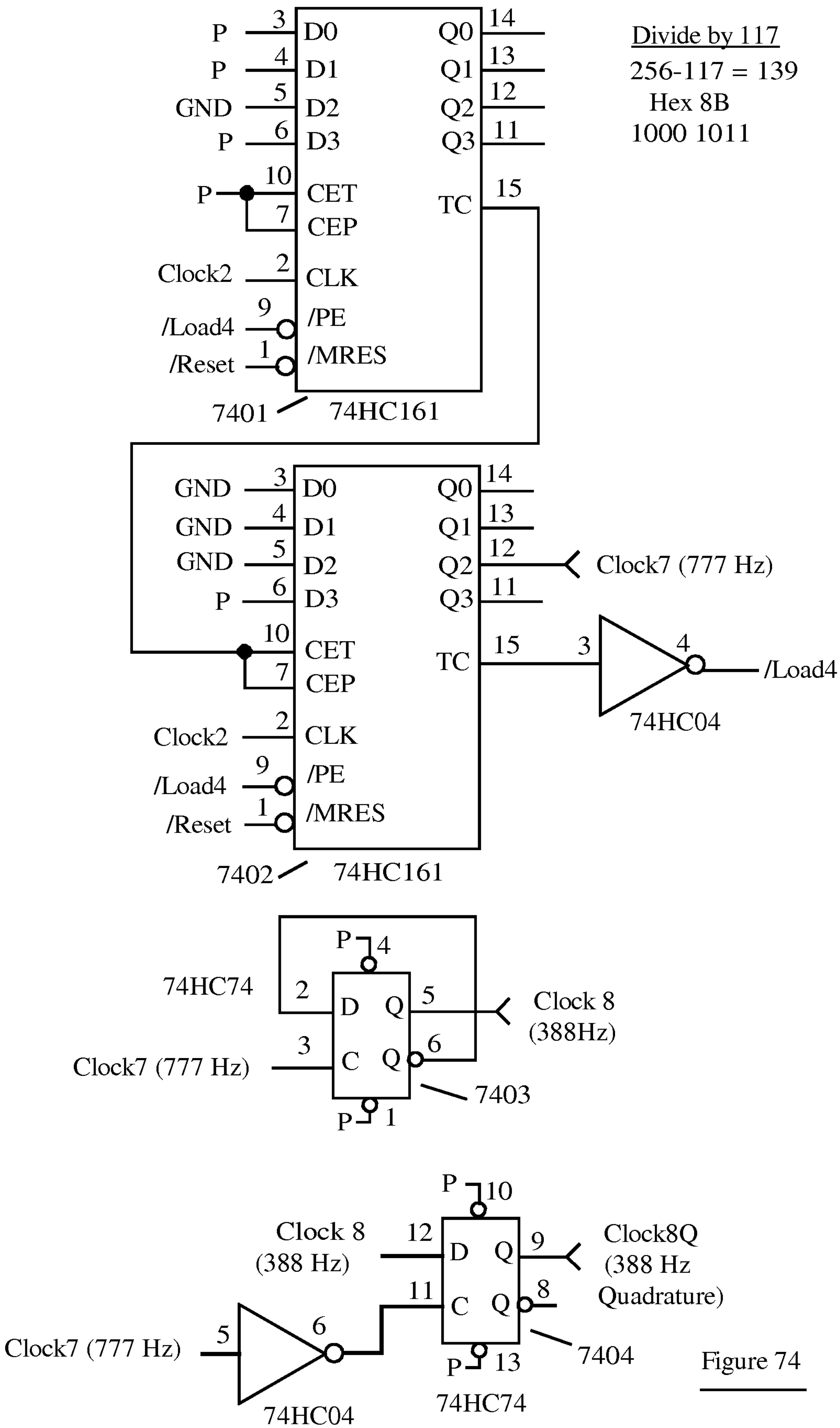

Divide by 117
256-117 = 139
Hex 8B
1000 1011
P
P
GND
P
P
D0
D1
D2
D3
CET
CEP
CLK
/PE
/MRES
Q0
Q1
Q2
Q3
TC
Clock2
/Load4
/Reset
7401
74HC161
GND
GND
GND
P
Clock7 (777 Hz)
/Load4
74HC04
7402
74HC161
74HC74
Clock 8
(388Hz)
Clock7 (777 Hz)
7403
Clock 8
(388 Hz)
Clock8Q
(388 Hz
Quadrature)
Clock7 (777 Hz)
74HC04
74HC74
7404

Figure 74

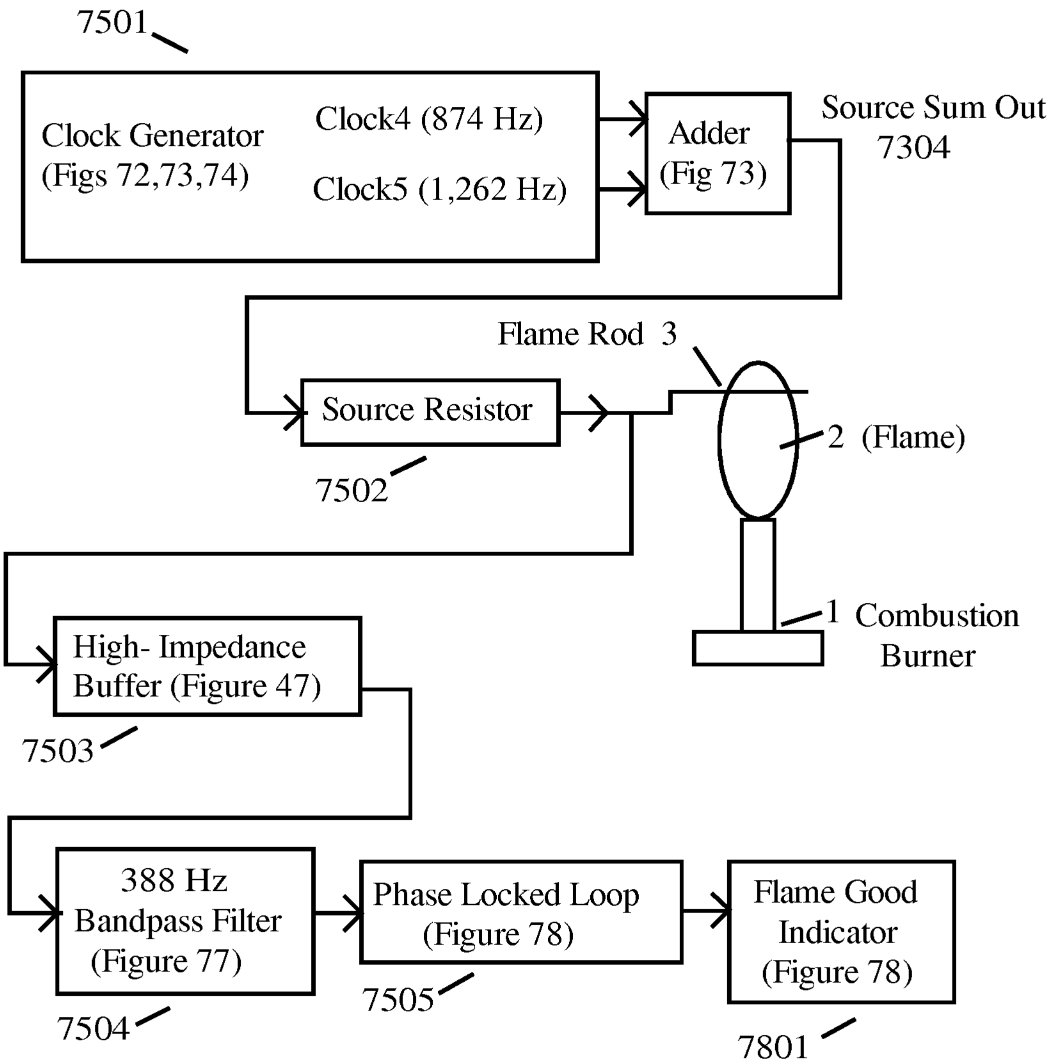

7501
Clock Generator
(Figs 72,73,74)
Clock4 (874 Hz)
Clock5 (1,262 Hz)
Adder
(Fig 73)
Source Sum Out
7304
Flame Rod 3
Source Resistor
7502
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 47)
7503
388 Hz
Bandpass Filter
(Figure 77)
7504
Phase Locked Loop
(Figure 78)
7505
Flame Good
Indicator
(Figure 78)
7801

Figure 75

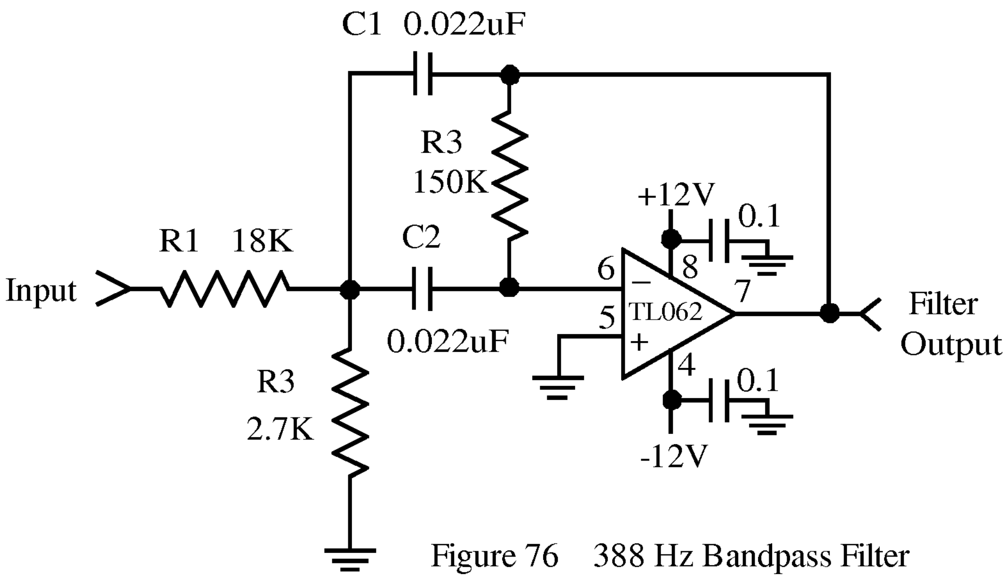



Figure 76 388 Hz Bandpass Filter

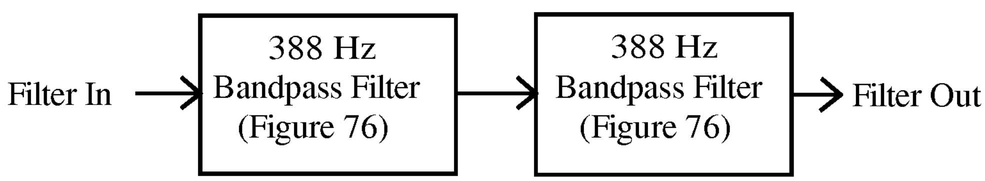



Figure 77 Two Cascaded Bandpass Filters

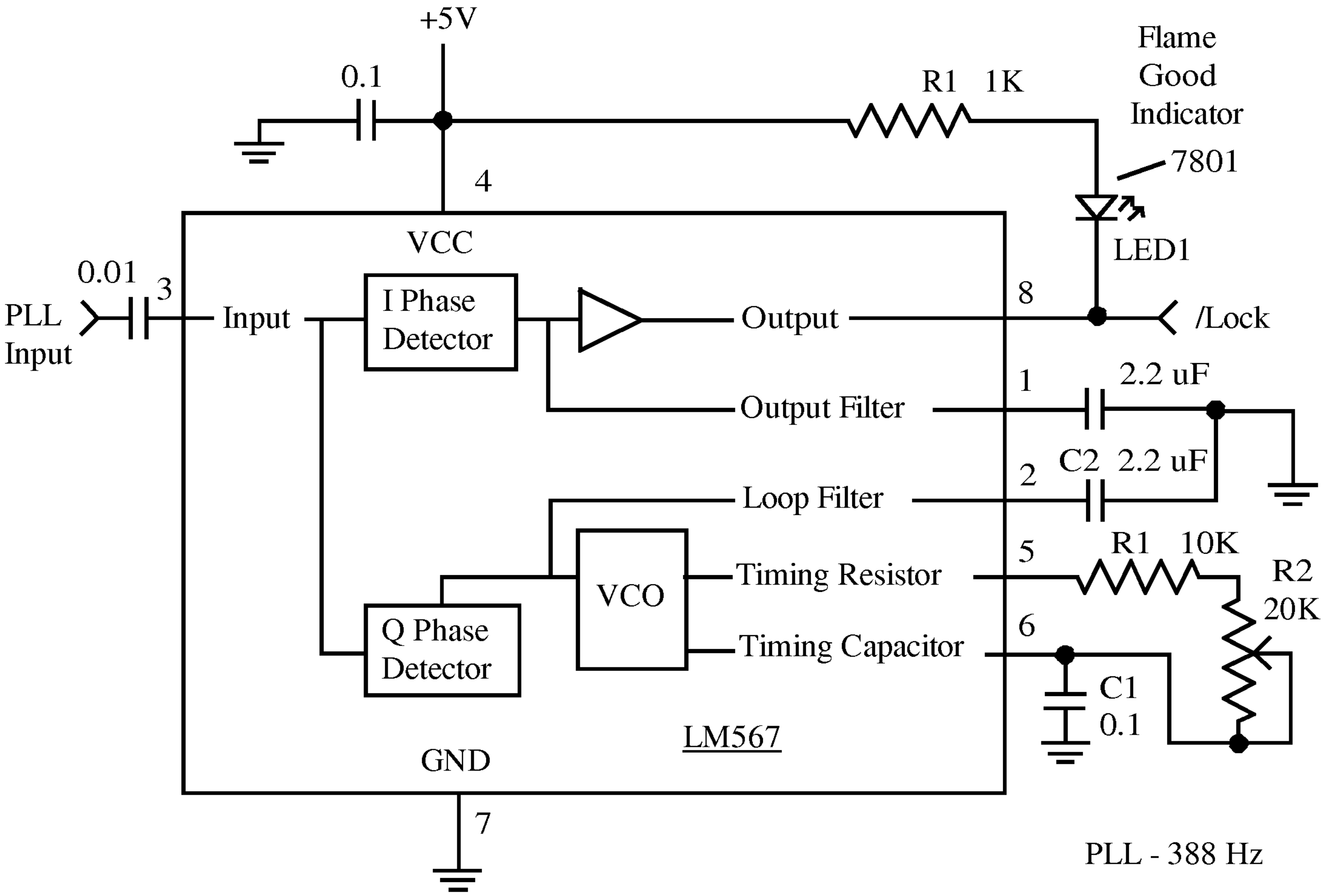

+5V
0.1
R1 1K
Flame Good Indicator
7801
4
LED1
VCC
0.01
3
PLL Input
Input
I Phase Detector
Output
8
/Lock
1
2.2 uF
Output Filter
2
C2 2.2 uF
Loop Filter
5
R1 10K
R2 20K
VCO
Timing Resistor
Q Phase Detector
6
Timing Capacitor
C1 0.1
LM567
GND
7
PLL - 388 Hz

Figure 78

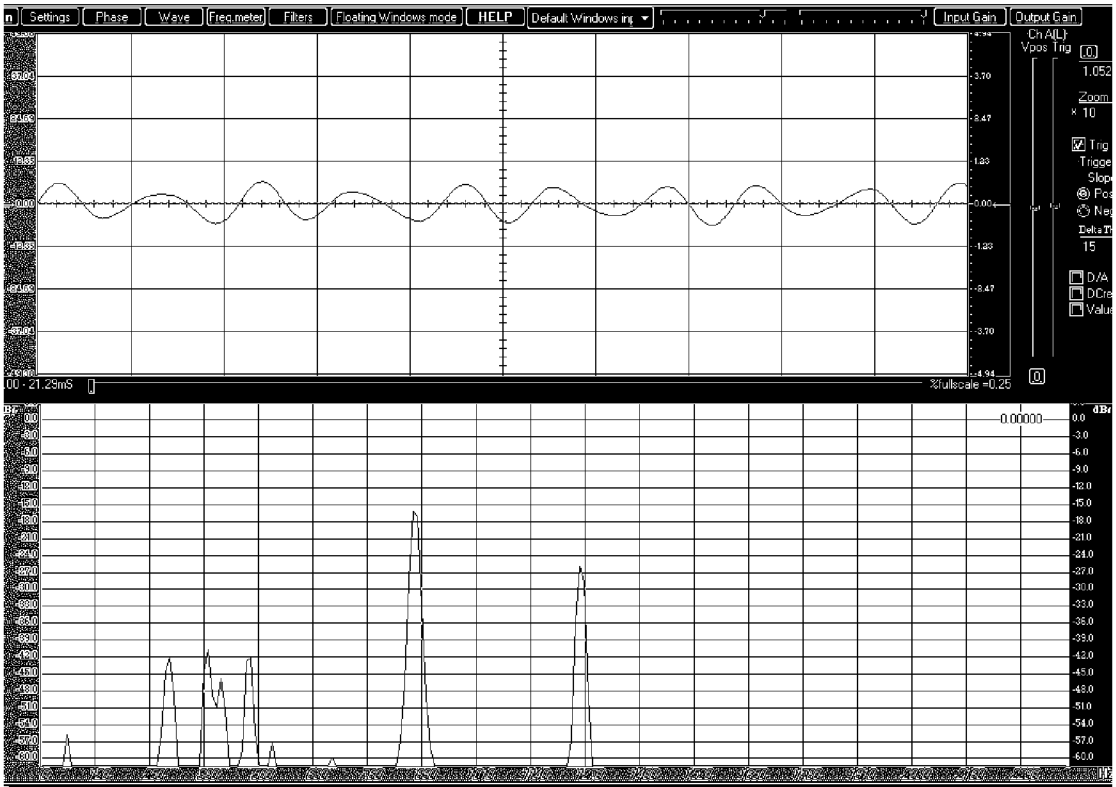


Figure 79a – Heterodyne Test – PLL Detector – Flame Off

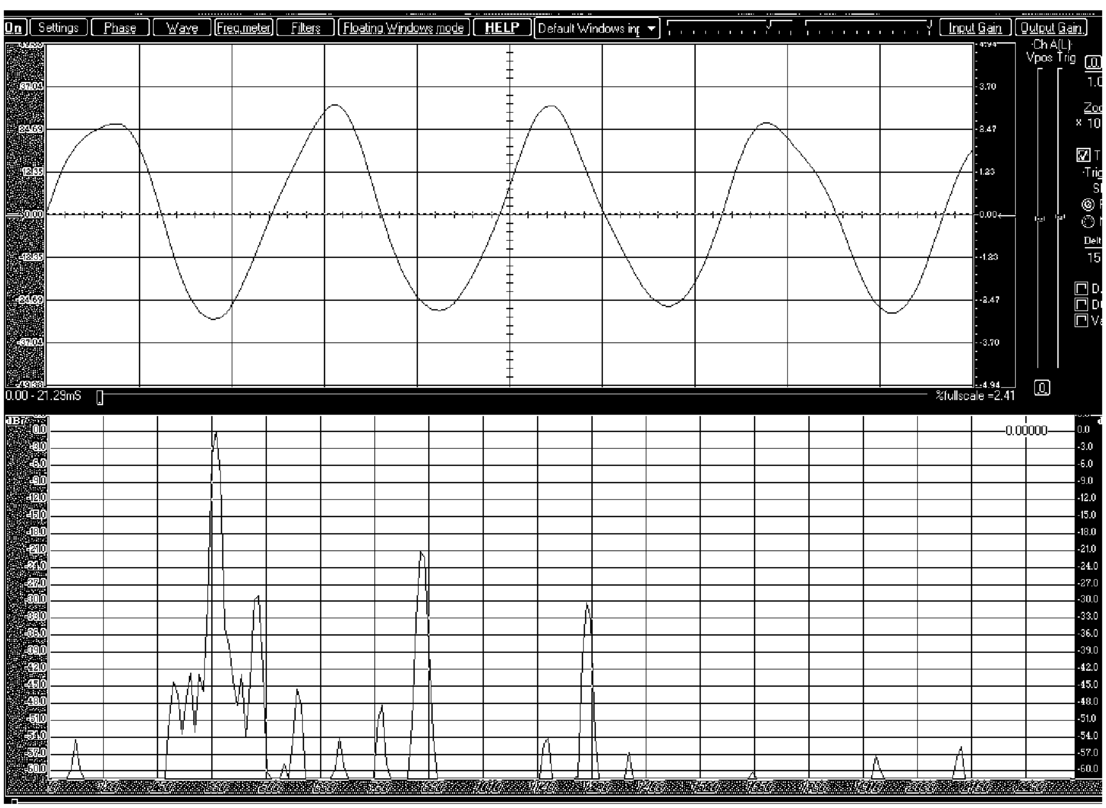


Figure 79b – Heterodyne Test – PLL Detector – Flame On

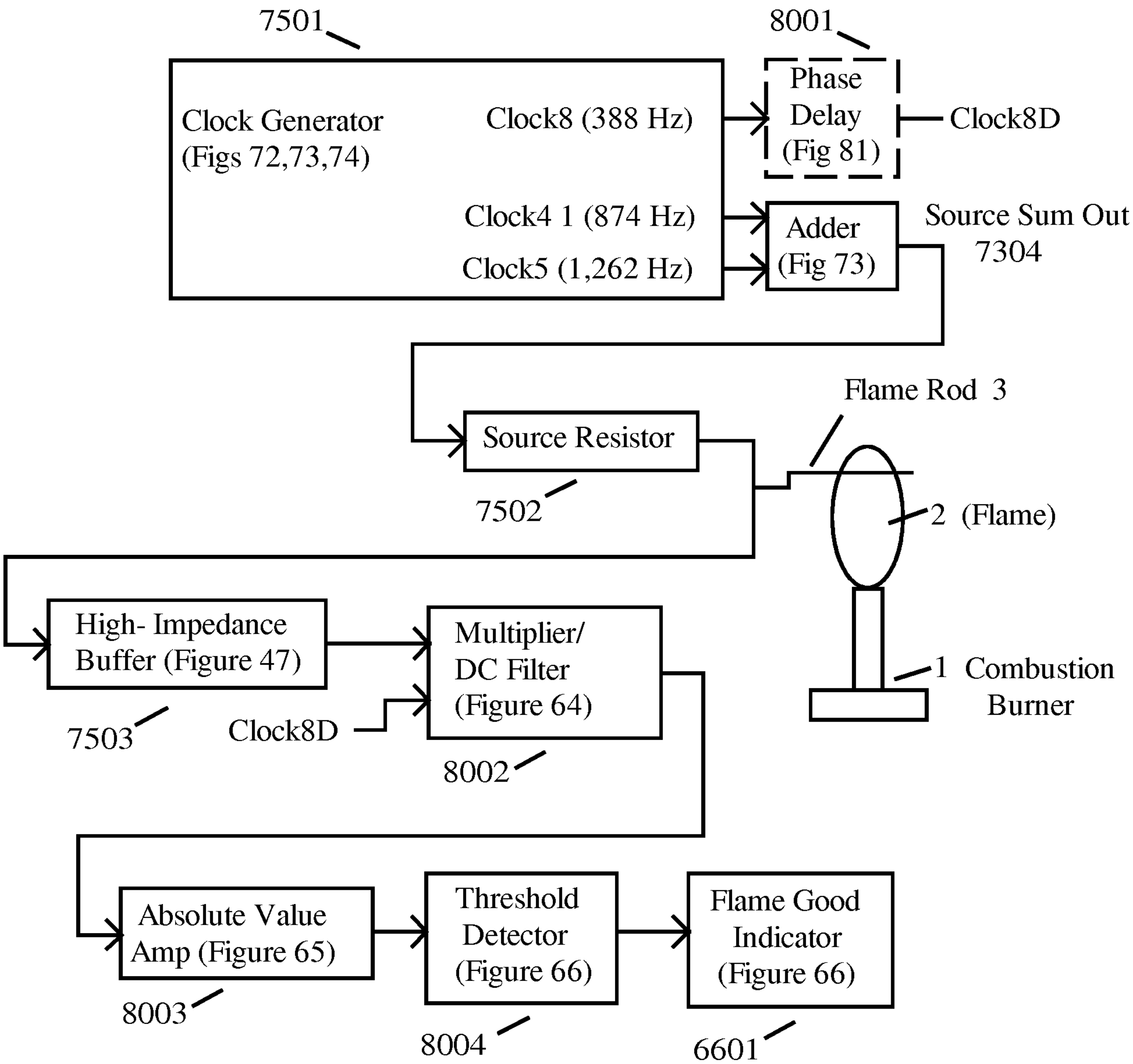



Figure 80

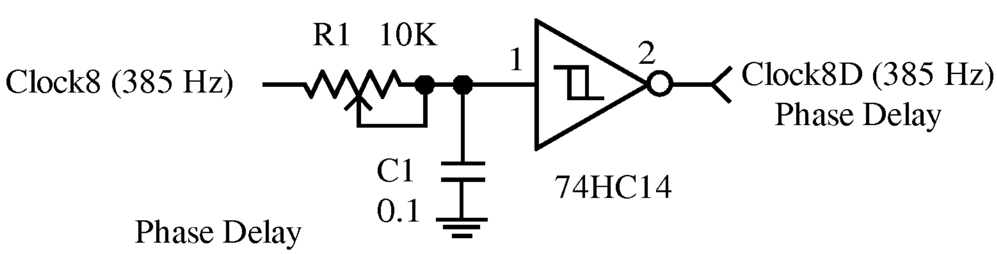



Figure 81

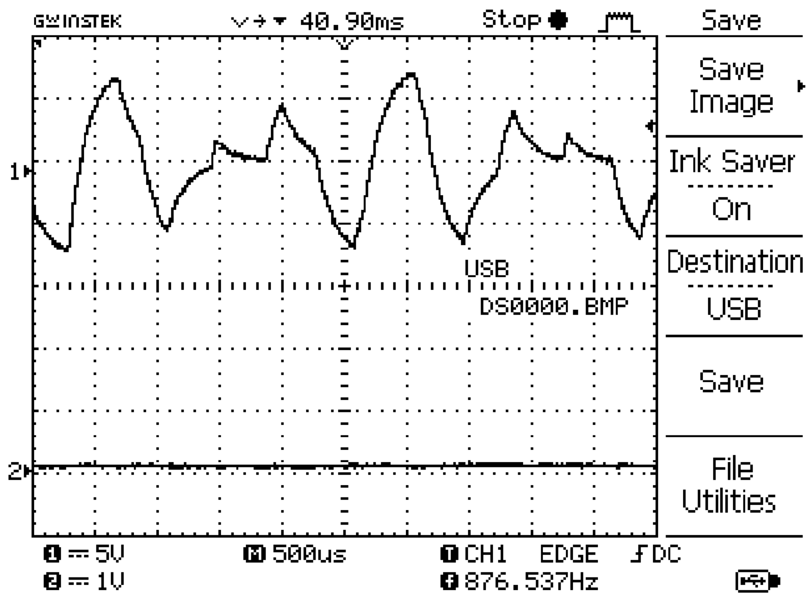



Figure 82a – Heterodyne Test – Simple Synchronous Detector – Flame Off

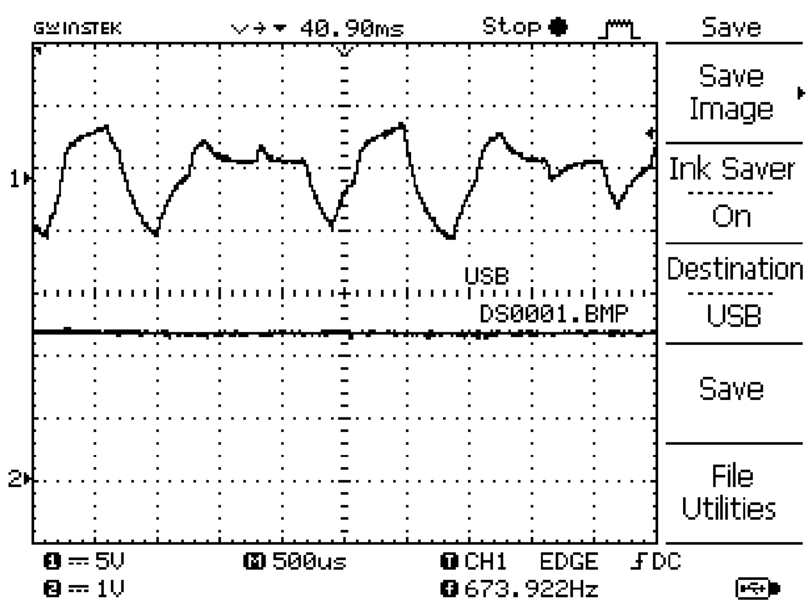



Figure 82b – Heterodyne Test – Simple Synchronous Detector – Flame On

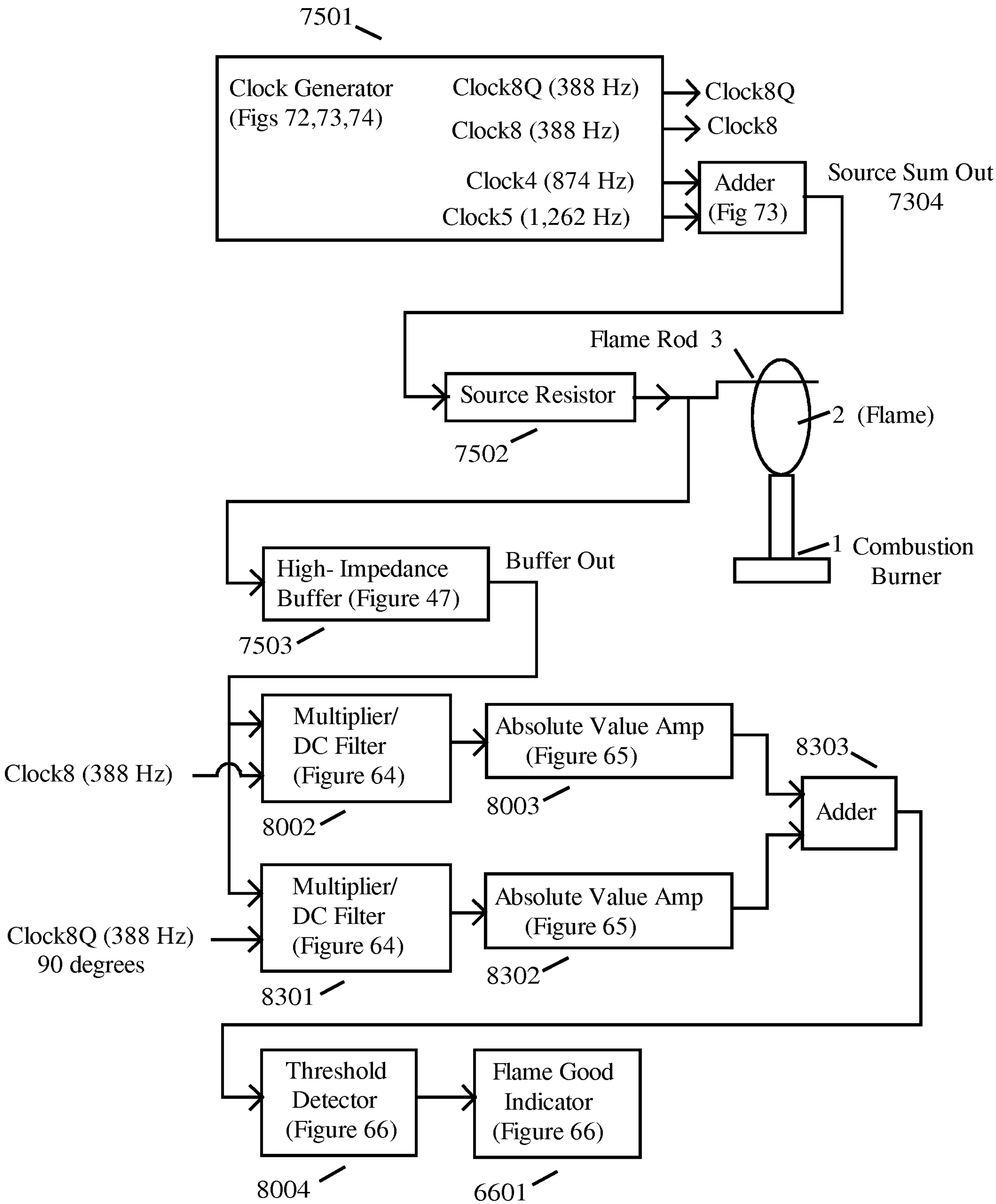

7501
Clock Generator
(Figs 72,73,74)
Clock8Q (388 Hz)
Clock8 (388 Hz)
Clock4 (874 Hz)
Clock5 (1,262 Hz)
Clock8Q
Clock8
Adder
(Fig 73)
Source Sum Out
7304
Flame Rod 3
Source Resistor
7502
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 47)
7503
Buffer Out
Multiplier/
DC Filter
(Figure 64)
8002
Clock8 (388 Hz)
Absolute Value Amp
(Figure 65)
8003
8303
Adder
Multiplier/
DC Filter
(Figure 64)
8301
Clock8Q (388 Hz)
90 degrees
Absolute Value Amp
(Figure 65)
8302
Threshold
Detector
(Figure 66)
8004
Flame Good
Indicator
(Figure 66)
6601

Figure 83

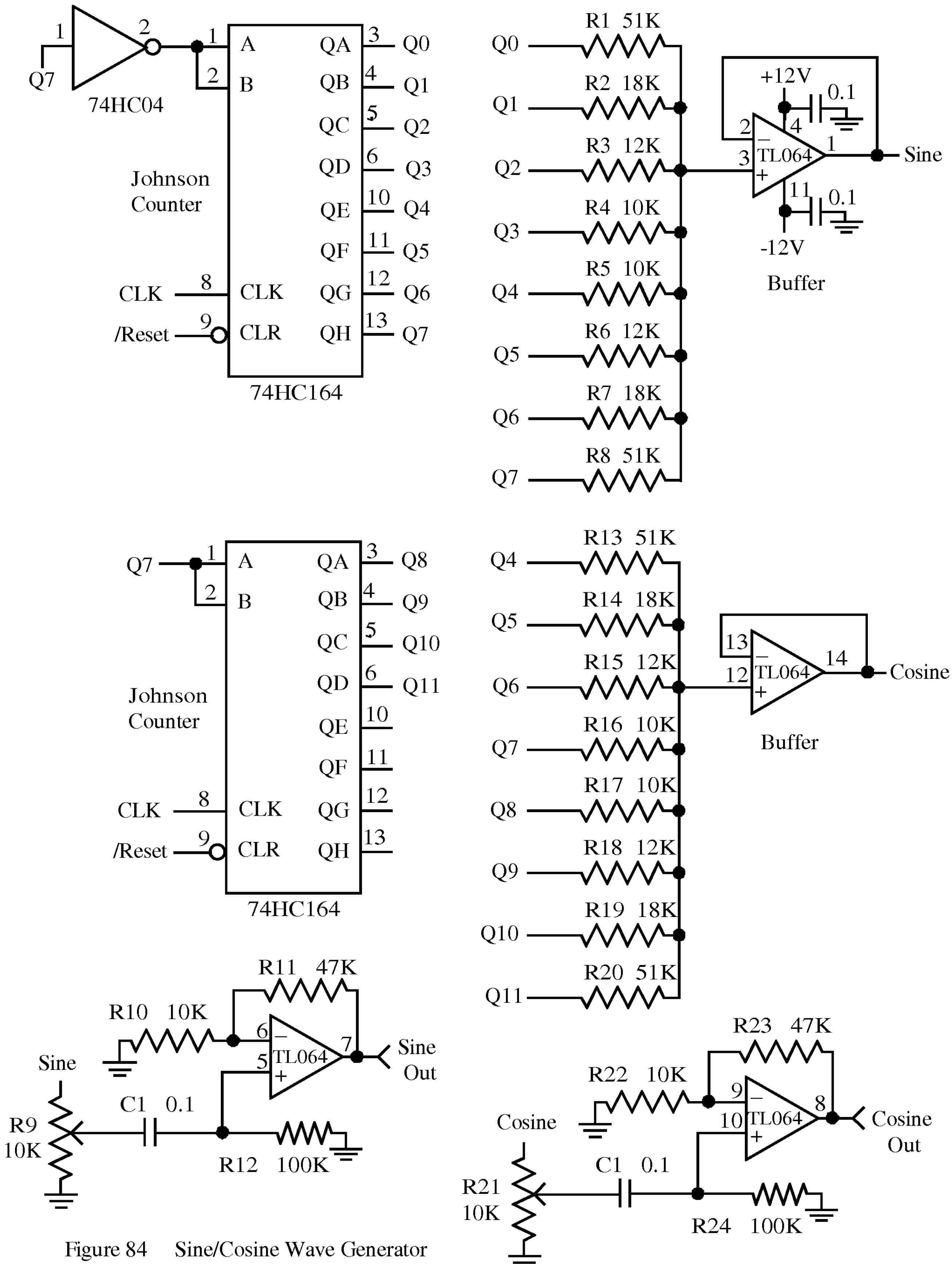



Figure 84 Sine/Cosine Wave Generator

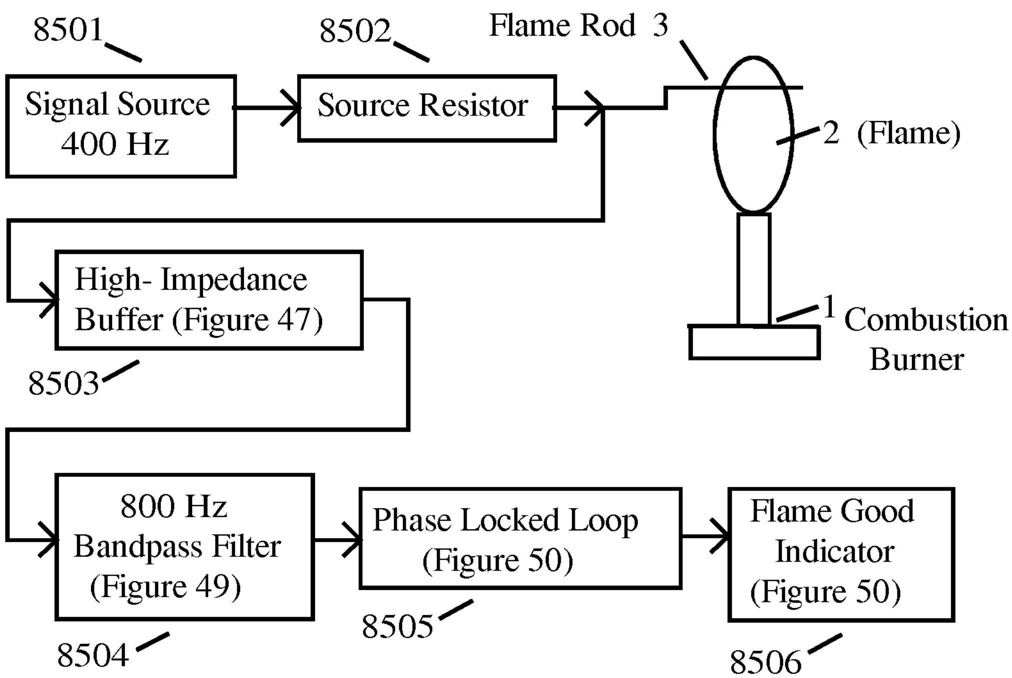

8501
Signal Source
400 Hz
8502
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion Burner
High- Impedance Buffer (Figure 47)
8503
800 Hz
Bandpass Filter
(Figure 49)
8504
Phase Locked Loop
(Figure 50)
8505
Flame Good Indicator
(Figure 50)
8506

Figure 85

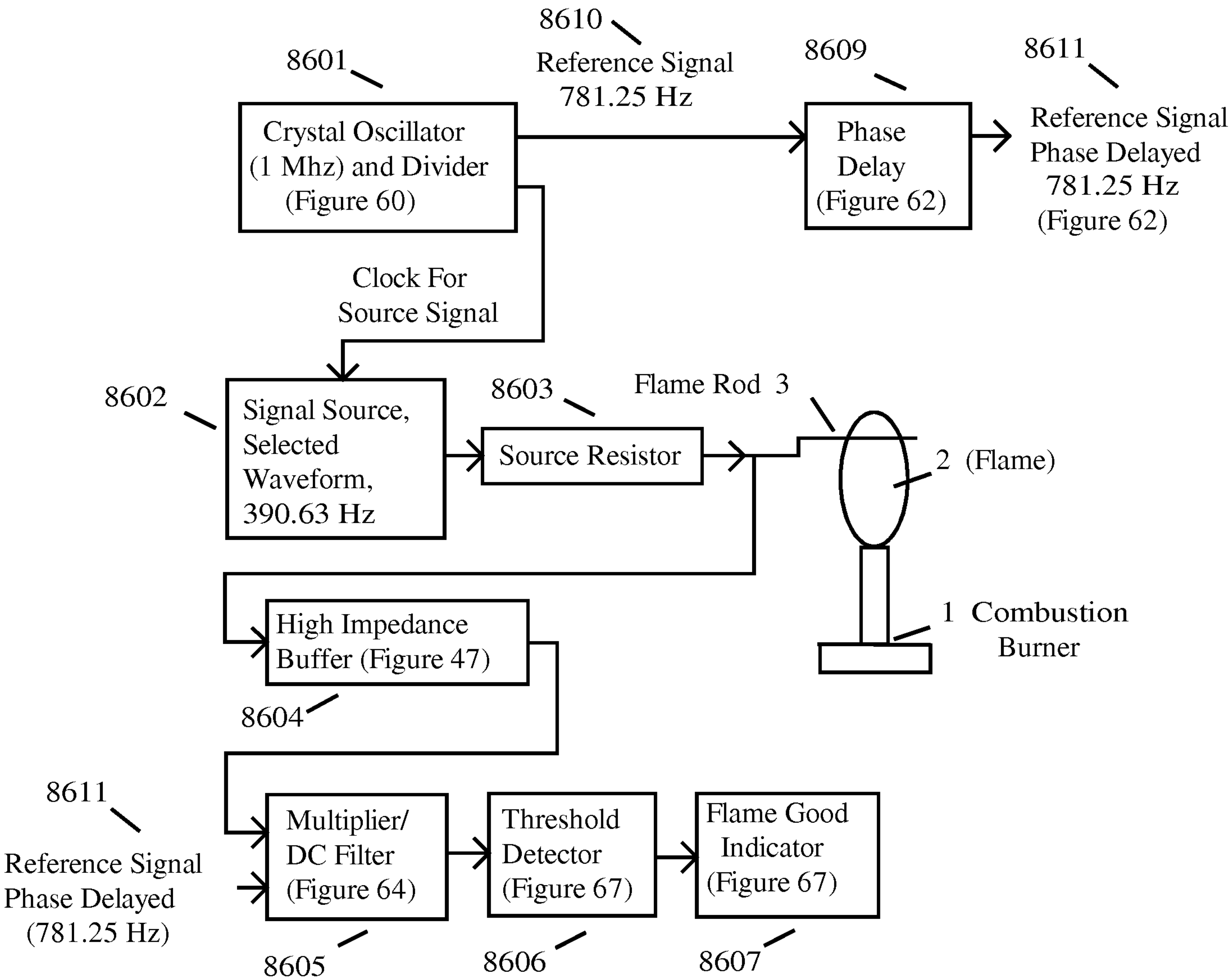

8610
Reference Signal
781.25 Hz
8601
Crystal Oscillator
(1 Mhz) and Divider
(Figure 60)
8609
Phase
Delay
(Figure 62)
8611
Reference Signal
Phase Delayed
781.25 Hz
(Figure 62)
Clock For
Source Signal
8602
Signal Source,
Selected
Waveform,
390.63 Hz
8603
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion
Burner
High Impedance
Buffer (Figure 47)
8604
8611
Reference Signal
Phase Delayed
(781.25 Hz)
Multiplier/
DC Filter
(Figure 64)
Threshold
Detector
(Figure 67)
Flame Good
Indicator
(Figure 67)
8605
8606
8607

Figure 86

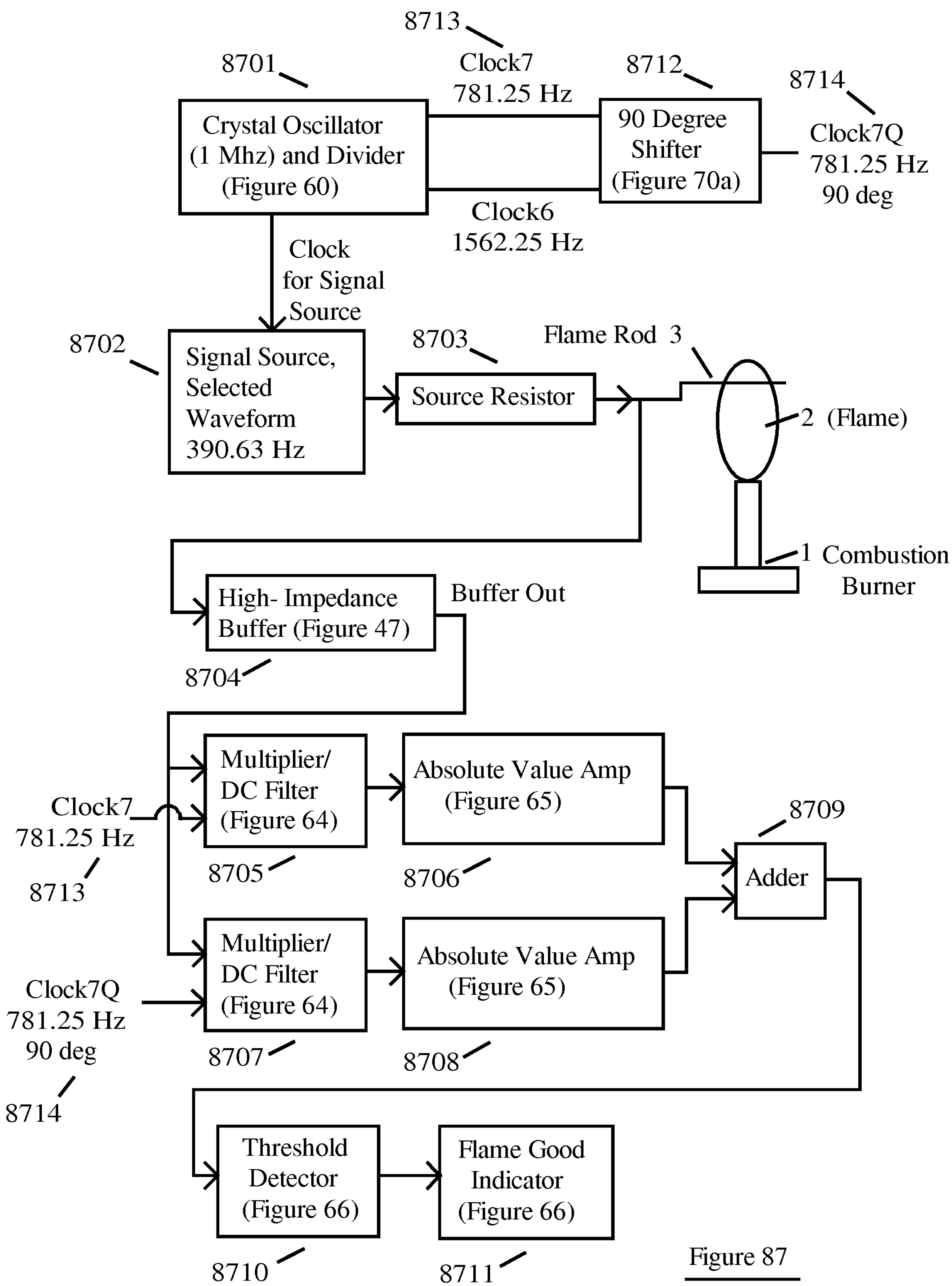

8713
Clock7
781.25 Hz
8701
8712
8714
Crystal Oscillator
(1 Mhz) and Divider
(Figure 60)
90 Degree
Shifter
(Figure 70a)
Clock7Q
781.25 Hz
90 deg
Clock6
1562.25 Hz
Clock
for Signal
Source
8702
Signal Source,
Selected
Waveform
390.63 Hz
8703
Source Resistor
Flame Rod 3
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 47)
Buffer Out
8704
Multiplier/
DC Filter
(Figure 64)
Absolute Value Amp
(Figure 65)
Clock7
781.25 Hz
8713
8705
8706
8709
Adder
Multiplier/
DC Filter
(Figure 64)
Absolute Value Amp
(Figure 65)
Clock7Q
781.25 Hz
90 deg
8714
8707
8708
Threshold
Detector
(Figure 66)
Flame Good
Indicator
(Figure 66)
8710
8711

Figure 87

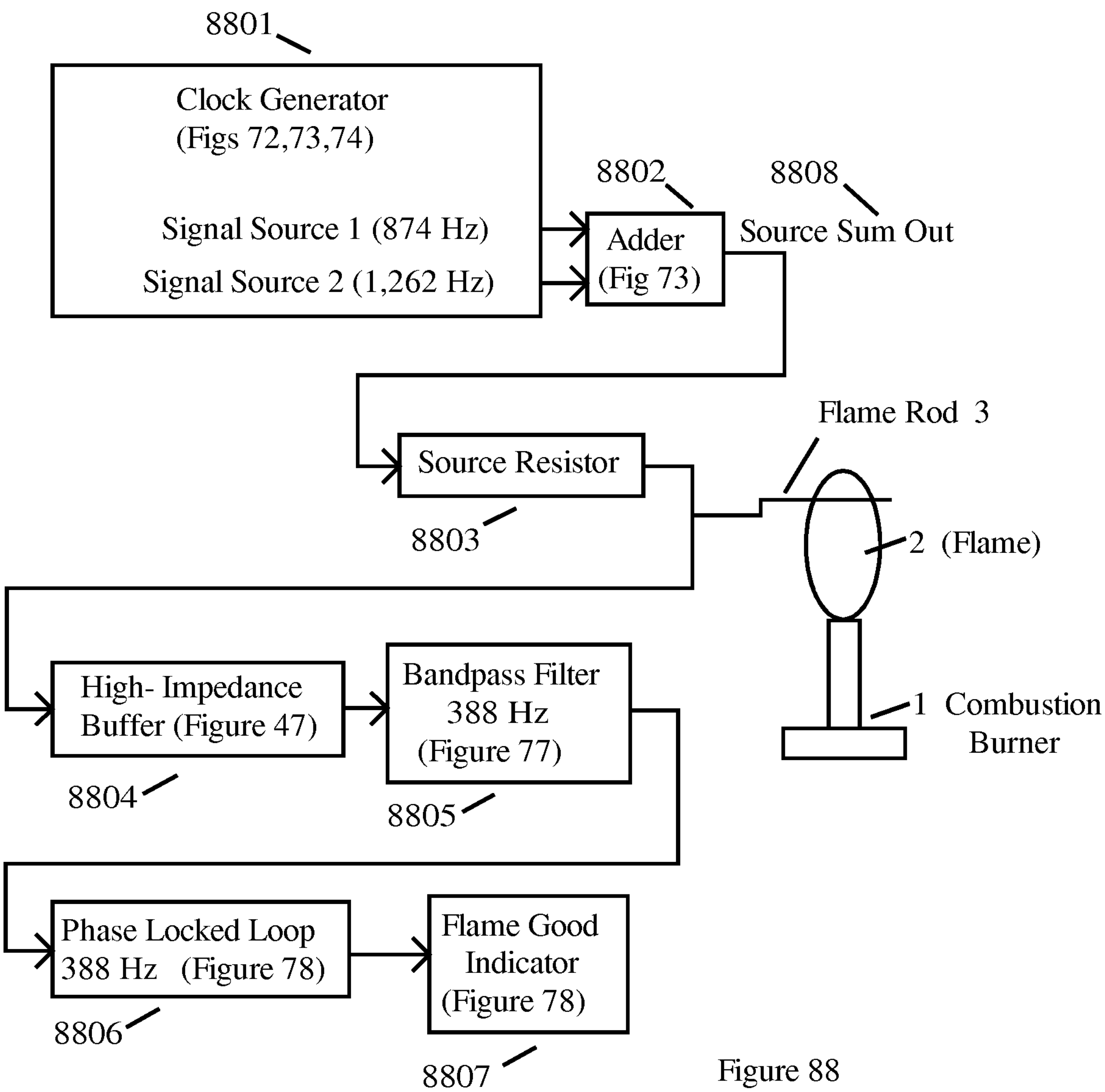
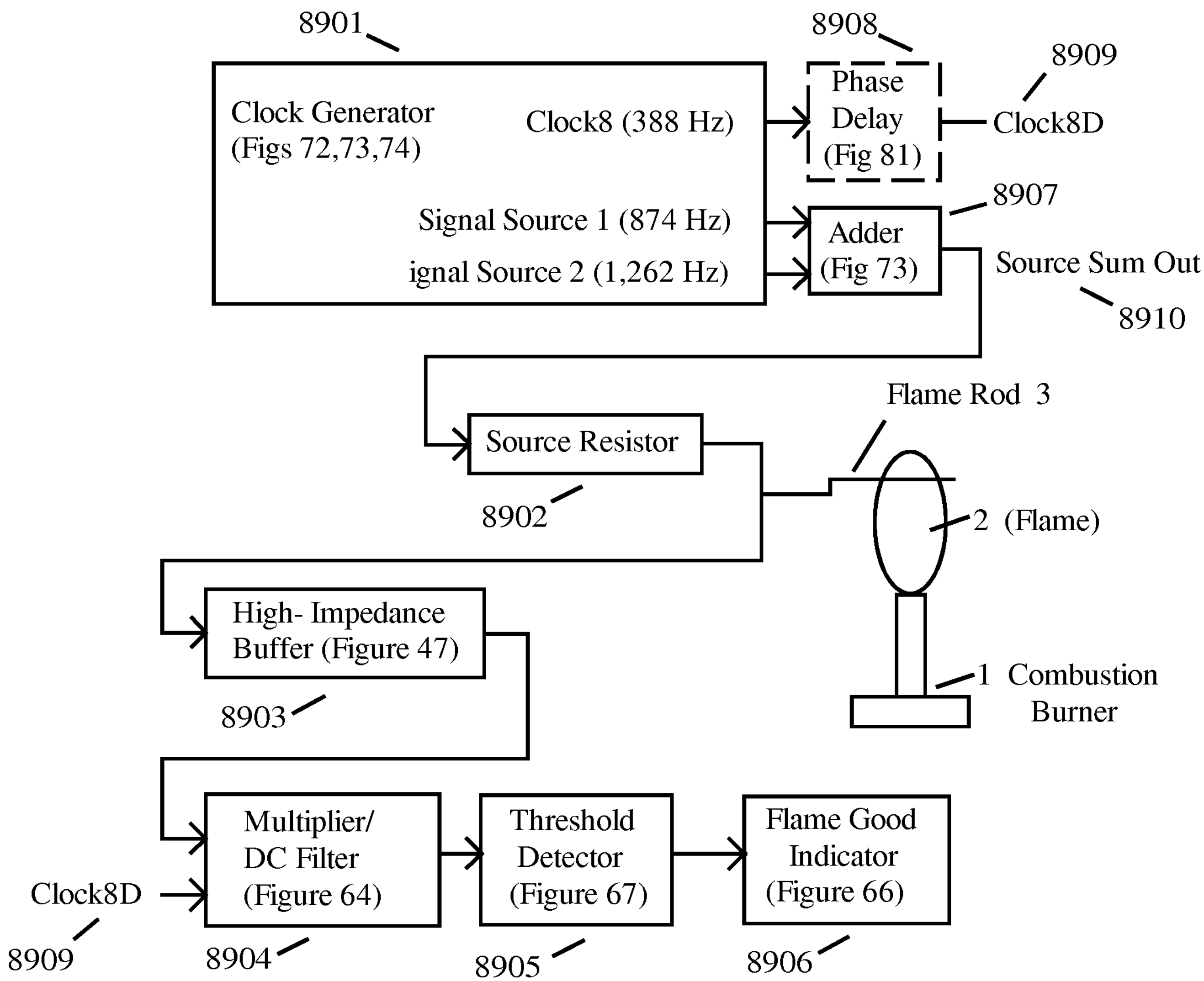

8801
Clock Generator
(Figs 72,73,74)
Signal Source 1 (874 Hz)
Signal Source 2 (1,262 Hz)
8802
Adder
(Fig 73)
8808
Source Sum Out
Source Resistor
8803
Flame Rod 3
2 (Flame)
1 Combustion Burner
High- Impedance Buffer (Figure 47)
8804
Bandpass Filter 388 Hz (Figure 77)
8805
Phase Locked Loop 388 Hz (Figure 78)
8806
Flame Good Indicator (Figure 78)
8807

Figure 88



8901
Clock Generator
(Figs 72,73,74)
Clock8 (388 Hz)
Signal Source 1 (874 Hz)
ignal Source 2 (1,262 Hz)
8908
Phase
Delay
(Fig 81)
8909
Clock8D
8907
Adder
(Fig 73)
Source Sum Out
8910
Flame Rod 3
Source Resistor
8902
2 (Flame)
High- Impedance
Buffer (Figure 47)
8903
1 Combustion
Burner
Multiplier/
DC Filter
(Figure 64)
Threshold
Detector
(Figure 67)
Flame Good
Indicator
(Figure 66)
Clock8D
8909
8904
8905
8906


Figure 89

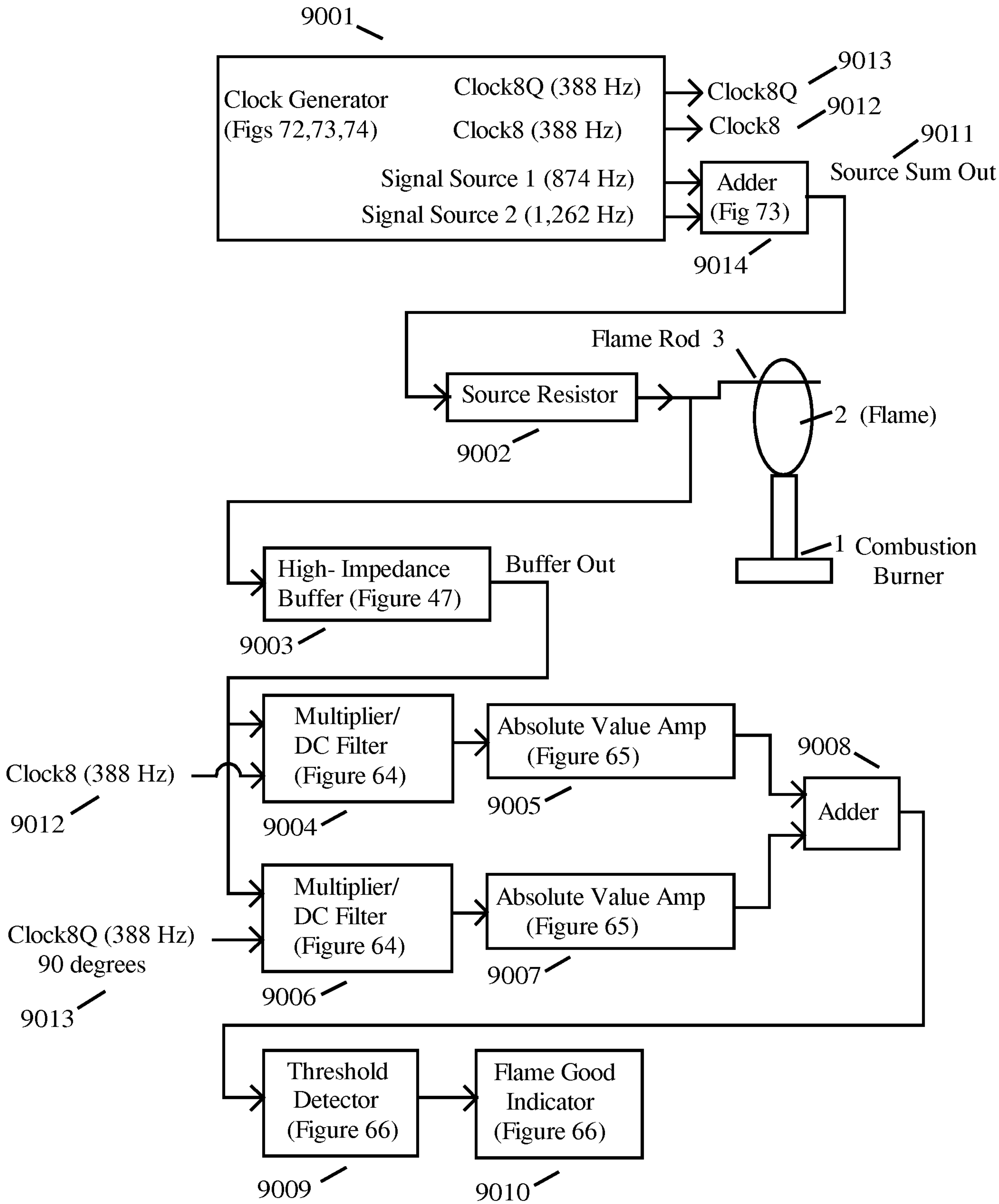

9001
Clock Generator
(Figs 72,73,74)
Clock8Q (388 Hz)
Clock8 (388 Hz)
Signal Source 1 (874 Hz)
Signal Source 2 (1,262 Hz)
Clock8Q
9013
Clock8
9012
9011
Source Sum Out
Adder
(Fig 73)
9014
Flame Rod 3
Source Resistor
9002
2 (Flame)
1 Combustion
Burner
High- Impedance
Buffer (Figure 47)
Buffer Out
9003
Multiplier/
DC Filter
(Figure 64)
Absolute Value Amp
(Figure 65)
9008
Clock8 (388 Hz)
9012
9004
9005
Adder
Multiplier/
DC Filter
(Figure 64)
Absolute Value Amp
(Figure 65)
Clock8Q (388 Hz)
90 degrees
9006
9007
9013
Threshold
Detector
(Figure 66)
Flame Good
Indicator
(Figure 66)
9009
9010

Figure 90

UNITED STATES PATENT APPLICATION

FOR

**FLAME SENSING SYSTEM**

INVENTOR: JED MARGOLIN

**FLAME SENSING SYSTEM**

## CROSS REFERENCES TO RELATED APPLICATIONS

**[001]** This application claims the benefit of U.S. Provisional Application No. 62/005,199 filed on May 30, 2014, which is hereby incorporated by reference herein.

## BACKGROUND OF THE INVENTION - Field of Invention

**[002]** This invention relates to the field of sensing flames in equipment such as gas furnaces using the electrical properties of flames. In such equipment it is necessary to sense (detect) that a flame is actually being produced when fuel is being provided to a combustion burner. Otherwise the unburnt fuel will continue to flow and build up, and may cause asphyxiation and if it finds an ignition source may explode.

The term “combustion” means the process of oxidation of molecules of combustible substances that occurs readily at high temperatures with the release of energy. It is accompanied by that phenomenon which is called "flame" and by the generation of "heat energy".

The term “flame” means a self-sustaining propagation of a localized combustion zone at subsonic velocities.

The term “combustion burner” means a device used for facilitating the combustion of a gas or a liquid. The term “burner” means the same as combustion burner.

The term “flame conductivity” means the electrical conductivity of a flame. The unit of conductivity is the “mho”. The term “flame conduction” means the same as flame conductivity.

The term “flame resistance” is the reciprocal of flame conductivity. The unit of resistance is the Ohm.

The term “flame rectification” means the property of flames to preferentially conduct electrical current depending on the direction of the electrical current.

The term “flame electrode” means an electrically conducting material immersed in a flame (when a flame is present), and which is electrically isolated from the combustion burner (except for a flame) and which may be electrically connected to something outside of the flame. The term “flame probe” means the same as flame electrode. The term “flame rod” means the same as flame electrode. The term “flame sensor” means the same as flame electrode.

The term “flame battery” means the voltage produced between a combustion burner and a flame electrode that is immersed in the flame produced by the combustion burner. The term “flame voltage” means the same as flame battery.

The term “flame proof” means proof that a flame exists. The term “proof of flame” means the same as flame proof.

The term “plasma” means a collection of gas where a large proportion of atoms have enough energy that their electrons have been stripped away, creating ions, and that the proportion of ions to intact atoms is high enough that Coulomb forces have a significant effect on the behavior of the collection of gas. The ions creating the plasma will be termed “plasma ions”.

The term “chemical ions” means reactive molecules, or atoms, that have unpaired electrons. The term “chemi-ionization” means the process by which molecules, or atoms, come to have unpaired electrons. The terms “chemi-ions” , “radical” , and “free radical” mean the same as chemical ions.

The term “thermionic emission” means the emission of electrons from the surface of an electrically conducting material when the material is heated to a temperature high enough to overcome the work function of the material, typically several electron volts. One electron volt is equal to approximately $1.602 \times 10^{-19}$ Joules.

The term “high impedance buffer” means a buffer whose input impedance is substantially higher than the impedance of the circuit it is intended to buffer. The terms “amplifier” and “buffer” will mean the same thing regardless of the gain of the circuit.

The term “mixer” means a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. The terms “mixing” and “to mix” mean using a mixer. When two signals are mixed in this manner it is also called heterodyning.

The term “flame good indicator” will mean the same as “indicator”.

The term “symmetrical square wave” means a square wave having a duty cycle of substantially 50%.

**BACKGROUND OF THE INVENTION – Prior Art**

**[003]** The electrical properties of flames comprise flame conduction, flame rectification, and the generation of a flame voltage between a metal burner and a flame rod.

U.S. Patent 1,688,126 **Method of and Apparatus for Control of Liquid Fuel Burners** issued Oct 16, 1928 to R.F. Metcalfe, assigned to Socony Burner Corporation *{IDS Cite 1}*. This patent teaches using the resistance of the flame for providing flame proof. It uses only the flame resistance, not flame rectification. Two electrodes are used (Contacts 7 and 8 in Metcalfe Figure 1). From page 3, right column, lines 70 – 79:

> One of the main features of my invention is to utilize the phenomenon of the variation in resistance to the passage of sparks between any two contacts. The resistance in this instance is offered by the gases within the combustion chamber 4. I have found that I may take advantage of this phenomenon by utilizing the resistance to the passage of sparks between the points of the spark-plug employed for igniting the combustible mixture.

In Metcalfe Figure 1 the secondary of Spark Coil 56 is used to produce an ignition spark between contacts 7 and 8. During ignition the resistance of the burning gas is reflected back through to the primary winding of Spark Coil 56. Since a spark coil has a high ratio of turns between the primary and secondary windings the resistance reflected back through the primary is much lower than if it was used directly. This lower resistance through the primary winding is apparently low enough to operate a relay (Electro-Magnet 58).

It appears that the spark is continuously produced. Later patents note that the continuous spark causes radio interference and they teach systems that do not require a continuous spark.

**[004]** U.S. Patent 2,112,736 **Flame Detector** issued March 29, 1938 to William D. Cockrell, assigned to General Electric *{IDS Cite 2}*. This patent teaches using flame rectification for providing flame proof. Cockrell Figure 1 shows an embodiment using one electrode (22) with the burner (2) used as the return. The AC used in the flame sensing circuit is used only for the flame sensing circuit and is not also used as a spark igniter. See Page 1, left column, line 41 – Page 2, right column, line 15.

**[005]** U.S. Patent 2,136,256 **Furnace Control System** issued Nov 8, 1938 to A.L Sweet, assigned to General Electric Company *{IDS Cite 3}*. This patent also teaches using flame rectification for providing flame proof and is an improvement on 2,112,736. Sweet introduces an additional electrode to allow the flame rectification circuit to operate reliably with an oil-fueled flame. See Page 1, left column, line 4 – Page 2, left column line 2.

However, the wires from the two electrodes are surrounded by a shield. See Page 6, left column lines 36-55 and Sweet Figure 4. Shielding the wires reduces the stray coupling from the mains power (60 Hz in the U.S.). It is possible that the problem Sweet has solved is the stray coupling from the mains power which may be made worse by the use of oil as a fuel.

**[006]** U.S. Patent 3,301,307 **Device for detecting the configuration of a burning flame** issued Jan 31, 1967 to Kazuo Kobayashi, et al, assigned to Ngk Insulators Ltd *{IDS Cite 4}*. This patent teaches the use of the flame battery for flame proof. From Column 2, lines 3 -15:

> The principle of the invention is based on, first of all, the recognition of the phenomenon that a negative potential to ground is produced in an electric conductor when it is located in a burning flame. It seems that such a phenomenon is due to an exchange of electric charges between the conductor acting as an electrode and ionized molecules through the contact surface of said electrode with the flame depending upon differences of temperature and degree of combustion between the inner and outer parts of said burning flame and atmospheric conditions. The phenomenon is inherent to flames and a potential difference in the order of 2-10 volts or more has been obtained by experiments.

**[007]** U.S. Patent 4,082,493 **Gas Burner Control System** issued April 4, 1978 to Dahlgren, assigned to Cam-Stat, Incorporated *{IDS Cite 5}*. This patent also teaches the use of the flame battery for flame proof. See Dahlgren Figure 2 and Column 3, lines 32 – 42.

**[008]** U.S. Patent 8,310,801 **Flame sensing voltage dependent on application** issued November 13, 2012 to McDonald, et al., assigned to Honeywell *{IDS Cite 6}*. This patent teaches using flame rectification for providing flame proof. The claimed novelty is that in order to avoid excessive component stress, energy consumption, increased electrical noise, and contamination build-up, when accuracy is critical a higher voltage is used. Once a flame has been established, the AC voltage may be adjusted to a lower level. See Column 2, lines 10 – 44.

However, McDonald has not produced evidence that the use of a high AC voltage causes excessive build-up of contamination on a flame rod, increased energy consumption that generates extra heat, or that it stresses associated electronic circuitry. The commonly accepted theory is that contamination of the flame rod is caused by the products of combustion, notably carbon. Also, any extra heat that might be produced would not be wasted because the purpose of a furnace is usually to produce heat. It is likely that the real value of McDonald's system is that, since his high voltage AC is produced electronically, it is isolated from the AC mains. This is in contrast to the commonly used practice of using the un-isolated AC mains for the flame rod voltage. Since the combustion burner is typically used as the electrical return path for the flame rod and is electrically connected to the equipment cabinet (which is required to be grounded) this requires that mains neutral and mains ground be connected. According to the National Electrical Code this may only be done (and is required to be done) at the service entrance to the building and no place else. As a result, an electrical connection problem outside the furnace at the service entrance may cause a flame sensing circuit to malfunction even though there is no problem in the furnace itself. Since McDonald's invention produces the high voltage AC for the flame rod electronically (and is isolated from the mains) it would not be subject to this failure mode.

**BACKGROUND OF THE INVENTION – Current Practice for providing Flame Proof**

**[009]** The current practice for providing flame proof uses the two general properties of flames: the optical properties of flames and the electrical properties of flame.

Flames have optical properties that range from infrared to ultraviolet. These optical properties are discussed in U.S. Patent 6,404,342 **Flame detector using filtering of ultraviolet radiation flicker** issued June 11, 2002 to Planer, et al. and assigned to Honeywell *{IDS Cite 7}*. From Column 1, lines 21 - 32:

> Another type of flame detector relies on directly on the radiation provided by the flame. However, the mere presence of visible or IR radiation does not necessarily indicate an active flame. Walls of combustion chambers tend to radiate visible and IR energy for a period of time after flame is lost. It was found, however, that active flames have characteristic flicker frequencies in the IR, visible, and UV wavelengths. Typically, an active flame flickers in the 5 to 15 hz. range (as well as in higher frequencies) in all of these wavelength bands. Heated

refractory walls or glowing particles have different flicker frequencies or none at all. So flicker in these wavelengths can be used to reliably indicate flame.

The electrical properties of flames comprise flame conduction, flame rectification, and the generation of a flame voltage between a metal burner and a flame rod. These properties are exemplified in the prior art already presented. However, there is another electrical property of flames, namely that flames may absorb microwave radiation. See *IDS Cite 8* **Prediction and Measurement of Electron Density and Collision Frequency in a Weakly Ionised Pine Fire** by Mphale, Mohan, and Heron. This electrical property appears to be used only for research and not for providing flame proof in operating equipment.

**BACKGROUND OF THE INVENTION – Processes That May Produce or Contribute to the Electrical Properties of Flames**

**[010]** The investigation of the electrical properties of flames goes back to at least the early 1900s with the work of J. J. Thomson. See *IDS Cite 9* for an excerpt from Thomson's work **Conduction of Electricity Through Gases** (1903, 1906) Chapter IX **Ionization in Gases from Flames**. Thomson begins the chapter with an observation that modern researchers in the field should take notice of. Writing in 1903 he observed:

> 121. It has been known for more than a century that gases from flames are conductors of electricity; a well-known application of this fact—the discharge of electricity from the surface of a non-conductor by passing a flame over It—was used by Volta in his experiments in Contact Electricity. We shall not attempt to give any historical account of the earlier experiments on this subject, because the conditions in these experiments were generally such that the interpretation of the results obtained is always exceedingly difficult and often ambiguous: the reason of this is very obvious—to investigate the electrical conditions of the flame wires are generally introduced, these become incandescent and so at once add to the electrical phenomena in the flame the very complicated effects we have been discussing in the last chapter.

**[011]** The electrical properties of flames comprise flame conduction, flame rectification, and the generation of a flame voltage between a metal burner and a flame rod (flame battery). Figure 1 shows a representative Combustion Burner (1), Flame (2), and Flame Rod (3). Figure 2 is a representative electrical model of the electrical properties of Figure 1. Experiments will show that this is an AC model and that the flame battery is an integral part of Flame Diode D (23). In the absence of a flame (Figure 3) the representative electrical model is an open circuit (Figure 4).

There are several processes that may account for the electrical properties of flames.

**[012]** **Is Flame a Plasma?**

An important question to ask in order to understand what causes the electrical properties of flames is: Is flame a plasma?

From the article **About Plasmas** from the Coalition For Plasma Science **Plasma and Flames – The Burning Question** *{IDS Cite 10}*:

> The Medium Answer: Whether a plasma exists in a flame depends on the material being burned and the temperature.
>
> •
> •
> •
>
> A plasma is an ionized gas. However, not all ionized gases are plasmas. In order for an ionized region of a flame to be plasma, it must contain enough charged particles for that region to exhibit unique electrical properties of plasma, which are distinctly different from properties of other states of matter.
>
> •
> •
> •
>
> Since the density of charged particles increases as temperature increases, a high-temperature region in a flame may contain enough charged particles to be a plasma. Lower-temperature flames contain no significantly ionized regions and no plasma.
>
> An example of a flame with relatively low temperatures is the flame of a household wax candle. The maximum temperature is less than 1,500 degrees Celsius, too low for much ionization to occur. However, some flames are much hotter than that. For example, in some burning mixtures of acetylene (made up of hydrogen and carbon) and oxygen, at a pressure of one atmosphere, the peak temperature in a flame has been measured to exceed 3,100 degrees Celsius.

Thus, the flame from a wax candle (less than 1,500 degrees Celsius) is not a plasma. The flame from acetylene and oxygen (around 3,100 degrees Celsius) probably is a plasma, at least in part.

**[013]** The flame of a typical wax candle burns at approximately 1,500 degrees Celsius at its hottest. The flames of interest here are those produced by the hydrocarbon fuels natural gas and propane. Natural gas (methane) is $CH_4$. Propane is $C_3H_8$. In a typical burner using the oxygen in the air as the oxidizer, and producing a premixed flame, the flame temperature of natural gas is approximately 1,980 degrees Celsius. The temperature of a premixed propane flame is about the same. So, we need to look further.

The article **Plasma Fundamentals and Applications** by Dr. I.J. Van der Walt, Senior Scientist Necsa contains a chart *{IDS Cite 11, PDF page 8}* that graphs the electron temperature verses electron density for various processes. Flames are toward the bottom of the graph for electron density. It is unlikely that the flame from natural gas or propane contains any appreciable plasma.

We should discuss temperature. The temperature of a gas is a measure of the average kinetic energy of the gas molecules as they collide with each other and with the walls of the container. If the container walls are rigid the molecules will bounce off. With a flame the walls are the atmosphere, and the boundary between the flame and the atmosphere is a function of atmospheric pressure. The collisions between the molecules in the flame and the molecules in the atmosphere produce diffusion. It is this diffusion that makes diffusion flames possible. An example of a diffusion flame is the flame produced by a wax candle. The other type of flame is called a premixed flame and is where the oxidizer (the oxygen in the atmosphere) is mixed with the fuel before combustion. Premixed flames produce a more stoichiometric mixture than diffusion flames, so they burn more completely (and hotter). For this reason most furnaces use premixed flames.

**[014]** **Chemical Ions**

The preceding doesn't mean there isn't a useable density of ions in a flame. There is, but they aren't plasma ions. They are chemical ions, or chemi-ions.

The oxidation of methane is: $\mathbf{CH_4 + 2O_2}$ **, flame or spark** $\rightarrow$ $\mathbf{CO_2 + H_2O}$ **+ energy**

However, Nature does not like to make or break more than one chemical bond at a time. So there are a number of intermediate species produced between $\mathbf{CH_4 + 2O_2}$ and $\mathbf{CO_2 + H_2O}$ **+ energy**. And it's a large number.

An excellent reference is **Introduction to Combustion** by Stephen R. Turns. See *IDS Cite 12, page 108, PDF page 3.*

Turns reports (citing GRI Mech 2.11) that at least 325 intermediate reactions have been found in the combustion of methane (natural gas). *See IDS Cite 12, page 159, PDF bottom of page 5.* A portion of the list is reproduced in Figure 14.

The presence of nitrogen in some of the equations indicates that the methane is being burned using air. By volume dry air contains 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide, and small amounts of other gases.

Nitrogen compounds form starting at about 800 degrees Celsius, much lower than the temperature at which methane burns. The various species of nitrogen are generally represented as $NO_x$ which is toxic and considered a pollutant.

**[015] <u>Additional Components in Natural Gas and Propane</u>**

There are more components in natural gas and propane. Since methane and propane are odorless, an odorant is added to make leaks easy to detect. The odorant most often used is mercaptan, which is methanethiol (also known as methyl mercaptan). Mercaptan is an organic compound with the chemical formula $CH_3SH$ (also written as $CH_4S$). The sulfur no doubt produces the putrid smell. The flue of a gas furnace does not have this smell because the mercaptan is broken down and forms sulfur oxides ($SO_2$ and $SO_3$). As long as the temperature of the flue gas is above the gas dewpoint temperature the sulfur oxides will vent into the air where they may combine with water to form $H_2SO_4$ (sulfuric acid). Furnaces that recapture heat from the flue gas may cause the flue gas to drop below the gas dewpoint temperature resulting in $H_2SO_4$ precipitating in the equipment. *{IDS Cite 13}*

Also, in the data reported by Turns a number of the formulas contain the letter “M”. “M” is not an element. In chemistry the letter “M” is used to represent an alkali metal. *{IDS Cite 14}.*

From Wikipedia *{IDS Cite 15*}:

> The alkali metals are the elements in Group 1 (1A). They are lithium, sodium, potassium, rubidium, cesium, and francium. These elements are best marked by their reactivity. Physically they are soft, shiny (when freshly prepared) solids with low melting points; they conduct electricity well. They all have one valence electron that they lose easily to almost any electronegative substance.

Why are there alkali metals in natural gas?

**[016]** Some are there naturally and some are there because of hydraulic fracturing, or "fracking". See U.S. Patent 4,317,487 **Method of recovering oil and other hydrocarbon values from subterranean formations** issued March 2, 1982 to Merkl, and assigned to Molecular Energy Research Company, Inc. See Column 2, line 59 – Column 3, line 11. {*IDS Cite 16}*

**[017]** There are even more components in the natural gas and propane used in furnaces and other equipment because Natural Gas is not 100% methane ($CH_4$) and Propane is not 100% propane ($C_3H_8$).

**Natural Gas** - From Turns pages 657-659 *{IDS Cite 12 – Turns pages 657-659; PDF pages 22-24}*

> Although there are no industry or governmental standards for pipeline natural gas, contracts between producers and pipeline companies define general ranges of composition and other properties [26, 27]. Processing removes solid matter (e.g., sand), liquid hydrocarbons, sulfur compounds, water, nitrogen, carbon dioxide, helium, and any other undesirable compounds to meet contract specifications. The removal of sulfur compounds results in making an acidic, i.e., *sour*, gas *sweet*. Table 17.11 shows typical values, or ranges, of important properties of pipeline gas based on the General Terms and Conditions of a set of geographically dispersed pipeline companies in the United States and Canada.
>
> The composition of natural gas varies widely depending upon the source. Examples for U.S. sources of natural gas are shown in Table 17.12. Compositions for natural gases from a variety of non-U.S. sources are provided in Table 17.13.

The following table (Table 1) is an abridged reproduction of Table 17.12 from Turns. The complete Turns Table 17.12 has been reproduced as Figure 15.

**Table 17.12** Composition (mol%) and properties of natural gas from sources in the United States [28][a]

| **Location** | **$CH_4$** | **$C_2H_6$** | **$C_3H_8$** | **$C_4H_{10}$** | **$CO_2$** | **$N_2$** |
|---|---|---|---|---|---|---|
| Alaska | 99.6 | — | — | — | — | 0.4 |
| Birmingham, | 90.0 | 5.0 | — | — | — | 5.0 |
| East Ohio[b] | 94.1 | 3.01 | 0.42 | 0.28 | 0.71 | 1.41 |
| Kansas City, | 84.1 | 6.7 | — | — | 0.8 | 8.4 |
| Pittsburgh, | 83.4 | 15.8 | — | — | — | 0.8 |

**Table 1 (Abridged Turns Table 17.12)**

Thus, in Turns' sample natural gas ranged from a high of 99.6% in Alaska to a low of 83.4% in Pittsburgh.

**[018] <u>Propane</u>**

There are three basic grades of propane: HD5, HD10, and Commercial Grade. From *IDS Cite 17* (Propane101):

> **HD-5 Propane**
>
> HD5 grade propane is "consumer grade" propane and is the most widely sold and distributed grade of propane in the U.S. market. HD5 is the highest grade propane available to consumers in the United States and is what propane companies ordinarily sell to their customers. What does HD5 propane mean in terms of specification to an ordinary consumer? It means that the propane is suitable and recommended for engine fuel use, which was the original purpose of the HD5 grade propane specification. HD5 spec propane consists of:
>
> Minimum of 90% propane
>
> Maximum of 5% propylene - propylene is used in the manufacture of plastics
>
> Other gases constitute the remainder (iso-butane, butane, methane, etc.)
>
> ⋮
>
> **HD-10 Propane and Commercial Propane**
>
> HD10 propane is a grade below HD5 and is commonly found in California. HD10 grade propane allows up to 10% propylene in the propane/propylene mixture and is still labeled as "propane". Because propylene is used in creating plastics, HD10 can possibly create problems in some engines and vehicle applications. Propylene can cause engine components to "gum" or stick during operation. However, HD 10 spec propane works just fine in domestic and commercial propane powered appliances. The only problem that may be encountered in using HD-10 propane involves its use as an engine fuel (vehicles, forklifts, etc.).
>
> ⋮
>
> Commercial grade propane and HD10 grade propane are sometimes used interchangeably due to the fact that both grades are sub-HD5 spec product and do not meet the standards of engine grade propane. Refineries use commercial propane in their processes and fractionation of chemicals for end use in numerous industries. Although commercial grade propane can be used in a manner similar to that of HD10 propane, it is not used in vehicle applications.

The article **The Truth About Propane** *{IDS Cite 18}* goes a little farther. After discussing the Gas Processors' Association standard for propane, GPA 2140 (1932) which was the original HD5 standard, it then addresses the commercial grade of propane:

> By contrast, since 1975, oil refineries were able to take advantage of the definition of propane in the ASTM (American Society for Testing and Materials) standard, ASTM Standard D1835, to market oil refining "odds and ends," known by chemical engineers as "slop," because they could claim that the slop fit the definition of "commercial grade" propane: any hydrocarbon mixture that held a flame.

With HD5 and HD10 you have an idea of what you are getting. Apparently, commercial grade propane is the hotdog of the oil refining business.

**[019]** The preceding paragraphs provide persuasive evidence that the temperature of the flame produced by the combustion of natural gas or propane is not high enough to produce an appreciable amount of plasma. Instead, the flame is a soup of chemical ions. This matters because the electrical properties of plasma may be different from the electrical properties of chemical ions.

In addition:

1. There are a large number of different chemical ions because there are a large number of intermediate chemical species;
2. The types of intermediate chemical species and their amounts will be affected by the exact composition of the gas (natural gas or propane) and there is a fairly wide latitude in the standards for the composition of natural gas and propane.
3. Gas obtained through fracking may contain a greater amount of alkali metals which may affect the electrical properties of the flame produced by the combustion of the gas.

**[020]** **<u>Gas Pressure</u>**

A flame is not a bunch of chemical ions and free electrons in a sealed container. Gas and air come into the burner under pressure and combusts, producing chemical ions and free electrons which then form a large number of short-lived intermediate species ending with $CO_2$, $H_2O$, NOx, sulfur oxides, and probably more types of molecules. Then they go shooting off into the atmosphere. This process continues as long as there is new gas (unless the flame goes out for some reason). Because the gas pressure moves the gas molecules before combustion it is likely that after combustion this gas pressure gives the chemical ions and electrons a group velocity. But because different ions may have different masses, and because of the much smaller mass of the electron, the negative chemical ions and the electrons may get to the flame rod first. And the free electrons are not just from chemical ionization.

**[021]** **Thermionic Emission**

As J.J. Thomson observed *{IDS Cite 9}*: "... to investigate the electrical conditions of the flame wires are generally introduced, these become incandescent and so at once add to the electrical phenomena in the flame the very complicated effects we have been discussing in the last chapter."

The effects caused by the incandescent wires are called Thermionic Emission. Thermionic emission is the emission of electrons from the surface of an electrically conducting material when the material is heated to a temperature high enough to overcome the work function of the material, typically several electron volts. One electron volt is equal to approximately $1.602 \times 10^{-19}$ Joules. Thermionic emission comes not just from the flame rod but also from the burner, assuming the burner is metal. (Some of the early flame experiments used a quartz burner.) In systems with two flame rods the second flame rod is also a source of thermionic emission.

**[022]** Thermionic emission was discovered (or maybe rediscovered) by Thomas Edison while trying to discover the reason for breakage of lamp filaments and uneven blackening (darkest near one terminal of the filament) of the bulbs in his incandescent lamps. He placed an extra wire inside the bulb and discovered that current would only flow in one direction. However, he used this discovery only as a governor to control the output of dynamos. See *IDS Cite 19* – U.S. Patent 307,031 **Electrical indicator** issued October 21, 1884 to T. A. Edison. From page 1, lines 16 – 29:

> I have discovered that if a conducting substance is interposed anywhere in the vacuous space within the globe of an incandescent electric lamp, and said conducting substance is connected outside of the lamp with one terminal, preferably the positive one, of the incandescent conductor, a portion of the current will, when the lamp is in operation, pass through the shunt-circuit thus formed, which shunt includes a portion of the vacuous space within the lamp. This current I have found to be proportional to the degree of incandescence of the conductor or candlepower of the lamp.

**[023]** John Fleming improved upon Edison's invention. See *IDS Cite 20* - U.S. Patent 803,684 **Instrument for converting alternating electric currents into continuous current** issued November 7, 1905 to J.A. Fleming, assigned to Marconi Wireless Telegraph Company of America.

From Fleming, page 1, lines 11 – 37:

> This invention relates to certain new and useful devices for converting alternating electric currents, and especially high-frequency alternating electric currents or electric oscillations, into continuous electric currents for the purpose of making them detectable by and measurable with ordinary direct-current instruments, such as a "mirror-galvanometer" of the usual type or any ordinary direct-current ammeter. Such instruments as the latter are not affected by alternating electric currents either of high or low frequency, which can only be measured and detected by instruments called "alternating current" instruments of special design. It is, however, of great practical importance to be able to detect feeble electric oscillations, such as are employed in Hertzian-wave telegraphy by an ordinary movable coil or movable needle mirror-galvanometer. This can be done if the alternating current can be “rectified” - that is, either suppressing all the constituent electric currents in one direction and preserving the others or else by changing the direction of one of the sets of currents which compose the alternating current so that the whole movement of electricity is in one direction.

Fleming had a reason for improving on Edison’s work because he was looking for an improved detector for Hertzian waves (radio waves). To be fair to Edison, in 1884 there were no manmade Herztian waves to be detected. Hertz did not begin his experiments until 1888 and Tesla and Marconi did not begin their experiments in radio until a few years later.

**[024]** **<u>Chemical Ions as an Electrolyte</u>**

The chemical ions in a flame may act much like the chemical ions in the electrolyte used in electrolytic rectifiers, electrolytic capacitors, and batteries. Technically, an electrolyte is a compound that ionizes when dissolved in suitable ionizing solvents such as water. *{IDS Cite 21}* For the purposes of this discussion we will assume that the compound is dissolved in a suitable solution.

Fleming’s patent *{IDS Cite 20}* makes reference to an electrochemical rectifier. From Page 1, lines 38-52:

> There are well-known forms of mechanical rectifier; also, there is a well-known form of electrochemical rectifier, depending on the fact that when a plate of carbon and aluminium is placed in any electrolyte which yields oxygen on electrolysis an electric current can only pass through this cell in one direction if below a certain voltage. Both these forms of rectifier are, however, inapplicable for high-frequency currents. I have found that the aluminium-carbon cell will not act with high-frequency currents.

Another name for an electrochemical rectifier is an electrolytic rectifier or an electrolytic cell.

From the 1917 Dissertation **Counter Electromotive Force in the Aluminum Rectifier** by Albert Lewis Fitch, page 15: *{IDS Cite 22}*:

I. INTRODUCTION.

THE anomalous action of aluminum in the electrolytic cell was first discovered by Wheatstone in 1855. Soon after this, Buff found that an electrolytic cell one electrode of which was aluminum would rectify the alternating current. Among the other men who have been interested in this cell may be mentioned Ducretet,[1] Hutin and Leblanc,[2] Montpellier,[3] Nodon,[4] Guthe,[5] Greene,[6] and Schulze.[7] The latter has perhaps done the largest amount of work of any. His articles have appeared from time to time in a number of magazines.

The earlier experimenters with this cell confined themselves to the study of aluminum but later investigation[7] has shown that many other metals possess this same property to a greater or less degree. Among these may be mentioned iron, nickel, cobalt, magnesium, cadmium, tin, bismuth, zirconium, tantalum, etc.

A great many electrolytes may be used in the rectifier. The most commonly used are the alums, phosphates, and carbonates; however Greatz and Pollak[8] have shown that any electrolyte which will liberate oxygen on electrolysis may be used more or less satisfactorily.

It has been found that the ability of the cell to rectify alternating current depends upon the current density at the aluminum anode,[9] the inductance and resistance of the circuit,[10] and its temperature.[11] The cell works best when the current density is high and the inductance, resistance, and temperature are low.

**[025]** The electrolytic rectifier led to the electrolytic capacitor. From U.S. Patent 1,077,628 **Electrolytic condenser** issued November 4, 1913 to Mershon *{Ref 23}* Page 1, lines 40-50:

The electrolytic condenser, like the electrolytic rectifier, depends for its action upon the properties of the film which may be formed electrolytically upon the surface of aluminum, tantalum, magnesium and other metals when immersed in certain electrolytes and subjected to the electric current. Inasmuch as the electrolytic rectifier is concerned in my invention, and as its explanation leads up to that of the condenser, it will be first described.

Mershon then presents a detailed explanation of the electrolytic rectifier followed by a detailed explanation of his electrolytic condenser (capacitor).

Both electrolytic rectifiers and electrolytic capacitors have two electrodes with an electrolyte between them. One electrode is termed the anode. While the other electrode is termed the cathode its purpose is only to provide electrical contact with the electrolyte which is the real cathode.

**[026]** Indeed, modern aluminum electrolytic capacitors have the capability of acting as rectifiers (but not very good ones). From Nichicon, a leading manufacturer of electrolytic capacitors in **General Descriptions of Aluminum Electrolytic Capacitors, 1-1 Principles of Aluminum Electrolytic Capacitors** *{IDS Cite 24, page 1}*:

> An aluminum electrolytic capacitor consists of cathode aluminum foil, capacitor paper (electrolytic paper), electrolyte, and an aluminum oxide film, which acts as the dielectric, formed on the anode foil surface.
>
> A very thin oxide film formed by electrolytic oxidation (formation) offers superior dielectric constant and has rectifying properties. When in contact with an electrolyte, the oxide film possesses an excellent forward direction insulation property. Together with magnified effective surface area attained by etching the foil, a high capacitance yet small sized capacitor is available.
>
> As previously mentioned, an aluminum electrolytic capacitor is constructed by using two strips of aluminum foil (anode and cathode) with paper interleaved. This foil and paper are then wound into an element and impregnated with electrolyte. The construction of aluminum electrolytic capacitor is illustrated in Fig. 1-1.
>
> *{Nichicon Figure 1-1 is reproduced as Figure 16}*
>
> Since the oxide film has rectifying properties, a capacitor has polarity. If both the anode and cathode foils have an oxide film, the capacitors would be bipolar (nonpola) type capacitor.

{Emphasis added}

Thus, even modern electrolytic capacitors show their origins as rectifiers. And Nichicon's paper says that electrolytes are not limited to liquid electrolytes. Solid electrolytes may also be used.

Therefore, even though the chemical ions in a flame have a much lower density than the chemical ions in an electrolyte they may nonetheless play some part in the electrical properties of a flame.

**[027]** Both electrolytic rectifiers and electrolytic capacitors have two electrodes and an electrolyte between them. Another device that has two electrodes and an electrolyte between them is the battery. (Technically, a battery has more than one battery cell but the term battery is frequently used to describe a single battery cell.) A battery cell has two electrodes with an electrolyte between them. The electrolyte can be liquid, solid, a paste, a gel, etc. What makes a battery cell different from an electrolytic capacitor? From the article: **Batteries and electrochemical capacitors** *{IDS Cite 25}*:

> Batteries can generally store significantly more energy per unit mass than ECs, as shown in figure 1a, because they use electrochemical reactions called faradaic processes. Faradaic processes, which involve the transfer of charge across the interfaces between a battery's electrodes and electrolyte solution, lead to reduction and oxidation, or redox reactions, of species at the interfaces. When a battery is charged or discharged, the redox reactions change the molecular or crystalline structure of the electrode materials, which often affects their stability, so batteries generally must be replaced after several thousand charge–discharge cycles.

Another way to look at it is that in a battery the electrolyte and the electrodes are chemically changed. (In rechargeable batteries the change can be mostly reversed by sending current through it.) In modern electrolytic capacitors the two electrodes are made of the same material, such as aluminum, so they have the same galvanic response. Hence, it is not a battery. As noted previously, in an electrolytic capacitor the purpose of one of the electrodes (the cathode electrode) is to provide an electrical contact to the electrolyte which is the real cathode. Also note that the electrodes in Fleming's electrolytic rectifier *{IDS Cite 20}* are carbon and aluminum but the electrolyte has to have the property that it produces oxygen on electrolysis.

Therefore, once again, even though the chemical ions in a flame have a much lower density than the chemical ions in an electrolyte they may nonetheless play some part in the electrical properties of a flame. If they do, then the materials used in the combustion burner and the flame rod will have an effect on the voltage produced by the flame battery.

**[028]** There is one more device that has two electrodes and an electrolyte: the electroplating cell. In an electroplating cell an electric current from anode to cathode causes the material in the anode to be deposited onto the cathode. *{IDS Cite 26}*

It is telling that the metals used in the electrodes are called "rectifier metals." *{IDS Cite 27:* U.S. Patent 3,956,080 **Coated valve metal article formed by spark anodizing** issued May 11, 1976 to Hradcovsky, et al.; Column 2 lines 10 – 48}

The current involved in flame sensing circuits is so small (generally <1 uA.) that it is unlikely that any significant electroplating is going on. Even if a small amount of electroplating does occur it is unlikely that it would have an effect on the electrical properties of the flame.

**[029] BACKGROUND OF THE INVENTION – Summary of the Processes that May Produce or Contribute to the Electrical Properties of Flames**

A. The electrical properties of flames comprise:

1. Flame conduction.
2. Flame rectification.
3. The generation of a flame voltage between a metal burner and a flame rod.

Figure 1 shows a representative Combustion Burner 1, Flame 2, and Flame Rod 3. Figure 2 is a representative electrical model of the electrical properties of Figure 1. Experiments will show that this is an AC model and that the flame battery is an integral part of Flame Diode D (23). In the absence of a flame (Figure 3) the representative electrical model is an open circuit (Figure 4).

B. The Processes that May Produce or Contribute to the Electrical Properties of Flames:

1. Chemical Ions - Although flames produced by burning natural gas ($CH_4$) or propane ($C_3H_8$) in air are not plasma they do contain a large number of different chemical ions. Some additional chemical ions are present because the gas contains impurities that are not removed during refining. Some are the result of substances that are intentionally added to the gas, such as mercaptan. Some (like alkali metals) may be present when the gas was extracted by fracking.

   The chemical ions may provide for a simple conductive path for electrical current (flame conductivity).

   The chemical ions may act as an electrolyte which, with the combustion burner and flame, acts as an electrolytic rectifier (flame rectifier), a battery (flame battery), or an electrolytic capacitor.

2. Gas pressure - Gas and air continually come into the burner under pressure and combust. The chemical ions and free electrons produced by combustion may have a group velocity but because the chemical ions have different masses and the electrons have a much smaller mass the negative chemical ions and the electrons may get to the flame electrode first.

3. Thermionic Emission – The metal parts in the flame, such as the combustion burner and the flame rod, are hot enough to emit electrons from their surface.

**[030] BACKGROUND OF THE INVENTION – Experiments**

It is already known that the conductivity of a flame is very low, meaning that the resistance is very high, on the order of megohms. This requires that a high impedance buffer be used. An example of a high impedance buffer is shown in Figure 5. There is a potential problem with a high impedance unbalanced buffer because it is subject to picking up stray AC from the mains power. Stray AC from the mains power is everywhere and it is almost impossible to keep it out of a high impedance buffer that has connections off-board . It is even worse in a typical home gas furnace.

A typical gas furnace has a cabinet divided into two sections: the blower compartment and the burner compartment. The blower compartment contains the air blower and the control electronics. The burner compartment contains the combustion burner with its associated parts (gas valve, igniter, flame rod, and maybe an inducer blower, etc.) and a heat exchanger. The return air from the house coming from the return duct(s) comes into the blower compartment and is sent through the heat exchanger in the burner compartment. The air is heated in the heat exchanger and sent to the air ducts to heat the house. The heat exchanger is heated by the flame but is designed to keep combustion products out of the air flow. The combustion products are vented separately out through the flue. The control electronics must be located in the blower compartment because the burner compartment is thermally hot. Very Hot. As a result the control electronics must be connected to the components in the burner compartment such as the gas valve, the igniter, the flame rod, the inducer blower, and the inducer blower pressure switch (if an inducer blower is used). Typically, the wires to these components are bundled together in one cable harness. (This is for ease of manufacturing.) Thus, the wire for the flame rod is in a bundle of wires which contain AC mains voltage for the inducer blower and the igniter. Pickup of stray AC is unavoidable unless a shielded cable were used for the flame sensor. The prior art shows that this was sometimes done but it adds expense and it is generally not done now.

For experimental use an instrumentation amplifier can be used. An instrumentation amplifier has high impedance differential inputs. A simple instrumentation amplifier can be constructed out of a general purpose FET quad operational amplifier such as the TL064 shown in Figure 6.

All of the experiments were done in the high desert of the Virginia City Highlands in Nevada at an altitude of approximately 6,000 feet. For some of the experiments the altitude and desert conditions may produce different results from experiments done at sea level.

**[031] Experiment 1 – Determine the capacitance between two wires**

Two wires were put side-by-side, held together with nylon lacing cord every few inches. The wires were not twisted together. The wires were AWG 14 gauge with insulation rated for 600V. This is typical of the wires used in home furnaces. The wires were ten feet long to make the measurement of capacitance easier.

The method used was to use the capacitance in an RC circuit shown in Figure 7. The time constant of the circuit is T = R(71) * C(72) and is the time for the output voltage to reach about 63.2% of its final value. A pulse generator with adjustable pulse width was used. With an input pulse of 10 VDC and R(71) = 1 megohm, for the pulse to reach 63.2% of 10V (6.32 V DC) was approximately 170 us. See Figure 9 for a screen capture of the oscilloscope. Since T = R(71) *C(72), C(72) = T / R(71) = (170 * 10**-6) /(1 * 10**6) = 170 x 10**-12 = 170 x 10**-12. Therefore, the capacitance was approximately 170 picofarads (pF). Subtracting 10 pF for the oscilloscope probe leaves 160 pF for the ten feet of wire, or 16 pF per foot. Assuming a cable length of 30 inches (2.5 feet) in the furnace from the control electronics to the burner compartment, that gives a capacitance of approximately 40 pF.

The circuit shown in Figure 8 represents the effects of capacitive coupling from a wire carrying 120VAC to a circuit with an input impedance of 1 megohms. The transfer function of the circuit is shown in Table 2 (Figure 10). Therefore, for

Vin = 120 VAC; R(82) = 1 megohm; C(81) = 40 pF; Frequency = 60 Hz

the magnitude of Vout is approximately 1.81 VAC. The phase is a phase lead of approximately 8.9 degrees.

The presence of other wires in the cable bundle could make this coupled voltage higher or lower. Even the relative position of the other wires in the cable bundle can affect the capacitive coupling since there will also be capacitance between the 120 VAC mains hot and the 120 VAC mains neutral also going to the igniter, the flame rod, the inducer blower, etc. These capacitances will cause the total equivalent circuit of capacitances to act as a capacitive voltage divider. Where stray capacitance is a problem the wire to the flame rod can run separately from the cable bundle at least several inches away from it.

**[032] Experiment 2 – Determine the DC characteristics of the flame battery**

This experiment was done using a Meker burner. A Meker burner is similar to a Bunsen burner but produces a larger-diameter flame. The burner that was used is believed to be made of nickel-plated brass. The test was done with a commercial flame rod from the inventor's Ruud propane furnace. In this test the flame rod was immersed in the flame about 0.75 inches from the surface of the burner.

One of the electrical characteristic of the flame is that a voltage is produced between a metal burner and a flame rod. See Figure 11. The open circuit flame voltage produced between VOut and Common was measured with the instrumentation amplifier in Figure 12 which is the instrumentation amplifier of Figure 6 (1201) with a 0.1 uF capacitor (1202) across the input terminals to reduce the stray 60 Hz pickup. The open circuit flame voltage from Flame Battery 112 measured about -1.27 Volts. See Figure 21a.

Referring to Figure 13, when the output voltage was loaded with a resistor of about 4.3 megohms (131) the voltage dropped to about -0.68 Volts, which is about half of the open circuit flame voltage. See Figure 21b. Therefore, the series resistance RB (111) is also 4.3 megohms.

**[033] Experiment 3 – Determine more DC characteristics of the flame battery**

A battery was connected to the flame rod through a current sense resistor in order to measure the flame current with the battery connected to produce a negative current and then reversed in order to produce a positive current. The configuration is shown in Figure 17 with the electrical model shown in Figure 18. Battery 1701 consisted of two 9V batteries with a total voltage of 19.0V (VBAT). Sense Resistor 1702 had a value of about 533K Ohms. The voltage across the current sense resistor was measured with the Instrumentation Amplifier 1804 with Capacitor 1805 across its inputs. See Figure 18.

Battery 1701 was connected to produce a negative current through the flame so that flame diode D(23) was off. The voltage measured across Sense Resistor 1702 was very small, about 40 mV. See Figure 22a. The current through the flame would therefore be I= 0.040V / 533K which is about 0.075 uA. Using the electrical model of Figure 2, the voltage across R2(22) is 19.0 – 0.04 = 18.96. With 0.075 uA going through R2(22), R2(22) = E / I = 18.96V / 0.075uA = 253 megohms. That would mean there is no R2(22).

Then the battery was connected to produce a positive current through the flame, thus turning flame diode D(23) on. The voltage measured across Sense Resistor 1702 was about 1.39V. See Figure 22b. The current through the flame is therefore 1.39V / 533K = 2.61 uA. Using the electrical model of Figure 2, the voltage across R1(21) is 19.0 - 1.39 = 17.61V. With 2.61 uA going through R1(21), R1(21) = E/I = 17.61V / 2.61uA = 6.75 megohms.

Since the following AC experiments show that there is, indeed, an R2(22), this experiment suggests that the electrical model in Figure 2 does not work properly for DC. Since the current invention uses the AC properties of flames, no further research into the DC model of the flame was pursued.

**[034] Experiment 4 – Determine the AC characteristics of the flame model**

Referring to Figure 19, a 100 Hz triangle wave having a 20Vp-p waveform (Signal Generator 1901) was applied to Source Resistor 1902 having a value of about 10 megohms. The electrical model is shown in Figure 20. This produced the output shown in Figure 23a. The most positive voltage was +2.79V. The most negative voltage was -7.20V.

Since the effective load is the 10 megohm resistor R3 (1902) from the signal generator (1901), when VSource is negative Flame Diode D(23) is not conducting so the circuit is a voltage divider Vout/VSource = R2(22)/[R2(22) + R3(1902)]. This works out to:

R3(1902) = R2(22) * (VOut/VSource-1) / (-VOut/VSource) ≈ 25.8 megohms.

When VSource is positive Flame Diode D(23) is conducting so we will be calculating the parallel resistance of R1(21) and R2(22) and call it “Req”. Vout/VSource = Req/[Req + R3(1902)]. This works out to R3(1902) = Req * (VOut/VSource-1) / (-VOut/VSource) ≈ 3.7 megohms.

Resistances R2(22) and R1(21) are in parallel and we know R2(22).

Req = [R1(21) * R2(22)]/[R1(21) + R2(22)] so R1(21) = Req * R2(22)/[R2(22)-Req]

Therefore, R1(21) ≈ 4.4 megohms.

There is an interesting section between -960 mV and 0 Volts. See Figure 23b. As the voltage reaches -960 mV from the negative direction the voltage slope suddenly changes. Then, at 0V it resumes its normal slope. The waveform between -960 mV and 0V has the characteristics of a capacitor charging under constant current. Then, at 0V the flame diode kicks in. (The triangle wave at the bottom is from Signal Generator 1901. The reason the slope is different is because the oscilloscope channel gain is different. The reason for including it is to show that the source waveform is linear.)

There is a similar region on the trailing side of the triangle wave between -120 mV and -640 mV. See Figure 23c.

This suggests that the flame diode is an electrolytic rectifier and is constantly formed and unformed by the AC current. It may also be unformed by the heat of the flame.

The experiment was repeated with a 200 Hz triangle waveform (also 20 Vp-p). The most positive voltage was +2.224V and the most negative voltage was -6.88V. See Figure 24a. The leading edge (Figure 24b) and trailing edge (Figure 24c) showed characteristics similar to those at 100 Hz. The experiment was then repeated with a 400 Hz triangle waveform (also 20 Vp-p). Again, the results were similar to the experiment performed at 100 Hz except that the voltage ranges were smaller and the trailing edge was less distinct. See Figure 25a, Figure 25b, and Figure 25c.

At 1 KHz the voltages continued to be even smaller and the trailing edge is almost completely indistinct. See Figure 26a, Figure 26b, and Figure 26c.

The results are summarized in the following Table 3.

| Frequency | Most Positive | Most Negative | Leading Section | Trailing Section |
|---|---|---|---|---|
| 100 Hz | +2.79 V | -7.20 V | -960 mV to 0 V | -640 mV to -1.20 V |
| 200 Hz | +2.24 V | -6.88 V | -760 mV to -120 mV | -680 mV to -1.39 mV |
| 400 Hz | +1.84 V | -6.32 V | -440 mV to +200 mV | -1.63 V to -2.00 V |
| 1 KHz | +0.92 V | -4.88 V | -340 mV to +440 mV | Indistinct |

**Table 3**

The observation that the trailing edge is more sensitive to the frequency (and thus the rate of change of current) than the leading edge section suggests a capacitive effect due to the flame diode.

**[035] Experiment 5 – Thermionic Emission**

Since the flame causes thermionic emission from the burner and the flame rod it might be useful to examine another device that uses thermionic emission: the vacuum tube. Thermionic emission was measured for the following vacuum tubes: 5U4GB, 5Y3GT, 6X4, and 12X4. All of them are dual diodes. The 5U4GB and 5Y3GT use a directly heated cathode, which means that the filament is used as the cathode. The 6X4 and 12X4 use an indirectly heated cathode, which means that the filament is used to heat another closely located structure which then acts as the cathode. The front pages of the datasheets for the 5U4GB, 5Y3GT, and 6X4/12X4 are reproduced in *IDS Cite 28*. The 6X4 and 12X4 are identical except that the 6X4 has a 6.3V filament while the 12X4 has a 12.6V filament.

Although four tubes of each type were tested, the results for only one tube of each type are being presented as being representative of the other tubes tested. The tests consisted of:

1. Powering the filament with a DC power supply adjusted to produce the appropriate voltage for each tube type;

2. Measuring the voltage produced at the Plate using the Instrumentation Amplifier of Figure 12 to reduce the effects of stray AC coupling from the AC mains.

Figure 27 shows the test setup for the 5Y4GB and 5Y3GT. DC Power Supply 2701 provides power to the filament of tube 2702. The voltage produced by tube 2702 is measured by Instrumentation Amp 2704 with the addition of Capacitor 2703 to reduce stray 60 Hz from the Mains. Figure 28 shows the test setup for the 6X4 and 12X4 which have indirectly heated cathodes shown as tube 2802. The selection of different pins was done using clip leads. The results for the 5U4GT are presented in Figure 29; the results for the 5Y3GT are presented in Figure 30.

Thermionic emission from the cathode produced a negative voltage at the plate. The amount of current produced was small. Although it was too small to be useful it was amazing to find any, because vacuum tubes are not generally considered a power generator, only a power regulator.

The 5U4GB and the smaller 5Y3GT both exhibited the properties that the voltage produced at the plate depended on which side of the filament was used as a reference. (In the second test for each tube the filament voltage was reversed. It showed that the phenomenon followed the sign of the filament voltage.)

This is probably a function of the structure of the tube. Both diodes in each tube are mechanically identical and separate from each other. Each one has a long filament and a long rectangularly shaped plate element surrounding it. The only thing the two diodes have in common is that the filaments are wired in series. Also, the tube elements are connected to the pins at the tube base only at the end of the respective elements.

The reason for testing the 6X4 and 12X4 was because they both use indirectly heated cathodes so that the thermionic emission from the cathode is solely thermal and the voltage on the filament should not make a difference. It was also the reason for testing both the 6X4 and the 12X4. The two tubes are identical except for the filament voltage.

The results for the 6X4 are presented in Figure 31; and the results for the 12X4 are presented in Figure 32. The 6X4 and 12X4 exhibited no difference in plate voltage between the two sections even though the filaments are also connected in series. Connecting the cathode to either side of the filament also showed no difference.

The tubes showed interesting results for the voltage between the filament and the cathode. Depending on the side of the filament used as a reference the voltage at the plate could be negative or positive. Undoubtedly this is because the filament and the cathode are so close together.

Since these tubes are used as rectifiers operating at hundreds of volts and are followed by DC filters these phenomena are of no consequence. They do show why, in tubes with gain used in amplifiers (such as triodes) a tube with a directly heated cathode filament operating on AC could introduce hum into the amplifier.

In vacuum tubes the direct effect of thermionic emission is small. However, thermionic emission does allow the vacuum tube to control large external currents. That is why they are used as rectifiers in power supplies. In flames, thermionic emission might also contribute to flame rectification. However, it is more likely that thermionic emission from the burner and from the flame rod produces large numbers of free electrons which promote conductivity and which are also scarfed up by the chemical ions and affect the electrical properties of the flame that way.

**[036] Experiment 6 – Flame battery with different flame rod materials**

The previous tests were done with a commercial flame rod from a Ruud propane furnace. Then it was discovered that the flame voltage was different when the flame rod was made from different materials. See Table 8. The test with aluminum had to be done quickly because it melts in the flame. The tests were done using the instrumentation amplifier in Figure 12 to reduce the stray AC from the mains. For measuring current the current sense resistor was 533 KOhms. The galvanized steel wire (AWG 14) did about the same as the Ruud Flame Rod, probably because the flame burned off whatever the steel was plated with. The surprise was that the silicon carbide did so well considering that the resistance of silicon carbide was so high compared to steel. (The resistance of the silicon carbide igniter was about 10 Ohms.) A higher resistance means that the electron mobility in the material is lower. Yet the work functions of the silicon carbide and the steel were similar.

| **Flame Rod Material** | **Flame Voltage** | **Current Sense Voltage** | **Current** |
|---|---|---|---|
| Ruud Flame Rod (probably chromium plated steel) | -1.63 V | -154 mV | 0.29 uA |
| Galvanized Steel Wire (AWG 14) | -1.62 V | -164 mV | 0.31 uA |
| Aluminum Wire (AWG 14) | -3.00 V | -272 mV | 0.51 uA |
| Copper Wire (AWG 14) | -1.55 V | -162 mV | 0.30 uA |
| Nichrome 60 (AWG xx) | -1.27 V | -172 mV | 0.32 uA |
| Tungsten (AWG xx) | -392 mV | -96 mV | 0.18 uA |
| Silicon Carbide (Igniter, not powered) | -1.55 V | -164 mV | 0.31 uA |

**Table 8**

**[037] Experiment 7 – Flame battery with two parallel flame rods**

Two Ruud commercial flame rods were immersed in the flame about 0.75 inches above the burner and about 0.25 inches apart. The results were that that the open circuit flame voltage was slightly lower than a single rod but the flame current was slightly higher. See Table 9. The flame voltage for the two flame rods together may have been lower because, with their additional width, neither one could be placed directly in the middle of the flame.

| | Voltage | Current |
|---|---|---|
| Single Flame Rod | -1.63 V | -0.29 uA |
| Two Flame Rods | -1.46 V | -0.35 uA |
| Difference | -10% | +21% |

**Table 9**

**[038] Experiment 8 – Flame battery with two vertically spaced flame rods**

The two Ruud Flame Rods were placed in the flame vertically spaced and the voltage between them was measured. The lower flame rod was about 0.5 inches above the burner and the upper flame rod was placed about 0.5 inches above the lower flame rod. The voltage at the upper flame rod measured about -304 mV referenced to the lower flame rod. There are possible reasons for this.

1. The upper flame rod was cooler than the lower flame rod. As a result it produced fewer electrons by thermionic emission than the lower flame rod. The lower flame won.

2. The gas pressure moving the chemical ions past the lower flame rod toward the upper flame rod.

**[039] Experiment 9 – Using flame rectification to produce harmonic distortion in a signal source**

The apparatus shown in Figure 19 and Figure 20 was used to introduce a signal source to a flame rod immersed in a flame and to buffer the output (VOut). Source Resistor R3 (1902) was about 10 megohms. The output of the instrumentation amplifier 2004 was connected to an input of a Behringer Q502USB mixer which digitized the signal and sent it to a PC's USB port. The PC ran a program called **Visual Analyzer** which is a real time software program that contains a comprehensive set of measurement instruments, including an FFT Analyzer *{IDS Cite 29}*. The spectra of the signal source were measured both with and without a flame. Since the flame also acts as a load resistor the amplitude of the signal source was adjusted as needed to provide a consistent reference of -3 dB as reported by Visual Analyzer.

Signal generator 1901 was used to produce a low distortion sine wave at about 200 Hz. Figure 33a shows the system with the flame off. When the flame was on, flame rectification caused harmonic distortion of the sine wave and produced harmonics, starting with the second harmonic at 400 Hz that was about 20 dB below the fundamental. See Figure 33b. The frequency of 200 Hz was used because the harmonics of 200 Hz do not coincide with harmonics of the 60 Hz mains. Since Figure 33a shows the system with the flame off, it proves that the harmonic distortion was caused by the flame. The reason 60 Hz is not used as the reference sine wave is because other equipment on the AC mains may cause distortion that could mimic the distortion caused by flame rectification. In addition, the AC mains power itself may be dirty, especially if it is coming from a portable generator or an inverter.

**[040]** The experiment was repeated using a symmetrical square wave as a signal source.
A symmetrical square wave contains the fundamental and odd harmonics only. See Figure 34a for the signal with the flame off. The second harmonic (400 Hz) in Figure 34b is produced by flame rectification, and is about 39 dB below the fundamental. Note that the fourth harmonic is 38 dB below the fundamental, slightly better than the second harmonic.

**[041]** The sine wave experiment was repeated with a reference frequency of 400 Hz. Figure 35a shows the spectrum without a flame. Figure 35b shows the distortion caused by flame rectification. The second harmonic is about 18 dB below the fundamental, slightly better than the test at 200 Hz.

The test was repeated at 400 Hz with a square wave. Figure 36a shows the spectrum without a flame. Figure 36b shows the distortion caused by flame rectification. The second harmonic is about 30 dB below the fundamental, about 9 dB better than the square wave test at 200 Hz.

**[042] Experiment 10 – Using flame rectification as a mixer to produce sum and difference frequencies of two signal sources.**

In this experiment the flame rectifier is used as a mixer. A mixer is a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. See IDS Cite *30* (Horowitz).

One type of mixer is a four-quadrant multiplier. For example, if you multiply two sine wave signals:

$$\sin(\omega 1t) * \sin(\omega 2t) \qquad \text{Equation 1}$$

and use a well known trigonometric identity you get:

$$½ * \cos(\omega 1 - \omega 2)t - ½ * \cos(\omega 1 + \omega 2)t \qquad \text{Equation 2}$$

Horowitz uses the example of multiplying two cosines:

$$\cos(\omega 1t) * \cos(\omega 2t) \qquad \text{Equation 3}$$

and uses a well known trigonometric identity to get

$$½ * \cos(\omega 1 - \omega 2)t + ½ * \cos(\omega 1 + \omega 2)t \qquad \text{Equation 4}$$

Both are equivalent because $\cos(\omega) = \sin(\pi/2 - \omega)$

Any non-linear circuit will produce sum and difference frequencies. However, depending on the non-linearity it may also produce harmonics of the two signals as well as components having other frequencies. The flame rectifier produces that kind of non-linearity.

**[043]** In this experiment two sine wave signals were used. The apparatus shown in Figure 37 and Figure 38 was used to introduce two signal sources to a flame rod immersed in a flame and to buffer the output (VOut). Source Resistor R3 (3702) and Source Resistor R5 (3704) were both about 10 megohms. The output of the instrumentation amplifier 3801 was connected to an input of a Behringer Q502USB mixer which digitized the signal and sent it to a PC's USB port. The PC ran a program called **Visual Analyzer** which is a real time software program that contains a comprehensive set of measurement instruments, including an FFT Analyzer *{IDS Cite 29}*. The spectra of the signal sources were measured both with and without a flame. Although the flame also acts as a load resistor the amplitudes of the signal sources was not adjusted between flame and no-flame tests.

Signal Source 1 (3701) was adjusted to produce a low distortion sine wave at about 900 Hz. Signal Source 2 (3703) was adjusted to produce a low distortion sine wave at about 1,300 Hz. Figure 39a shows the two signals through the system with no flame. These signals were both at about -7 dB. With a flame (Figure 39b) flame conductivity reduced the two signals to -12 dB. Flame rectification produced a signal at the Difference Frequency of 400 Hz (1,300-900), the Sum Frequency of 2,200 Hz (1,300+900), = 400, and several other components. These other components are produced because the flame rectifier is not a four-quadrant multiplier. For example, there is a component at 500 Hz which is the difference between Signal Source 1 (3701) at 900 Hz and the Difference Frequency at 400 Hz.

We are only interested in the Sum and Difference Components. Their relative amplitudes are: the Difference Frequency (400 Hz) is 15 dB below the signal sources; the Sum Frequency (2,200 Hz) is also 15 dB below the signal sources.

**[044]** In Figure 40 Signal Source 1 is 900 Hz and Signal Source 2 is 1,460 Hz. It produces a Difference Frequency of 560 Hz and a Sum Frequency of 2,360 Hz. The difference between Signal Source 1 (3701) at 900 Hz and the Difference Frequency at 560 Hz is 340 Hz which is the component below the Difference Frequency (560 Hz) in Figure 40.

In Figure 41 Signal Source 1 (3701) is 900 Hz and Signal Source 2 (3703) is 1,350 Hz. It produces a Difference Frequency of 450 Hz and a Sum Frequency of 2,250 Hz. The difference between Signal Source 1 (3701) at 900 Hz and the Difference Frequency at 450 Hz is 450 Hz which is the same as the Difference Frequency so it does not appear as a separate component.

The important result is that these components are only produced by the presence of a flame.

**[045]** The above mixer test was repeated with symmetrical square waves with Signal Source 1 (3701) having a frequency of about 910 Hz and Signal Source 2 (3703) having a frequency of about 1,410 Hz. Figure 42a shows the results without a flame. Symmetrical square waves contain the fundamental with only odd harmonics. In Figure 42a the harmonics of the square waves are not shown in order to focus on the fundamental frequencies and lower frequencies. Figure 42b shows the results when a flame is present. Again, the harmonics of the square waves are not shown in order to focus on the fundamental frequencies and lower frequencies. As with the experiment with sine waves, when a flame is present the mixing of the two signal sources (910 Hz and 1,410 Hz) produces signals at the sum of the two mixing signals (at 2,320 Hz) and the difference of the two mixing frequencies (at 500 Hz) along with the difference between Signal Source 1 (3701) and the Difference Frequency at 410 Hz. (The other components will be ignored.)

We are only interested in the Sum and Difference Components. Their relative amplitudes are: the Difference Frequency (500 Hz) is 9 dB below the signal sources; the Sum Frequency (2,320 Hz) is 15 dB below the signal sources.

**[046] Experiment 11 – Making a simple low distortion sine wave generator**

In this experiment a Johnson Counter was used to make a simple sine wave generator and its output was analyzed. The circuit is shown in Figure 43a.

A Johnson Counter is actually a shift register with the output of the last stage inverted and fed back to the input stage. As a result a shift register with n stages produces a sequence having 2*n states.

The Johnson Counter in Figure 43a uses an eight-bit shift register (4301). The bit sequence starting from a cleared state is shown in the following Table 10:

| ABCDEFGH | ABCDEFGH |
|---|---|
| 00000000 | 11111111 |
| 10000000 | 01111111 |
| 11000000 | 00111111 |
| 11100000 | 00011111 |
| 11110000 | 00001111 |
| 11111000 | 00000111 |
| 11111100 | 00000011 |
| 11111110 | 00000001 |

**<u>Table 10</u>**

The outputs of the shift register stages are connected to resistors having values calculated to take advantage of the symmetrical properties of a sine wave.

A simple oscillator for producing the clock signal for the shift register is shown in Figure 43b. The Johnson Counter must start from one of the states in Table 10. The state of all zeroes is convenient because the 74HC164 shift register (4301) has an input to clear all of the registers. A circuit to produce a Reset signal on Power-up is shown in Figure 43c.

The results are very good and are shown in Figure 44. With a 210 Hz fundamental normalized at 0 dB the 2nd harmonic is at -61 dB, the 3rd harmonic is at -51 dB, and the 5th harmonic is at -54 dB. Note that the second harmonic (at -61 dB) is even lower than the 60 Hz mains (at -54 dB) which gets into almost everything. The result is a sine wave with a total harmonic distortion (THD) of less than 0.4%. Therefore, even though the waveform looks a little chunky in the time domain (the upper part of Figure 44) no filtering is needed to produce a low distortion sine wave with this simple circuit.

Low distortion sine waves may also be produced by well known analog circuits such as those using Operational Amplifiers or Operational Transconductance Amplifiers. The use of Operational Amplifiers to produce sine waves is taught in **Sine-Wave Oscillator**, Application Notes SLOA060 by Texas Instruments *{IDS Cite 31}*. An example of a low distortion sine wave generator using Operational Transconductance Amplifiers is shown in the datasheet for the LM13700 *{IDS Cite 32, Figure 17}*. Low distortion sine waves may also be produced by well known digitals methods such by stepping through a table of sine values and sending them to a Digital-to-Analog Converter (DAC). As an alternative the sine values can be calculated algorithmically and sent to a DAC.

**[047] Experiment 12 – Produce a symmetrical square wave.**

A simple method for producing a symmetrical square wave is shown in Figure 45. The 74HC14 Integrated circuit (4501) is an inverter with a Schmidt trigger input. The delay caused by capacitor C1 (4502) and resistors R1 and R2 (4503 and 4504) causes the inverter (4501) to oscillate. The 74HC74 (4505) symmetrically divides the output of inverter (4501) by two. The output is adjustable by potentiometer 4506, AC coupled, and then amplified by TL062 (4507).

**[048] Experiment 13 – Detecting a harmonic signal produced by flame rectification with a phase locked loop (PLL).**

The setup is shown in Figure 46. Sine Wave 4601 (at 400 Hz) is applied through Source Resistor 4602 to Flame Rod 3. Flame Rod 3 is also connected to the input of High Impedance Buffer 4603 (shown in Figure 47). The output of High Impedance Buffer 4603 is connected to the input of the 800 Hz Bandpass Filter 4604 (Figure 49). As is shown in Figure 49 the 800 Hz Bandpass Filter 4604 is made by cascading two 800 Hz Bandpass Filters, each of which is shown in Figure 48. The output of 800 Hz Bandpass Filter 4604 is connected to the input of Phase Locked Loop 4605 (Figure 50) which detects the 800 Hz second harmonic of Sine Wave 4601 caused by flame rectification. Figure 51a and Figure 51b show the results when a flame is not present. When a flame is not present the output of Phase Locked Loop 4605 is high (Figure 51a) which means that Phase Locked Loop 4605 is not locked. Figure 51b shows the output of 800 Hz Bandpass Filter 4604. The signal at 800 Hz is the result of ringing in Bandpass Filter 4604 and its amplitude is below the amplitude of the fundamental frequency at 400 Hz. It is even below the amplitude of the stray pickup of 60 Hz from the Mains. Figure 52a and Figure 52b show the results when a flame is present. When a flame is present the output of Phase Locked Loop 4605 is low which means that Phase Locked Loop 4605 is locked. As shown in Figure 50 an LED (5001) is connected to the output of the Phase Locked Loop to serve as the “Flame Good” indicator so that it comes on when the output of the Phase Locked Loop is low.

**[049]** There are two things to note about the 800 Hz signal. First, In Figure 52b the amplitude is approximately 27 dB above the 400 Hz fundamental. Second, the 800 Hz signal has prominent sidelobes. These sidelobes are caused by flame rectification causing the stray 60 Hz mains to modulate the 800 Hz signal. The absence of these sidelobes in Figure 51b (no flame) is further evidence that the 800 Hz signal in Figure 51b is produced by ringing in 800 Hz Bandpass Filter 4904. This experiment successfully and reliably detects a flame.

**[050]** An alternative, if it is desired to reduce the ringing see Figure 53. Instead of using 800 Hz Bandpass Filter 4604 (Figure 49) made by cascading two 800 Hz Bandpass Filters (from Figure 48) a single 800 Hz Bandpass Filter 5302 (Figure 48) can be used if it is preceded by a 400 Hz notch filter 5301 (Figure 54b) to attenuate the 400 Hz fundamental of this arrangement. An example of a notch filter is shown in Figure 54a. This is a series LC circuit. However, instead of using an actual inductor, a simulated inductor is used as shown in Figure 54b.

The need for pre-filtering in this experiment was dictated by the dynamic range of the 567 phase locked loop that was used. A phase locked loop with a greater dynamic range would not need a pre-filter.

**[051]** The previous experiment with the sine wave source was repeated but used a symmetrical square wave instead of a sine wave. Figure 55 shows the setup, which is the same as for the sine wave test except that a symmetrical square wave (5501) is used. The results are shown in Figure 56a and Figure 56b (flame off) and Figure 57a and Figure 57b (flame on). The signal at 1200 Hz is the third harmonic of the square wave and is attenuated by Bandpass Filter 4604 about the same as the 400 Hz fundamental. This experiment also successfully and reliably detects a flame.

**[052]** As with the sine wave test there was some ringing in the cascaded 800 Hz Bandpass Filter. This can also be reduced by using a single 800 Hz Bandpass Filter (Figure 48) preceded by a 400 Hz notch filter (Figure 54b) to attenuate the 400 fundamental. However, it may also require a notch filter to attenuate the signal at 1200 Hz (the third harmonic of the fundamental) produced by the square wave.

**[053] Experiment 14 – Detecting a harmonic signal produced by flame rectification with a simple synchronous detector – square wave signal source**.

The setup is shown in Figure 58. As per Equation 2, when two signals are multiplied together signals at the sum and difference frequencies of the two signals are produced. If the frequencies of the two signals are the same, the sum frequency is twice the original frequency and the difference frequency is zero frequency. Zero frequency is DC. If the two input signals are normalized to an amplitude of 1.0 and the two frequencies are exactly in phase, the DC term is +1.0 . If the two frequencies are 180 degrees out of phase the DC term is -1.0 . If the two signals are 90 degrees out of phase the DC term is 0.0 . If the two signals are of different frequencies, even if the difference is small, the DC term will also be zero. For example, if the two input frequencies are 1 Hz apart, then the difference frequency will be 1 Hz, not DC.

**[054]** A Phase Locked Loop uses this principal to control the frequency of the Voltage Controlled Oscillator (VCO). The frequency of the VCO is driven so that the difference frequency between the VCO and the signal to be detected is zero. In our case we know exactly the frequency of the signal to be detected (the second harmonic) because we are generating the fundamental frequency. For this experiment we will use a crystal oscillator and a counter to produce the second harmonic (781.25 Hz). Half of that (390.63 Hz) is the fundamental. Because these two signals are produced by a digital counter operating from the same clock, their frequencies are exactly locked together. See Figure 60, which is represented as Oscillator and Divider 5801 in Figure 58.

**[055]** Referring to Figure 60, oscillator 6001 is a crystal oscillator module operating at 1 Mhz. A crystal oscillator was used because of its good temperature stability but other types of oscillators may be used. The first counter (6002) is configured as a divide-by-ten counter to produce a clock at 100 KHz. The second counter (6003) and third counter (6004) are configured as straight binary counters. The outputs used in this experiment are 781.25 Hz (Clock 7) and 390.63 Hz (Clock 8). In Figure 61 the 390.63 Hz (Clock 8) signal goes through a level control and a DC blocking capacitor, and is amplified. This is represented as Signal Source 5802 in Figure 58.

**[056]** As shown in Figure 58, Signal Source 5802 is connected to Flame Rod 3 through Source Resistor 5803. The junction of Flame Rod 3 and Source Resistor 5803 is connected to High Impedance Buffer 5804 shown in detail in Figure 63. The output of High Impedance Buffer 5804 is connected to a first input of Multiplier/DC Filter 5805. A second input to Multiplier/DC Filter 5805 connected to the 781.25 Hz (Clock 7) which is the frequency of the second harmonic of Signal Source 5802 produced by Flame 2 when a flame is present. Referring to Figure 64, Multiplier/DC Filter 5805 is a four quadrant multiplier that multiplies an analog signal by a digital signal. When Analog Switch 6403 is turned off, Op Amp 6404 operates only as an inverting amplifier with a gain of -1 [–1 * R3 (6402) / R2 (6401)]. When Analog Switch 6403 is turned on, Op Amp 6404 still operates as an inverting amplifier with a gain of -1 [–1 * R3 (6402) / R2 (6401)]. However it also operates as a non-inverting amplifier with a gain of +2 [1 + R3 (6402) / R2 (6401)]. The net result is that it operates as a non-inverting amplifier with a gain of +1. Since the gain is switched between +1 and -1 the analog input is multiplied by either +1 or -1. The DC Filter is of conventional design and uses two cascaded first-order low pass filters.

**[057]** Because the output of the 5805 Multiplier/DC Amp can range between positive and negative voltages depending on the phase between the second harmonic of Signal Source 5802 and the reference Clock 7 the absolute value of the voltage is taken in Absolute Value Amp 5806 (Figure 65) so that it can only be positive, and a threshold test is applied in Threshold Detector 5807 (Figure 66). When the voltage exceeds a selected value Flame Good Indicator 6601 (Figure 66) is turned on. As an alternative, the threshold test can be for the voltage being greater than the positive threshold or less than the negative threshold. The method used for this test will be to take the absolute value and use a single positive threshold test. Figure 65 and Figure 66 are combined in Figure 67. The advantage of this system is that its operation is not sensitive to temperature. As long as oscillator 6001 (Figure 60) is working everything else is locked to that frequency even if the oscillator drifts some.

**[058]** As was previously discussed even if the two signals have exactly the same frequency but are 90 degrees out of phase the output of the multiplier will be zero. How could this 90 degree phase shift happen? It could happen because in some systems the wire going to the flame rod may be bundled with other wires creating appreciable capacitance on the flame rod wire. See Experiment #1. One way of dealing with this potential problem is to be able to have an adjustable time delay in one of the signals, either the fundamental frequency going to the flame rod (390.63 Hz) or in the second harmonic signal (781.25 Hz) going to the Multiplier 5805. The time delay produces a phase delay. See Figure 59 with Phase Delay 5901. An example of a simple circuit to produce an adjustable time delay is shown in Figure 62.

**[059]** The results of the test using the setup of Figure 59 are shown in Figure 68a (flame off) and Figure 68b (flame on). The top part of each figure is the spectrum at the output of High Impedance Buffer 5804. No bandpass filter was used. The bottom part of each figure is a screen capture of the voltage at the output of Absolute Value Amp 5806.

With the flame off (Figure 68a) the spectrum shows the fundamental of the square wave signal source of 390.63 Hz at the reference of 0 dB. The third harmonic (1171.89 Hz) is 12 dB below that. The second harmonic (781.25 Hz) is an artifact of some kind but is 48 dB below the fundamental. The stray AC from the 60 Hz mains is 31 dB below the fundamental. The output of Absolute Value Amp 5806 is about 0.3 Volts.

With the flame on (Figure 68b) the spectrum shows the fundamental of the square wave signal source of 390.63 Hz at -4 dB. The third harmonic (1171.89 Hz) is 12 dB below that. The second harmonic (781.25 Hz) is 26 dB below the fundamental. The stray AC from the 60 Hz mains is 29 dB below the fundamental. The output of Absolute Value Amp 5806 is about 1.3 Volts. This gives a ratio of 1.3/0.3 = 4.3:1 for flame on versus flame off. The use of a bandpass filter (Figure 49) would improve this ratio but even without it this test with the Meker Burner shows this circuit to be a robust system for detecting the presence of a flame.

**[060]** The drawbacks of using an adjustable phase delay circuit (Figure 62) are that: 1) it has to be adjusted and 2) the capacitance in the cable bundle could change if the cable bundle is moved around. Another way to deal with the problem of phase delay is to use a quadrature detector as shown in Figure 69. The quadrature detector uses two multipliers. The first input of both the first Multiplier 5805 and the second Multiplier 6902 comes from the High Impedance Buffer 5804. In the first Multiplier (5805) the second input is the 781.25 Hz reference. In the second Multiplier (6902) the second input is the 781.25 Hz signal delayed by 90 degrees. This 90 degree delay is performed by the circuit in Figure 70a. The timing chart of the circuit is shown in Figure 70b. The output of Multiplier 5805 goes to Absolute Value Amp 5806 and the output of Multiplier 6902 goes to Absolute Value Amp 6903. The outputs of Absolute Value Amp 5806 and Absolute Value Amp 6903 are then added in Adder 6904. (The precise magnitude would be obtained by taking the square root of the sum of squares. In this application it is sufficient to simply sum the absolute values.) Threshold Detector 5807 (shown in detail in Figure 66) applies a threshold test and, when the voltage is above a selected threshold, turns on Flame Good Indicator 6601. The use of the quadrature detector makes any phase delay in the system irrelevant.

**[061]** Performance can be improved by using a low distortion sine wave instead of a symmetrical square wave. Figure 71 shows a low distortion sine wave used for the Signal Source with a quadrature detector. For simplicity square waves are used in the quadrature detector. Sine waves could be used there, too, which would require additional circuit complexity. It would also require that the multipliers accept two analog signals instead of one analog signal and one digital signal. Such multipliers are more expensive than the simple circuit shown in Figure 64.

In Figure 71 Signal Source 7101 uses the Johnson Counter shown in Figure 43a. Since the Johnson Counter uses 16 clocks for a single sine wave period the input clock is 16 x 390.63 ≈ 6.25 KHz. The remainder of the circuits operates the same way as the circuit in Figure 69

**[062] Experiment 15 – Using flame rectification to mix two signals and detect the difference frequency (the heterodyne method).**

These experiments were done with the two signal sources having symmetrical square waves. As Experiment 10 shows, the results can be expected to be substantially the same if two low distortion sine waves were used. Experiment 10 was done first with sine waves with the results shown in Figures 39a and 39b and then with symmetrical square waves with the results shown in Figures 42a and 42b.

While two free running oscillators may be used to produce the two signal sources this can only be used when a phase locked loop is used to detect the difference signal produced by flame rectification. Since the use of a synchronous detector requires that the two signal sources and the reference signal be locked together, for the purposes of this experiment a common clock will be used to produce the signal sources even when a phase locked loop is used for the detector.

Also, although this experiment will detect the difference signal, it is equally applicable to a system that detects the sum frequency.

**[063]** Since we want to have a master clock from which we can derive three frequencies that cannot be derived from each other we start by producing the product of the three frequencies. That way we know we can derive each frequency from the master clock. We will select 900 Hz and 1,300 Hz to give us a difference frequency of 400 Hz. The product of 900 * 1,300 * 400 = 468.0 Mhz. We can scale that down quite a bit with integers. See the following Table 11.

| | | Master Clock (Hz) | Divisor 1 | Freq 1 | Divisor 2 | Freq 2 | Divisor 3 | Freq 3 |
|---|---|---|---|---|---|---|---|---|
| | | 468,000,000 | 520,000 | 900.000 | 360,000 | 1,300.00 | 1170000 | 400 |
| Divide by | 1000 | 468,000 | 520 | 900.000 | 360 | 1,300.00 | 1170 | 400 |
| Divide by | 5000 | 93,600 | 104 | 900.000 | 72 | 1,300.00 | 234 | 400 |

**Table 11**

If we start with a 1 MHz oscillator we can divide 1 MHz by 11 and get 90.909 KHz. If we use that instead of 93.600 KHz, by using the same divide ratios we get frequencies of:
Frequency 1 = 874.126 Hz, Frequency 2 = 1,262.626 Hz, and Frequency 3 = 388.500 Hz .
Frequency 1 will be Signal Source 1, Frequency 2 will be Signal Source 2, and Frequency 3 will be the difference frequency between Frequency 1 and Frequency 3. The difference frequency is also scaled, and becomes 388.500 Hz.

Since all of the divide ratios are even we will divide them by two to double all the resulting output frequencies and then divide the resulting output frequencies by two to obtain symmetrical square waves. The clock chain is shown in Figure 72, Figure 73, and Figure 74. In Figure 72 the master oscillator Clock 1 (7201) operates at 1 MHz. Counter 7202 divides it by 11 to produce Clock 2 at 90.909 KHz. Counters 7203 and 7204 divide it by 52 to produce Clock 3 at 1,748 Hz. Flip Flop 7205 divides it by two to produce Clock 4 at 874.126 Hz (Frequency 1). In Figure 73 Counters 7301 and 7302 divide Clock 2 (90.909 KHz) by 36 to produce Clock 5 at 2,525.252 Hz. Flop Flop 7303 divides it by two to produce Clock 6 at 1,262.626 Hz (Frequency 2). In Figure 74 Counter 7401 and 7402 divide Clock 2 (90.909 KHz) by 117 to produce Clock 7 at 777.001 Hz. Flop Flop 7403 divides it by two to produce Clock 8 at 388.500 Hz (Frequency 3). Flip Flop 7404 uses Clock 7 and Clock 8 to produce a quadrature version of Clock 8. However, because Clock 8 is not symmetrical, instead of Clock 8Q being 90 degrees out of phase with Clock 8, it is about 79 degrees out of phase. That is close enough for this application. If necessary it can be made closer by using the existing clocks with additional circuitry.

**[064]** When it is desired to use low distortion sine waves for Signal Source 1 and Signal Source 2 this can be accomplished by using a 16 MHz oscillator for oscillator 7201 which will scale all frequencies by a factor of 16. Signal Source 1 and Signal Source 2 can then be produced by using a Johnson Counter shown in Figure 43a for each signal source. Where the difference reference of 388.500 is to be a square wave Clock 8 may be further divided by 16. Where the difference reference is to be a sine wave, Clock 8 can be used with the Johnson Counters shown in Figure 84 to produce both sine and cosine versions of the difference reference of 388.500 Hz.

**[065]** The system where the Signal Detector is a phase locked loop is shown in Figure 75. The Clock Generator 7501 produces and combines Signal Source 1 and Signal Source 2 to produce the Source Sum 7304. (The details are shown in Figure 72, Figure 73, and Figure 74.) The Source Sum 7304 is connected to Flame Rod 3 through Source Resistor 7502. The junction of Flame Rod 3 and Source Resistor 7502 is also connected to the input of High Impedance Buffer 7503. The output of High Impedance Buffer 7503 is connected to the input of Bandpass Filter 7504 (shown in detail in Figure 77). The Output of Bandpass Filter 7504 is connected to the input of Phase Locked Loop 7505 (shown in detail in Figure 78). When Flame 2 is present it acts as a mixer to produce signals at the sum and difference frequencies of Signal Source 1 and Signal Source 2. Phase Locked Loop 7505 is configured to detect the signal at the difference frequency. When a flame is present the output of Phase Locked Loop 7505 (shown in more detail in Figure 78) turns on the Flame Good Indicator 7801.

In the results shown by the **Visual Analyzer** program the signal was taken at the output of Bandpass Filter 7504. Figure 79a shows the spectrum with the flame off. As with the harmonic tests there is some ringing in Bandpass Filter 7504 at 388.5 Hz. Figure 79b shows the spectrum with the flame on. With the flame on, the Difference Frequency (388.5 Hz) is about 36 dB louder than it is with the flame off. The amplitude with the flame off is below the detection threshold of Phase Locked Loop 7505. With the flame on, Phase Locked Loop 7505 robustly detects the 388.5 Hz difference frequency. As noted previously, the need for pre-filtering was dictated by the dynamic range of the 567 phase locked loop that was used. A phase locked loop with a greater dynamic range would not need a pre-filter.

**[066]** The system where the Signal Detector is a simple synchronous detector is shown in Figure 80. The Clock Generator 7501 produces and combines Signal Source 1 and Signal Source 2 to produce the Source Sum 7304. (The details are shown in Figure 72, Figure 73, and Figure 74.) The Source Sum 7304 is connected to Flame Rod 3 through Source Resistor 7502. Clock Generator 7501 also produces a Reference Signal Clock8 at the frequency of the difference frequency between Signal Source 1 and Signal Source 2. Clock8 goes to Phase Delay 8001 (shown in detail in Figure 81) which provides an adjustable phase delay (Clock8D) for those systems that need it. For those systems that do not need the phase delay it can be omitted and Clock8 is used instead of Clock8D. The junction of Flame Rod 3 and Source Resistor 7502 is also connected to the input of High

Impedance Buffer 7503. The output of High Impedance Buffer 7503 is connected to a first input of Multiplier/DC Filter 8002. (The details of Multiplier/DC Filter 8002 are shown in Figure 64.) The second input of Multiplier/DC Filter 8002 is connected to the output of Phase Delay 8001 Reference Signal Clock8D. The output of Multiplier/DC Filter 8002 is connected to the input of Absolute Value Amp 8003 which produces the absolute value of its input. The output of Absolute Value Amp 8003 is connected to the input of Threshold Detector 8004. (The details of Threshold Detector 8004 are shown in Figure 66.) Threshold Detector 8004 applies a threshold test and, when the voltage is above a selected threshold, turns on Flame Good Indicator 6601. The results are shown in Figure 82a and Figure 82b, looking at the output of Absolute Value Amp 8003. Figure 82a shows an output of 0.1 volts with the flame off. Figure 82b shows an output of 2.4 volts with the flame on. Therefore, this method robustly detects the presence of a flame.

**[067]** The system where the Signal Detector is a quadrature synchronous detector is shown in Figure 83. The Clock Generator 7501 produces and combines Signal Source 1 and Signal Source 2 to produce the Source Sum 7304. (The details are shown in Figure 72, Figure 73, and Figure 74.) The Source Sum 7304 is connected to Flame Rod 3 through Source Resistor 7502. Clock Generator 7501 also produces a Reference Signal Clock8 at the frequency of the difference frequency between Signal Source 1 and Signal Source 2. Clock Generator 7501 also produces Reference Signal Clock8Q which has the same frequency as Reference Signal Clock8 but is nominally 90 degrees out of phase. (In this implementation it is 79 degrees out of phase). The Source Sum 7304 is connected to Flame Rod 3 through Source Resistor 7502. The junction of Flame Rod 3 and Source Resistor 7502 is also connected to the input of High Impedance Buffer 7503. The output of High Impedance Buffer 7503 is connected to the first input of Multiplier/DC Filter 8002 as well as to the first input of Multiplier/DC Filter 8301. (The details of Multiplier/DC Filter 8002 and Multiplier/DC Filter 8301 are shown in Figure 64.) The second input of Multiplier/DC Filter 8002 is connected to Reference Signal Clock8. The second input of Multiplier 8301 is connected to Reference Signal Clock8Q. The output of Multiplier/DC Filter 8002 is connected to the input of Absolute Value Amp 8003 which produces the absolute value of its input. The output of Multiplier/DC Filter 8301 is connected to the input of Absolute Value Amp 8302 which produces the absolute value of its input. The outputs of Absolute Value Amp 8003 and Absolute Value Amp 8302 are summed in Adder 8303. The output of Adder 8303 is connected to the input of Threshold Detector 8004. (The details of Threshold Detector 8004 are shown in Figure 66.) Threshold Detector 8004 applies a threshold test and, when the voltage is above a selected threshold, turns on Flame Good Indicator 6601.

## OBJECTS AND ADVANTAGES

**[068]** The objects and advantages of the current invention are to produce a flame sensing system that uses a low voltage and does not rely on the connection between AC Mains neutral and ground. In addition, in some of the embodiments the operation of the circuits is not subject to temperature sensitivity. If the components are rated to work at -40 degrees Celsius then the flame sensing system will work at -40 degrees Celsius.

## SUMMARY OF THE INVENTION

**[069]** In the following preferred embodiments flame rectification is used to cause distortion of a selected waveform. The term "selected waveform" means a waveform selected to not have substantial harmonics of interest of the fundamental frequency. An example of a selected waveform is a symmetrical square wave. A symmetrical square wave contains components at the fundamental frequency and only odd harmonics. Any even harmonics present will be due solely to the distortion caused by flame rectification, so the even harmonics will be the harmonics of interest. A symmetrical square wave can be produced by several well known methods such as by a simple free-running oscillator followed by a flip-flop to divide the frequency by two to make it symmetrical, or by a stable oscillator such as a crystal oscillator followed by a divider chain as required. Another example of a selected waveform is a low distortion sine wave. A low distortion sine wave contains only the fundamental frequency. Any harmonics present (whether even or odd) will be due solely to the distortion caused by flame rectification and will therefore be harmonics of interest. A low distortion sine wave can be produced by several well known methods including the use of a Johnson Counter.

**[070]** In a first preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and flame rectification is used to cause **distortion in a selected waveform**. Because the distortion caused by the flame rectifier produces harmonics of interest the waveform is selected to not contain those harmonics. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signal. The selected harmonic of the selected waveform is detected by a **Phase-Lock-Loop (PLL)**. If necessary a filter can be used to reduce the possibility of saturating the input of the PLL. For example, this filter may comprise a high pass filter to reduce the fundamental, a notch filter to reduce the fundamental, or a bandpass filter to pass the selected harmonic, all using well-known circuits. Since the selected harmonic is produced only in the presence of a flame this constitutes proof of flame which can be displayed on an indicator and/or used by a furnace controller.

**[071]** In a second preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and flame rectification is used to cause **distortion in a selected waveform**. Because the distortion caused by the flame rectifier produces harmonics of interest the waveform is selected to not contain those harmonics. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signal. The selected harmonic of the selected waveform is detected by a **simple synchronous detector** which is a multiplier that multiplies the signal from the high impedance buffer by a reference signal at the same frequency as the selected harmonic. This reference signal should be produced from the oscillator that produces the selected waveform. The output of the simple synchronous detector is filtered by a simple DC filter and may be further processed in an absolute value amplifier to form the absolute value of the results. The results go to a threshold detector having a selectable threshold and which produces a signal indicating the presence of the selected harmonic. Since the selected harmonic is produced only in the presence of a flame this constitutes proof of flame which can be displayed on an indicator and/or used by a furnace controller.

**[072]** In a third preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and flame rectification is used to cause **distortion in a selected waveform**. Because the distortion caused by the flame rectifier produces harmonics of interest the waveform is selected to not contain those harmonics. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signal. The selected harmonic of the selected waveform is detected by a **quadrature synchronous detector** of standard design which makes the signal detector insensitive to phase. The quadrature synchronous detector consists of two multipliers. The output of the high impedance buffer goes to the first input of the first multiplier and also to the first input of the second multiplier. The second input to the first multiplier receives a first reference signal having the same frequency as the selected harmonic to be detected and is derived from the fundamental frequency of the selected waveform. The second input to the second multiplier receives a second reference that is substantially 90 degrees out of phase with the first reference signal. The output of each multiplier is separately processed in its own absolute value amplifier to form the absolute value of each result. The output of each absolute value amplifier is summed in an adder. The output of the adder goes to a threshold detector having a selectable threshold and which produces a signal indicating the presence of the selected harmonic.

Since the selected harmonic is produced only in the presence of a flame this constitutes proof of flame which can be displayed on an indicator and/or used by a furnace controller.

**[073]** In the following preferred embodiments flame rectification is used as a mixer to cause two signals having selected waveforms to produce sum and difference signals.

In a fourth preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and **flame rectification is used as a mixer to cause two signals having selected waveforms to produce sum and difference signals**. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signals. The sum and/or difference signals are detected thereby providing flame proof. The two signals having selected waveforms should be of different frequencies. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signal. As an example, the difference frequency of the two selected waveforms is detected by a **Phase-Lock-Loop (PLL)**. If necessary a filter can be used to reduce the possibility of saturating the input of the PLL. For example, this filter may comprise a bandpass filter to pass the difference frequency. Since the difference frequency is produced only in the presence of a flame the detection of a signal at the difference frequency constitutes proof of flame which can be displayed on an indicator and/or used by a furnace controller.

**[074]** In a fifth preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and **flame rectification is used as a mixer to cause two signals having selected waveforms to produce sum and difference signals**. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signals. The sum and/or difference signals are detected thereby providing flame proof.
The two signals having selected waveforms should be of different frequencies. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signal. As an example, the difference signal at the difference frequency of the two selected waveforms is detected by a **detector using a simple synchronous detector** which is a multiplier that multiplies the signal from the high impedance buffer by a reference signal at the same frequency as the difference frequency. This reference signal should be produced from the oscillator that produces the selected waveform. The output of the simple synchronous detector is filtered by a simple DC filter and may be further processed in an absolute value amplifier to form the absolute value of the results. The results go to a threshold detector having a selectable threshold and which produces a signal indicating the presence of the difference signal. Since the difference

signal is produced only in the presence of a flame this constitutes proof of flame which can be displayed on an indicator and/or used by a furnace controller.

**[075]** In a sixth preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and **flame rectification is used as a mixer to cause two signals having selected waveforms to produce sum and difference signals**. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signals. The sum and/or difference signals are detected thereby providing flame proof. The first signal and the second signal should be of different frequencies. The sum and/or difference frequencies may be detected by using **a quadrature synchronous detector** of standard design which makes the signal detector insensitive to phase. The quadrature synchronous detector consists of two multipliers. The output of the high impedance buffer goes to the first input of the first multiplier and also to the first input of the second multiplier. The second input to the first multiplier receives a first reference signal having the same frequency as the difference signal to be detected and is derived from the clock that produces the two selected waveforms. The second input to the second multiplier receives a second reference that is substantially 90 degrees out of phase with the first reference signal. The output of each multiplier is further processed in its own absolute value amplifier to form the absolute value of each result. The output of each absolute value amplifier is summed in an adder. The output of the adder goes to a threshold detector having a selectable threshold and which produces a signal indicating the presence of the difference signal. Since the difference signal is produced only in the presence of a flame this constitutes proof of flame which can be displayed on an indicator and/or used by a furnace controller.

**[076]** In all of the preferred embodiments the circuitry can be mostly analog or it can be a combination of less analog and more digital. For example, the selected waveforms may be produced using a Direct Digital Synthesizer (DDS). In addition, such as a system using only a flame rod, a high impedance buffer, and a digital signal processor (DSP) or a suitable microcontroller having an analog-to-digital converter (ADC) the DSP (or microcontroller) can use software to perform the functions of producing symmetrical square waves (or low distortion sine waves), implementing a synchronous detector (either simple or quadrature), and driving an indicator. The use of a DSP (or microcontroller) also presents an additional option. The mostly analog systems described that use a synchronous detector are performing a continuous Fourier Transform at a selected frequency. The DSP (or microcontroller) can also do that. Alternatively, it can do the following:

1. Use either a prestored frame of data representing the Signal Source or calculate a frame of the Signal Source during runtime;
2. At substantially the same time that the frame of data representing the Signal Source is being sent out, capturing a frame of data from the High Impedance Buffer;
3. After the frame of data is captured it can be analyzed by the DSP (or microcontroller) by using a Discrete Fourier Transform at the desired frequency (or a few desired frequencies) or by performing a full Fast Fourier Transform (FFT) to analyze the full spectrum.
4. Since it is not necessary for data frames to be continuous a data frame can be sent and captured, then the DSP (or microcontroller) can take some time to perform the analysis of the received data frame.

An example of how this may be used is to look at the 60 Hz stray pickup from the Mains. This information could be used during manufacturing or installation to warn of cable placement problems. The analysis of the data may also be used to characterize flame quality.

**[077]** In addition to its uses in gas furnaces the embodiments of the invention may also be used in other appliances such as gas hot water heaters and gas ovens. Another application may be in outdoor gas grills, heaters or torches where the flame may be extinguished by the wind. In this application the circuitry may be powered by batteries recharged by solar photovoltaic cells. A control unit for the unit may also be used to provide additional functions such as a clock/timer. It may also use a sensor such as a strain gauge to measure the weight of a fuel tank (such as a propane cylinder) to accurately measure the amount of fuel remaining. It may also contain a security camera, microphone, and motion sensor. The invention may also be used in jet engines and rocket engines where flame detection is critical because flames are essential to their operation.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[078]** The invention may best be understood by referring to the following description and accompanying drawings which illustrate the invention. In the drawings:

**[079]** Figure 1 is a general illustration showing a flame rod immersed in a flame produced by a combustion burner. Figure 2 is a general illustration showing an electrical model of a flame rod immersed in a flame produced by a combustion burner.

**[080]** Figure 3 is a general illustration showing a flame rod and a combustion burner but no flame. Figure 4 is a general illustration showing an electrical model of a flame rod and a combustion burner but no flame.

**[081]** Figure 5 is a general illustration showing the electrical circuit for a high impedance unbalanced buffer.

**[082]** Figure 6 is a general illustration showing the electrical circuit for a high impedance balanced instrumentation amplifier.

**[083]** Figure 7 is a general illustration showing the RC model used to determine the capacitance of two wires positioned next to each other. Figure 8 is a general illustration of the RC model used to determine the voltage produced in a resistor from capacitive coupling.

**[084]** Figure 9 is a general illustration showing the waveform produced by the circuit of Figure 7 when driven by a pulse generator having an adjustable pulse width.

**[085]** Figure 10 is a general illustration showing the derivation of the frequency response of Figure 8.

**[086]** Figure 11 is a general illustration showing an electrical model of a flame battery.

**[087]** Figure 12 is a general illustration showing the instrumentation amplifier of Figure 6 with a capacitor added to the input.

**[088]** Figure 13 is a general illustration showing the method of testing electrical model of Figure 11.

**[089]** Figure 14 is a reproduction of Table 5.4 from the Turns reference (Reference 12). Figure 15 is a reproduction of Table 17.12 from the Turns reference (Reference 12).

**[090]** Figure 16 is a reproduction of Table 1-1 from the Nichicon reference (Reference 24).

**[091]** Figure 17 is a general illustration showing the method used for measuring the flame conductivity when driven by a DC source. Figure 18 is a general illustration showing the electrical circuit for the method used for measuring the flame conductivity when driven by a DC source.

**[092]** Figure 19 is a general illustration showing the method used for measuring the flame conductivity when driven by an AC signal source. Figure 20 is a general illustration showing the electrical circuit for the method used for measuring the flame conductivity when driven by an AC signal source.

**[093]** Figure 21a is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 21b is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame.

**[094]** Figure 22a is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 22b is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame.

**[095]** Figure 23a is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 23b is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 23c is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame.

**[096]** Figure 24a is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 24b is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 24c is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame.

**[097]** Figure 25a is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 25b is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 25c is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame.

**[098]** Figure 26a is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 26b is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame. Figure 26c is a screen capture from an oscilloscope showing the results of a test to determine the electrical characteristics of a flame.

**[099]** Figure 27 is a general illustration showing the electrical circuit used for test the thermionic emission from the 5Y4GB and 5Y3GT vacuum tubes.

**[100]** Figure 28 is a general illustration showing the electrical circuit used for testing the thermionic emission from the 6X4 and 12X4 vacuum tubes. Figure 29 is the table of test data obtained by testing a 5U4GB vacuum tube. Figure 30 is the table of test data obtained by testing a 5Y3GT vacuum tube. Figure 31 is the table of test data obtained by testing a 6X4 vacuum tube. Figure 32 is the table of test data obtained by testing a 12X4 vacuum tube.

**[101]** Figure 33a is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a sine wave at 200 Hz with no flame. Figure 33b is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a sine wave at 200 Hz with a flame.

**[102]** Figure 34a is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a square wave at 200 Hz with no flame.

Figure 34b is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a square wave at 200 Hz with a flame.

**[103]** Figure 35a is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a sine wave at 400 Hz with no flame. Figure 35b is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a sine wave at 400 Hz with a flame.

**[104]** Figure 36a is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a square wave at 400 Hz with no flame. Figure 36b is a screen capture of the display of a spectrum analyzer program showing the results of an experiment in flame rectification done with a square wave at 400 Hz with a flame.

**[105]** Figure 37 is a general illustration showing the method used for performing the test when flame rectification is used as a mixer of two signal sources.

**[106]** Figure 38 is a general illustration showing the electrical circuit for the method used for performing the test when flame rectification is used as a mixer of two signal sources.

**[107]** Figure 39a is a screen capture of the display of a spectrum analyzer program showing the results of an experiment using flame rectification as a mixer done with sine waves at 900 Hz and 1,300 Hz with no flame present. Figure 39b is a screen capture of the display of a spectrum analyzer program showing the results of an experiment using flame rectification as a mixer done with sine waves at 900 Hz and 1,300 Hz with a flame present.

**[108]** Figure 40 is a screen capture of the display of a spectrum analyzer program showing the results of an experiment using flame rectification as a mixer done with sine waves at 900 Hz and 1,460 Hz with a flame present.

**[109]** Figure 41 is a screen capture of the display of a spectrum analyzer program showing the results of an experiment using flame rectification as a mixer done with sine waves at 900 Hz and 1,350 Hz with a flame present.

**[110]** Figure 42a is a screen capture of the display of a spectrum analyzer program showing the results of an experiment using flame rectification as a mixer done with square waves at 910 Hz and 1,410 Hz with no flame present. Figure 42b is a screen capture of the display of a spectrum analyzer program showing the results of an experiment using flame rectification as a mixer done with square waves at 910 Hz and 1,410 Hz with a flame present.

**[111]** Figure 43a is a general illustration showing an electrical circuit for using a Johnson Counter to produce a sine wave. Figure 43b is a general illustration showing an electrical circuit for a simple clock oscillator. Figure 43c is a general illustration showing an electrical circuit for a simple Power-On-Reset circuit.

**[112]** Figure 44 is a screen capture of the display of a spectrum analyzer program showing the spectrum produced by using a Johnson Counter to generate a sine wave.

**[113]** Figure 45 is a general illustration showing an electrical circuit for an oscillator with a symmetrical square wave output.

**[114]** Figure 46 is a general illustration showing the use of a sine wave signal source with a phase locked loop to provide flame proof.

**[115]** Figure 47 is a general illustration showing an electrical circuit for an AC coupled high impedance buffer.

**[116]** Figure 48 is a general illustration showing an electrical circuit for a bandpass filter.

**[117]** Figure 49 is a general illustration showing two of the bandpass filters of Figure 52 cascaded.

**[118]** Figure 50 is a general illustration showing an electrical circuit for a phase locked loop (PLL).

**[119]** Figure 51a and Figure 51b are screen captures of a test with the flame off.

**[120]** Figure 52a and Figure 52b are screen captures of a test with the flame on.

**[121]** Figure 53 is a general illustration showing the use of a symmetrical square wave signal source with a phase locked loop to provide flame proof.

**[122]** Figure 54a is a general illustration showing an electrical circuit for a series LC notch filter. Figure 54b is a general illustration showing an electrical circuit for a series LC notch filter where the inductor is a simulated inductor.

**[123]** Figure 55 is a general illustration showing the use of a symmetrical square wave signal source to provide flame proof.

**[124]** Figure 56a and Figure 56b are screen captures of a test with the flame off.

**[125]** Figure 57a and Figure 57b are screen captures of a test with the flame on.

**[126]** Figure 58 is a general illustration showing the use of a symmetrical square wave with a simple synchronous detector to provide flame proof.

**[127]** Figure 59 is a general illustration showing the use of a symmetrical square wave with a simple synchronous detector and an adjustable phase delay to provide flame proof.

**[128]** Figure 60 is a general illustration showing an electrical circuit for an oscillator and counter.

**[129]** Figure 61 is a general illustration showing an electrical circuit for an AC coupled amplifier.

**[130]** Figure 62 is a general illustration showing an electrical circuit for a time delay circuit with an adjustable time delay.

**[131]** Figure 63 is a general illustration showing an electrical circuit for an AC coupled high impedance buffer.

**[132]** Figure 64 is a general illustration showing an electrical circuit for a multiplier and DC filter.

**[133]** Figure 65 is a general illustration showing an electrical circuit for an amplifier that produces the absolute value of its input.

**[134]** Figure 66 is a general illustration showing an electrical circuit for a threshold detector and output indicator

**[135]** Figure 67 is a general illustration showing the combination of Figure 65 and Figure 66.

**[136]** Figure 68a shows screen captures of the results of a test with the flame off. Figure 68b shows screen captures of the results of a test with the flame on.

**[137]** Figure 69 is a general illustration showing the use of a symmetrical square wave with a quadrature synchronous detector to provide flame proof.

**[138]** Figure 70a is a general illustration showing an electrical circuit for producing a 90 degree phase shift for a clock. Figure 70b is a general illustration of a timing chart showing the timing signals for Figure 71a.

**[139]** Figure 71 is a general illustration showing the use of a sine wave with a quadrature synchronous detector to provide flame proof.

**[140]** Figure 72, Figure 73, and Figure 74 are general illustrations showing an electrical circuit for a clock generator.

**[141]** Figure 75 is a general illustration showing the use of flame rectification as a mixer with a Phase Locked Loop used to detect the difference frequency.

**[142]** Figure 76 is a general illustration showing an electrical circuit for a bandpass circuit. Figure 77 is a general illustration showing two bandpass circuits cascaded.

**[143]** Figure 78 is a general illustration showing an electrical circuit for a phase locked loop.

**[144]** Figure 79a and Figure 79b are screen captures of a test using a phase locked loop detector.

**[145]** Figure 80 is a general illustration showing the use of flame rectification as a mixer with a simple synchronous detector used to detect the difference frequency.

**[146]** Figure 81 is a general illustration showing an electrical circuit for providing an adjustable phase delay.

**[147]** Figure 82a and Figure 82b are screen captures of a heterodyne test using a simple synchronous detector.

**[148]** Figure 83 is a general illustration showing the use of flame rectification as a mixer with a quadrature synchronous detector used to detect the difference frequency.

**[149]** Figure 84 is a general illustration showing an electrical circuit for using Johnson Counters to produce both sine and cosine waves.

**[150]** Figure 85 is a general illustration showing the use of flame rectification to produce harmonic distortion of a selected waveform and detect the harmonic distortion with a phase locked loop.

**[151]** Figure 86 is a general illustration showing the use of flame rectification to produce harmonic distortion of a selected waveform and detect the harmonic distortion with a simple synchronous detector.

**[152]** Figure 87 is a general illustration showing the use of flame rectification to produce harmonic distortion of a selected waveform and detect the harmonic distortion with a quadrature synchronous detector.

**[153]** Figure 88 is a general illustration showing the use of flame rectification as a mixer with a phase locked loop detector used to detect the difference frequency.

**[154]** Figure 89 is a general illustration showing the use of flame rectification as a mixer with a simple synchronous detector used to detect the difference frequency.

**[155]** Figure 90 is a general illustration showing the use of flame rectification as a mixer with a quadrature synchronous detector used to detect the difference frequency.

## DETAILED DESCRIPTION

**[156]** In the following description, numerous specific details are set forth to provide a thorough understanding of the invention. However, it is understood that the invention may be practiced without these specific details. In other instances well-known circuits, structures, and techniques have not been shown in detail in order not to obscure the invention.

**[157]** In the first embodiment flame rectification causes **distortion of a signal source having a selected waveform**, producing a selected harmonic signal that does not otherwise exist in the selected waveform. In this specific example the selected harmonic is the second harmonic but other harmonics may be selected. The selected harmonic is detected by using a **phase locked loop**.

The system is shown in Figure 85. Signal Source 8501 produces a 400 Hz Selected Waveform that is selected to not contain even harmonics. Examples of selected waveforms that do not contain even harmonics include low distortion sine waves and symmetrical square waves. Signal Source 8501 is applied through Source Resistor 8502 to Flame Rod 3. Flame Rod 3 is also connected to the input of High Impedance Buffer 8503 (shown in more detail in Figure 47).

The output of High Impedance Buffer 8503 is connected to the input of the 800 Hz Bandpass Filter 8504 (Figure 49). As is shown in Figure 49 the 800 Hz Bandpass Filter 8504 is made by cascading two 800 Hz Bandpass Filters, each of which is shown in more detail in Figure 48. In some instances a single 800 Hz Bandpass Filter (Figure 48) may be used. In some instances no filter may be needed at all. The output of 800 Hz Bandpass Filter 8504 is connected to the input of Phase Locked Loop 8505 (shown in more detail in Figure 50). The output of Phase Locked Loop 8505 is connected to Flame Good Indicator 8506 (shown in Figure 50 as LED 5001). When Phase Locked Loop 8505 detects the 800 Hz second harmonic of the 400 Hz Signal Source 8501 Phase Locked Loop 8505 turns on Flame Good Indicator 8506 to signify that a flame is present. Since the 400 Hz Signal Source 8501 does not contain the 800 Hz second harmonic signal, the 800 Hz second harmonic can only be present due to flame rectification which is caused by a flame.

**[158]** In the second embodiment flame rectification causes **distortion of a signal source having a selected waveform**, producing a second harmonic that does not otherwise exist in the selected waveform. In this specific example the selected harmonic is the second harmonic but other harmonics may be selected. The selected harmonic is detected by using a **simple synchronous detector**.

The system is shown in Figure 86. Crystal Oscillator and Divider 8601 (shown in more detail in Figure 60) produces two clocks. The first clock is used to produce Signal Source, Selected Waveform 8602 at 390.63 Hz. The second clock is a Reference Signal 8610 at exactly twice the frequency (781.26 Hz) of Signal Source 8602. Signal Source 8602 produces a 390.63 Hz Selected Waveform that is selected to not contain even harmonics. Examples of selected waveforms that do not contain even harmonics include low distortion sine waves and symmetrical square waves.

Signal Source 8602 is applied through Source Resistor 8603 to Flame Rod 3. Flame Rod 3 is also connected to the input of High Impedance Buffer 8604 (shown in more detail in Figure 47). The output of High Impedance Buffer 8604 is connected to a first input of Multiplier/DC Filter 8605 (shown in more detail in Figure 64). A second input of Multiplier/DC Filter 8605 is connected to the output of Phase Delay 8609 which produces a phase delayed version (8611) of Reference Signal 8610. Phase Delay 8609 is shown in more detail in Figure 62) In some systems the Reference Signal 8610 can be used directly without a Phase Delay 8611.

The output of Multiplier/DC Filter 8605 is connected to the input of Threshold Detector 8606 (The details of Threshold Detector 8606 are shown in Figure 67 and in some implementations may omit

Absolute Value Amp 65.) Threshold Detector 8606 applies a threshold test and, when the voltage is above a selected threshold, turns on Flame Good Indicator 8607 to signify that a flame is present. (Flame Good Indicator 8607 is shown in Figure 66 as LED 6601). Since the 390.63 Hz Signal Source 8602 does not contain the 781.25 Hz second harmonic signal, the 781.25 Hz second harmonic can only be present due to flame rectification which is caused by a flame.

**[159]** In the third embodiment flame rectification causes **distortion of a signal having a selected waveform**, producing a selected harmonic that does not otherwise exist in the selected waveform. In this specific example the selected harmonic is the second harmonic but other harmonics may be selected. The selected harmonic is detected by using a **quadrature synchronous detector**.

The system is shown in Figure 87. Crystal Oscillator and Divider 8701 (shown in more detail in Figure 60) produces three clocks. The first clock is used to produce Signal Source, Selected Waveform 8702 at 390.63 Hz. The second clock is a first Reference Signal (8713) at exactly twice the frequency (781.26 Hz) of Signal Source 8702. The third clock is used to produce a second Reference Signal (8714) through 90 Degree Shifter 8712 that is also exactly twice the frequency (781.26 Hz) of Signal Source 8702 but is substantially 90 degrees out of phase with the first Reference Signal (8713).

Signal Source 8702 produces a 390.63 Hz Selected Waveform that is selected to not contain even harmonics. Examples of selected waveforms that do not contain even harmonics include low distortion sine waves and symmetrical square waves. Signal Source 8702 is applied through Source Resistor 8703 to Flame Rod 3. Flame Rod 3 is also connected to the input of High Impedance Buffer 8704 (shown in more detail in Figure 47). The output of High Impedance Buffer 8704 is connected to a first input of Multiplier/DC Filter 8705 (shown in more detail in Figure 64). The output of High Impedance Buffer 8704 is also connected to a first input of Multiplier/DC Filter 8707. A second input of Multiplier/DC Filter 8705 is connected to the first Reference Signal (8713) from Oscillator and Divider 8701. A second input of Multiplier/DC Filter 8707 is connected to the second Reference Signal (8714) from 90 Degree Shifter 8712.

The output of Multiplier/DC Filter 8705 is connected to the input of Absolute Value Amp 8706 which produces the absolute value of its input. (Absolute Value Amp 8706 is shown in more detail in Figure 65.) The output of Multiplier/DC Filter 8707 is connected to the input of Absolute Value Amp 8708. The output of Absolute Value Amp 8706 is connected to a first input of Adder 8709. The output of Absolute Value Amp 8708 is connected to a second input of Adder 8709 which sums the inputs from Absolute Value Amp 8706 and Absolute Value Amp 8708. The output of Adder 8709 is connected to the input of Threshold Detector 8710. (The details of Threshold Detector 8710 are shown in Figure 66.) Threshold Detector 8710 applies a threshold test and, when the voltage is above a selected threshold, turns on Flame Good Indicator 8711 to signify that a flame is present. (Flame Good Indicator 8711 is shown in Figure 66 as LED 6601). Since the 390.63 Hz Signal Source 8702 does not contain the 781.25 Hz second harmonic signal, the 781.25 Hz second harmonic can only be present due to flame rectification which is caused by a flame.

**[160]** In the fourth embodiment flame rectification is used as a **mixer to cause two signals having selected waveforms to produce sum and difference signals.** The sum and/or difference frequencies may be detected by a detector comprising a **phase locked loop**.

The system is shown in Figure 88. Clock Generator 8801 produces two signal sources, Signal Source 1 at 874 Hz and Signal Source 2 at 1,262 Hz. Although Signal Source 1 and Signal Source 2 can be produced by a variety of means (such as by two free-running oscillators) here they are produced by a crystal oscillator and a clock chain shown in more detail in Figures 72, 73, and 74.

Signal Source 1 and Signal Source 2 are summed in Adder 8802 to produce Source Sum Out 8808. Source Sum Out 8808 is applied through Source Resistor 8803 to Flame Rod 3. Flame Rod 3 is also connected to the input of High Impedance Buffer 8804 (shown in more detail in Figure 47).

The output of High Impedance Buffer 8804 is connected to the input of the 388 Hz Bandpass Filter 8805 (Figure 77). As is shown in Figure 77 the 388 Hz Bandpass Filter 8805 is made by cascading two 388 Hz Bandpass Filters, each of which is shown in more detail in Figure 76. In some instances a single 388 Hz Bandpass Filter (Figure 76) may be used. In some instances no filter may be needed at all. The output of 388 Hz Bandpass Filter 8805 is connected to the input of Phase Locked Loop 8806 (shown in more detail in Figure 78). The output of Phase Locked Loop 8806 is connected to Flame Good Indicator 8807 (shown in Figure 78 as LED 7801). When Phase Locked Loop 8806 detects the 388 Hz Difference Frequency between Signal Source 1 and Signal Source 2 Phase Locked Loop 8806 turns on Flame Good Indicator 8807 to signify that a flame is present. Since the 388 Hz Difference Frequency is produced only by flame rectification and the presence of the 388 Hz signal proves that a flame is present.

**[161]** In the fifth embodiment flame rectification is used as a **mixer to cause two signals having selected waveforms to produce sum and difference signals**. The sum and/or difference frequencies are detected using a **simple synchronous detector**.

The system is shown in Figure 89. Clock Generator 8901 produces three signals: Signal Source 1 at 874 Hz, Signal Source 2 at 1,262 Hz and a Reference Signal Clock8 at 388 Hz. Reference Signal Clock8 is a reference that is exactly the same frequency as the difference between Signal Source 1 and Signal Source 2. Reference Signal Clock8 goes to Phase Delay 8908 to produce Reference Signal Clock8D (8909) which is a phase delayed version of Reference Signal Clock8. The purpose in producing a phase delayed version of Reference Signal Clock8 is because some flame systems may introduce a phase delay due to parasitic capacitance and the high input impedance of High Impedance Buffer 8903. In a system that does not produce such a phase delay, Phase Delay 8908 may be omitted and Reference Signal Clock8 may be used directly instead of Reference Signal Clock8D (8909). (Clock Generator 8901 is shown in more detail in Figure 72, Figure 73, and Figure 74.)

Signal Source 1 and Signal Source 2 are summed in Adder 8907 to produce Source Sum Out 8910. Source Sum Out 8910 is applied through Source Resistor 8902 to Flame Rod 3. Flame Rod 3 is also connected to the input of High Impedance Buffer 8903 (shown in more detail in Figure 47).

The output of High Impedance Buffer 8903 is connected to a first input of Multiplier/DC Filter 8904 (shown in more detail in Figure 64). A second input of Multiplier/DC Filter 8904 is connected to Reference Signal Clock8D 8909 (if Phase Delay 8908 is used) or Reference Signal Clock8 (if a phase delay is not needed). The output of Multiplier/DC Filter 8904 is connected to the input of Threshold Detector 8905 (The details of Threshold Detector 8905 are shown in Figure 67 and in some implementations may omit Absolute Value Amp 65.) Threshold Detector 8905 applies a threshold test and, when the voltage is above a selected threshold, turns on Flame Good Indicator 8906 to signify that a flame is present. (Flame Good Indicator 8906 is shown in Figure 66 as LED 6601). Since the 388 Hz Difference Signal is only produced when Signal Source 1 and Signal 2 are mixed by flame rectification the 388 Hz Difference Signal can only be caused by a flame.

**[162]** In the sixth preferred embodiment flame rectification is used as a **mixer to cause two signals having selected waveforms to produce sum and difference signals**. The sum and/or difference frequencies are detected using a **quadrature synchronous detector**.

The system is shown in Figure 90. Clock Generator 9001 produces four signals: Signal Source 1 at 874 Hz, Signal Source 2 at 1,262 Hz, Reference Signal 1 (9012) at 388 Hz which is exactly the same frequency as the difference between Signal Source 1 and Signal Source 2, and a Reference Signal 2 (9013) which is at the same frequency as Reference Signal 1 but has a phase delay of approximately 90 degrees. The details of Clock Generator 9001 are shown in Figures 72, 73, and 74.

Signal Source 1 and Signal Source 2 are summed in Adder 9014 to produce Source Sum Out 9011. Source Sum Out 9011 is applied through Source Resistor 9002 to Flame Rod 3. Flame Rod 3 is also connected to the input of High Impedance Buffer 9003 (shown in more detail in Figure 47).

The output of High Impedance Buffer 9003 is connected to a first input of Multiplier/DC Filter 9004 (shown in more detail in Figure 64) and also to a first input of Multiplier/DC Filter 9006. A second input of Multiplier/DC Filter 9004 is connected to Reference Signal Clock8 (9012). A second input of Multiplier/DC Filter 9006 is connected to Reference Signal Clock8Q (9013) which is approximately 90 degrees out of phase with Reference Signal Clock8 (9012). The output of Multiplier/DC Filter 9004 is connected to the input of Absolute Value Amp 9005 which produces the absolute value of its input. The output of Multiplier/DC Filter 9006 is connected to the input of Absolute Value Amp 9007 which produces the absolute value of its input. The output of Absolute Value Amp 9005 is connected to a first input of Adder 9008. The output of Absolute Value Amp 9007 is connected to a second input of Adder 9008. Adder 9008 sums the two inputs and provides the sum to Threshold Detector 9009. (The details of Threshold Detector 9009 are shown in Figure 66.) Threshold Detector 9009 applies a threshold test and, when the voltage is above a selected threshold, turns on Flame Good Indicator 9010 to signify that a flame is present. (Flame Good Indicator 9010 is shown in Figure 66 as LED 6601). Since the 388 Hz Difference Signal is only produced when Signal Source 1 and Signal 2 are mixed by flame rectification the 388 Hz Difference Signal can only be caused by a flame. The use of quadrature synchronous detection thus described makes any phase delays in the flame system irrelevant.

**[163]** While preferred embodiments of the present invention have been shown, it is to be expressly understood that modifications and changes may be made thereto.

## ABSTRACT OF THE DISCLOSURE

This invention relates to the field of sensing flames in equipment using a combustion burner such as gas furnaces by using the electrical properties of flames. In a first group of embodiments flame rectification is used to cause distortion of a signal having a selected waveform. A harmonic of the distorted waveform is detected thereby providing flame proof. In a second group of embodiments flame rectification is used as a mixer to cause two signals having selected waveforms to produce sum and difference signals. The sum and/or difference signals are detected thereby providing flame proof.

**Claims**

I claim:

1. A system for detecting the presence of a flame comprising:

   a. a combustion burner;

   b. a flame rod;

   c. a signal source having a selected waveform connected to said flame rod;

   d. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

   e. a harmonic signal detector having an input connected to the output of said high impedance buffer;

   f. an indicator connected to the output of said harmonic signal detector;

whereas

   g. said flame from said combustion burner causes harmonic distortion of said signal source having a selected waveform producing a harmonic signal, and

   h. said harmonic signal detector is configured to detect said harmonic signal and indicate the results on said indicator.

2. The system of claim 1 whereby said signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

3. The system of claim 1 whereby said harmonic signal detector comprises a phase locked loop tuned to the frequency of said harmonic signal.

4. The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform and a reference signal having the same frequency as said harmonic signal, and said harmonic signal detector comprises a simple synchronous detector comprising:

   a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

   b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

5. The system of claim 1 further comprising a master clock configured to produce said signal having a selected waveform, a first reference signal having the same frequency as said harmonic signal, and a second reference signal having the same frequency as said first reference signal but is

approximately 90 degrees out of phase with said first reference signal, and said harmonic signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

6. A system for detecting the presence of a flame comprising:

a. a combustion burner;

b. a flame rod;

c. a first signal source having a selected waveform connected to said flame rod;

d. a second signal source having a selected waveform connected to said flame rod;

e. a high impedance buffer having an input connected to said flame rod and whose return current path is provided by said combustion burner through said flame;

f. a signal detector having an input connected to the output of said high impedance buffer;

g. an indicator connected to the output of said signal detector;

whereas

h. said flame from said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a first mixing signal at the sum of the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform as well as a second mixing signal at the difference between the frequencies of said first signal source having a selected waveform and said second signal source having a selected waveform, and

i. said signal detector is configured to detect said first mixing signal or said second mixing signal and indicate the results on said indicator.

7. The system of claim 6 whereby said signal detector comprises a phase locked loop tuned to said first mixing frequency or to said second mixing frequency.

8. The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, and a reference signal having the same frequency as said first mixing signal or said second mixing signal, and said signal detector comprises a simple synchronous detector comprising:

a. a multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said reference signal;

b. a threshold detector having an input connected to the output of said multiplier, and which is configured to produce an output when a selected threshold is exceeded.

9. The system of claim 6 further comprising a master clock configured to produce said first signal having a selected waveform, said second signal having a selected waveform, a first reference signal having the same frequency as said first mixing signal or said second mixing signal, and a second reference signal having the same frequency as said first reference signal but is approximately 90 degrees out of phase with said first reference signal, and said signal detector comprises a quadrature synchronous detector comprising:

a. a first multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said first reference signal;

b. a second multiplier having a first input connected to the output of said high impedance buffer and a second input connected to said second reference signal;

c. a first absolute value amp having an input connected to the output of said first multiplier;

d. a second absolute value amp having an input connected to the output of said second multiplier;

e. an adder having a first input connected to the output of said first absolute value amp and a second input connected to the output of said second absolute value amp;

f. a threshold detector having an input connected to the output of said adder and which is configured to produce an output when the value of the signal level exceeds a selected level.

10. The system of claim 6 whereby said first signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

11. The system of claim 6 whereby said second signal source having a selected waveform is selected from a group consisting of an approximately symmetrical square wave and a low distortion sine wave.

12. A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a signal source having a selected waveform introduced to said flame rod;
d. providing a high impedance buffer to buffer a flame rod signal from said flame rod;
e. providing a harmonic signal detector to receive the output of said high impedance buffer;
f. providing an indicator to receive the output of said harmonic signal detector;

whereas

g. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said signal source having a selected waveform to produce harmonics of the fundamental frequency of said selected waveform,
h. said harmonic signal detector is used to detect the presence of at least one of said harmonics of said selected waveform and indicate the presence of said at least one of said harmonics of said selected waveform on said indicator, and
i. said presence of said at least one of said harmonics of said selected waveform is proof of the presence of said flame.

13. The method of claim 12 where said step of providing a harmonic signal detector comprises providing a phase locked loop.

14. The method of claim 12 where said step of providing a harmonic signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

15. A method for detecting the presence of a flame comprising the steps of:

a. providing a combustion burner;
b. providing a flame rod;
c. providing a first signal source having a selected waveform introduced to said flame rod;
d. providing a second signal source having a selected waveform introduced to said flame rod;
e. providing a high impedance buffer to buffer a flame rod signal from said flame rod;
f. providing a signal detector to receive the output of said high impedance buffer;

g. providing an indicator to receive the output of said signal detector;

whereas

h. in the presence of a flame produced by said combustion burner flame rectification between said flame rod and said combustion burner causes said first signal source having a selected waveform and said second signal source having a selected waveform to mix producing a sum signal at the sum frequency of said first signal source and said second signal source and a difference signal at the difference frequency of said first signal source and said second signal source,

i. said signal detector is used to detect the presence of said sum signal or said difference signal and indicate the presence of said sum signal or said difference signal on said indicator, and

j. said presence of said sum signal or said difference signal is proof of the presence of said flame.

16. The method of claim 15 where said step of providing a signal detector comprises providing a phase locked loop.

17. The method of claim 15 where said step of providing a signal detector comprises providing a master clock and either a simple synchronous detector or a quadrature synchronous detector.

18. A method for detecting the presence of a flame comprising the steps of:

a. providing two signal sources to said flame;

b. using flame rectification to cause said two signal sources to mix;

c. providing a signal detector to detect a mixing signal produced by said two signal sources; and

d. providing an indicator to indicate the results of said signal detector.

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# Prediction and Measurement of Electron Density and Collision Frequency in a Weakly Ionised Pine Fire

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**Abstract** Pine litter flame is a weakly ionised medium. Electron-neutral collisions are a dominant form of particle interaction in the flame. Assuming flame electrons to be in thermal equilibrium with neutrals and average electron-neutral collision frequency to be much higher than the plasma frequency, the propagation of microwaves through the flame is predicted to suffer signal intensity loss. A controlled fire burner was constructed where various natural vegetation species could be used as fuel. The burner was equipped with thermocouples and used as a cavity for microwaves with a laboratory quality network analyzer to measure wave attenuation. Electron density and collision frequency were then calculated from the measured attenuation. The parameters are important for numerical prediction of electromagnetic wave propagation in wildfire environments. A controlled pine litter fire with a maximum flame temperature of 1080 K was set in the burner and microwaves (8–10.5 GHz) were caused to propagate through the flame. A microwave signal loss of 1.6–5.8 dB was measured within the frequency range. Based on the measured attenuation, electron density and electron-neutral collision frequency in pine fire were calculated to range from $0.51–1.35\times10^{16}$ $m^{-3}$ and $3.43–5.97\times10^{10}$ $s^{-1}$ respectively.

**Keywords** Wildfire · Microwave attenuation · Weakly ionised gas · Chemi-ionisation · Thermal ionization

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## 1 Introduction

The absorption of energy by electrons in the flame may results in a considerable signal intensity loss for microwaves propagating it. When the weakly ionised flame medium is illuminated with electromagnetic energy, electrons are accelerated by the electric field of the incident waves. Assuming that interaction between electrons and neutrals is elastic, the neutrals gain little kinetic energy during collisions mainly because they are relatively massive. Electrons are scattered isotropically such that the average velocity after collision is zero. In this way energy is transferred from the microwaves to the flame.

Weakly ionised gases at atmospheric pressure can effectively absorb microwaves. The absorption rate is directly related to $N_e/\upsilon_{eff}$; where $N_e$ is electron density and $\upsilon_{eff}$ is momentum transfer collision frequency [1]. Several studies have taken advantage of the effect and determined ionisation and momentum transfer collision frequency in flames and hot vapours, e.g., Smith *et al.*, [11], Belcher *et al.*, [12], Shuler *et al.*, [13] and Sturgeon *et al.*, [14]. Belcher *et al.* [12] studied the absorption of centimetric waves in a 1.45 cm wide alkali seeded coal gas-air flame at 2200 K. From the absorption measurements, Belcher *et al.* [12] determined collision frequency and electron density to be $8.8\times10^{10}$ $s^{-1}$ and $2.0\times10^{17}$ $m^{-3}$ respectively. Smith *et al.*, [11] carried out a very similar experiment but with hydrogen-air flames at a temperature range of 1900–2000 K. Using electrodynamical theory, Smith *et al.*, [11] calculated electron density to range from 0.8–$1.5\times10^{17}$ $m^{-3}$ in the flames. Comparatively, clean unseeded flames contain lower ionisation than seeded flames. E.g., Adler, [15] conducted an experiment in which radio waves were caused to propagate through pure jet fuel flames at a temperature of 1920 K. Using propagation theory, [15] observed ionisation and collision frequency of $1.9\times10^{12}$ $m^{-3}$ and $6.5\times10^{8}$ $s^{-1}$ respectively. Shuler *et al.* [13] also performed a microwave propagation experiment on unseeded lean hydrogen-oxygen flames at adiabatic temperatures which ranged from 2400–3000 K. Electron density in the hydrogen-oxygen flames ranged from 2.5–$3\times10^{15}$ $m^{-3}$ and average momentum transfer collision frequency was determined to be $2.6\times10^{11}$ $s^{-1}$.

Based on studies by [1, 2, 11–14], microwave communication efficiency on wildfire grounds, where adiabatic flame temperatures could be up to 1900°C, may be impaired by the weakly ionised environment. Strong microwave attenuation is anticipated to occur at very hot regions of the fire [3, 4]. Active remote sensing devices such as radars at microwave frequencies are used to detect large scale fires. In very high intensity wildfires (90 $MWm^{-1}$) with electron densities up to $10^{18}$ $m^{-3}$, flame dielectric constants are low. This may significantly attenuate reflected radar signals.

Propagation test have been carried out in wildfire environments. In the experiments, signals were caused to propagate above fire. As consequence, no significant attenuation was observed. The experiment investigates microwave propagation at a very hot and weakly ionised region of a pine fire with emissive power of 62 $KWm^{-2}$. Signal attenuation was measured using a 2-port Vector Network Analyser (VNA). Flame electron density and electron-neutral collision frequency were then calculated from the s-parameter determined attenuation.

## 2 Ionisation In The Flame

Combustion of vegetation material is exothermic in nature. The very hot environment produced in the reaction zone thermally excites flame particles. The excited particles are then thermally ionised to produce electrons and ions on selective basis determined by temperature and ionization potential. Particles that appreciably thermally ionise in the flame are alkalis and graphitic carbon ($C_n$) owing to their low ionisation potential and work function of 4.34 and 4.35 eV respectively [5]. Thermal ionisation of flame species (P(g)) occurs by the following reaction equation:

$$P(g) \Leftrightarrow P^{+}(g) + e^{-} \tag{1}$$

Another possible mechanism by which significant ionization may occur in vegetation fuel flames is chemi-ionisation (e.g., in [6]). In the process, dissociation reactions provide part of the energy required for ionization since there are exothermic and the rest is from the flame. Exited methyl radical CH* is a known contributor to chemi-ionisation in flames eg. in Sorokin *et al.* [6]. CH radical reacts with oxygen atoms in the flame to produce $CHO^{+}$, a primary ion in hydrocarbon flames [7] and electrons according to the following reaction equation:

$$CH^{*} + O \Leftrightarrow CHO^{+} + e^{-} \tag{2}$$

## 3 Prediction of electron density and collision frequency

### 3.1 Estimation of electron density in the fire

During combustion, volatiles are released from the vegetation's organic matrix and drawn into the combustion zone of the fire by convective currents. Potassium species form a large fraction of ionisable particulates in the volatiles. Potassium compounds are first decomposed into respective atoms and the later species are ionized upon excitation. Potassium atoms also exist in the volatiles. The atoms result from radical or hydrogen reduction of potassium-charcoal (K-O-C) complex [18]. If only atoms of potassium are considered and temperature together with other physical properties of the fire are averaged over the whole burner volume, then the mass of potassium drawn into the flame with the volatiles per a unit time ($P_{mass}$) can be given by the relation;

$$P_{mass} = \frac{K_p . V_f}{V_v} \quad (kg) \tag{3}$$

where $K_p$ is percentage of potassium in vegetation on dry weight basis while $V_f$ and $V_v$ represent volatile flux and vertical velocity respectively. The number of potassium atoms ($\mu$) swept into a unit volume V in a unit time is

$$\mu = \frac{P_{mass} . A_v}{0.03903} \quad (atoms) \tag{4}$$

where $A_v = 6.02 \times 10^{23}$ (Avogadro number).

Flame electron density ($N_e$) can be estimated to be [19];

$$N_e = \left(K_1 N_p\right)^{1/2}\left[\left(1 + \frac{K_1}{4N_p}\right)^{1/2} - \left(\frac{K_1}{4N_p}\right)^{1/2}\right] \tag{5}$$

where $K_I$ is ionisation equilibrium constant and $N_p$ is the total number of ionised potassium particles given by;

$$N_p = 7.335 \times 10^{27}\ .\mu/T \quad \left(m^{-3}\right) \tag{6}$$

The ionisation equilibrium constant for ionisation ($K_I$) is given by Saha equation as;

$$K_I = \frac{2P_{m^+ int}}{P_{m\,int}} \left(\frac{2\pi\,.M_e kT}{h^2}\right)^{3/2} \exp\left(\frac{-(E_i)}{kT}\right) \tag{7}$$

where $P_{mint}$ and $P_{m^+ int}$ are internal partition function of particles; $E_i$, $M_e$, k and h are ionization energy, mass of an electron, Boltzmann and Plank constants respectively.

### *3.1.1 Typical calculation of electron density in a pine fire*

Consider a high efficiency pine needle fire (99% combustion efficiency). Also consider the needles to have average potassium content ($K_p$) of 1.0% of their dry weight. Vertical velocity and flux of volatiles from combustion pine needles could be taken as 5 $ms^{-1}$ and 0.1 $kgms^{-2}$ respectively as in Clark *et al.* [20]. If 5% percent of the inherent potassium species are ionisable atoms and are drawn together with other volatiles into the combustion zone at an average temperature of 1100 K, then the overall percentage of potassium at in the volatiles is 0.05%. Assuming that most of the potassium in the flame is that which is emitted as atoms from radical reduction of K-O-C complex then mass of potassium per unit volume per unit time ($P_{mass}$) as calculated from (3) is $1.0\times10^{-5}$ kg. The number of potassium atoms swept into the unit volume (μ) is calculated from Equation (4) as $1.542\times10^{20}$atoms. The partition function of potassium ion and atom at the temperature is 1 and 2 respectively. The mass of electron and ionisation potential of potassium are $9.1\times10^{-31}$ kg and 4.34 eV respectively. Plank and Boltzmann's constants are $6.64\times10^{-34}$ Js and $8.617\times10^{-5}$ $eVK^{-1}$. Substituting the parameters into (7) gives $K_I$. The value of $K_I$ is then used with the value of $N_p$ to calculate electron density according to (5). In this case, electron density is calculated to be $1.32\times10^{16}$ $m^{-3}$.

### 3.2 Estimation of flame electron-neutral collision frequency

The momentum transfer collision frequency (υ) of the fire plume could be estimated from the expression [12]:

$$\upsilon = P.d^2.\left\{\frac{\pi}{2.k.M_e T}\right\}^{1/2} \tag{8}$$

where P and d are pressure and air molecule diameter respectively. Other parameters are as defined earlier. Diameter of air molecules varies from 0.2–0.3 nm. Using Equation (8) for a fire which is at atmospheric pressure, flame collision frequency is estimated to range from $4.26–9.59\times10^{10}$ $s^{-1}$.

## 4 Flame propagation constant

Propagation constant (γ) of a dielectric medium such as the weakly ionised flame is given by the following relation:

$$\gamma = \alpha_f + i\beta_f \tag{9}$$

where $\alpha_f$ and $\beta_f$ are attenuation and phase constants. When x-band microwaves illuminate weakly ionised, highly collisional atmospheric pressure flame plasma, $\alpha_f$ and $\beta_f$ are related to electron-neutral collision frequency ($\varphi_{eff}$) and ionisation by the expressions:

$$\alpha_f \cong \frac{\varphi_{eff}}{2c}\left[\frac{\omega_p^2}{\left(\omega^2+\varphi_{eff}^2\right)}\right] \tag{10}$$

and

$$\beta_f \cong \frac{\omega}{c}\left[1+\frac{\omega_p^4}{8\left(\omega^2+\varphi_{eff}^2\right)^2}\frac{\varphi_{eff}^2}{\omega^2}\right] \tag{11}$$

where $\omega$ and c are propagation cyclic frequency and speed of light in vacuum respectively.

## 5 Experimental set up

### 5.1 VNA system and combustion fuel

The equipment used to measure the microwave absorption by the flames consists of a hexagonally shaped burner with an insulated wooden casing, a Hewlett-Packard 8577 C VNA with x-band horns and a computer. To the inside of the burner, a thick (8 cm wide) thermally insulating material known as Fiberflex® was used to protect wood from the fire and heat. The material was lined to form a combustion area that is circular in base cross section. Two vent holes of 25 mm diameter were drilled on each of the sides, except the ones with horn inlets, to allow air to enter and mix with fuel during combustion. Two holes of horn dimensions were also cut out from the burner casing directly opposite to each other and wooden supports were provided to secure the horns firmly to the wooden casing. The internal diameter of the burner was lined up with Fiberflex® was set to 50 cm. Adding to or slightly reducing the insulating material varied the propagation path length. Two x-band transmit-receive horns were used in the experiment. They were connected to VNA through the two-port s-parameter test set by coaxial cables. High quality mode transition adapters were used to make the connections between coaxial cables and the horns. The set up is shown in Fig. 1.

A pine litter of bulk density of 4.92 $kgm^{-3}$ was collected ten (10) days before the experiment and left to dry in a laboratory to maximise combustion efficiency during burning.

### 5.2 Flame temperature measurement

A thermocouple tree of about 1.25 m high was constructed from a steel pipe of diameter 0.025 m. Side "arms" of length 0.4 m were attached at every 0.25 m of tree's height to hold at least four thermocouples. The thermocouples used were cut from a 100 m double braided fiberglass insulated chromel-alumel (24-G/G) thermocouple wire 50 μm in diameter. The thermocouple wire had fibre glass shield which can withstand temperatures up to 450°C. The type K thermocouple wires were then electro-fused at one end to make perfect junction and then tested with a hot air gun and a multimeter. The thermocouples were then fixed to tree "arms" by means of a muffler tape and the electro-fused junctions were left protruded 1 cm beyond the "arm" length into the flame. The thermocouples were then wired to PICO® Tech TC-O8 data logger to read in the temperatures in to a computer throughout each experiment.

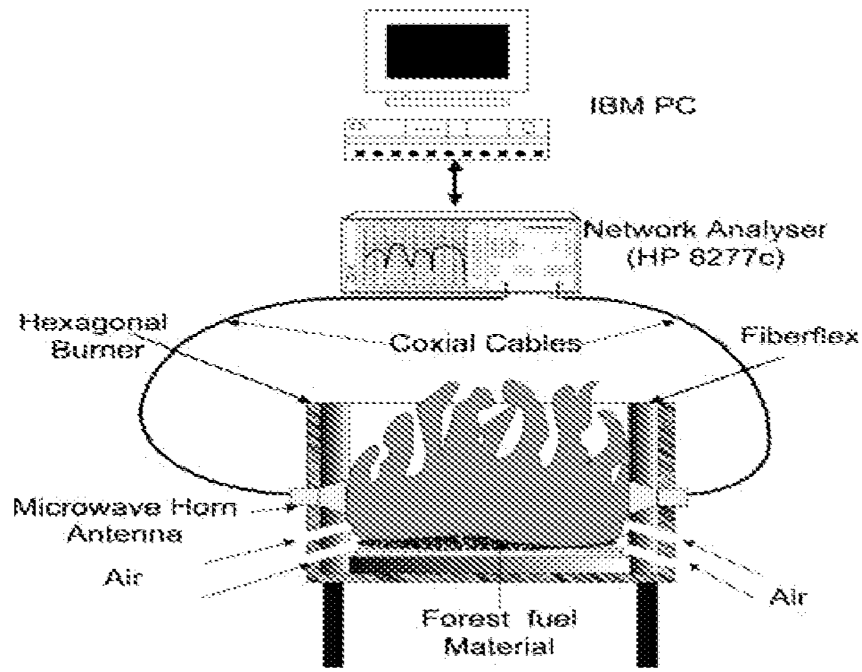



**Fig. 1** VNA set up for $S_{21}$ and $S_{11}$ parameter measurements.

### 5.3 S-parameter measurements

The 8577C VNA set is designed to sweep from 50 MHz to 40 GHz and logging in 601 s-parameter data points in each and every sweep. The data can then be uploaded and analysed by the computer. The analyzer takes 2 s to sample over one sweep, and then there is a latency of about 50 s before the next sweep can be initiated. Before the VNA was used it was calibrated first. The calibration method used in the experiment was the Transmit-Reflect-Line (TRL). Varadan *et al.* [8] give a full account of calibrating a network analyser using TRL method. However, for the experiment, the frequency range of interest was between 8 and 10.5 GHz. Several sweeps and logging of s-parameters were carried, but those for which flames filled the entire internal hollow space of the burner were chosen for s-parameter analysis. The selected logged in s-parameters were those at AS1, AS2, AS3 and AS4, which corresponded to the times 72, 135, 217 and 274 s since ignition.

### 5.4 Determination of propagation constant from s-parameter

The VNA measures the scattering parameters (s-parameters) from which the propagation constant can be calculated. From the s-parameters analysis, propagation constant is related to the propagation factor (T) by the relation:

$$\gamma = [\ln(1/T)]/d \tag{12}$$

where d is the length of the path traversed by the electromagnetic beam through the flame. S-parameters ($S_{11}$ and $S_{21}$) determined from the VNA are then used to calculate propagation factor using the relation;

$$T = \left[\frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\,\Gamma}\right] \tag{13}$$

where Γ is reflection coefficient , which is given by the relation:

$$\Gamma = \Omega \pm \sqrt{\Omega^2 - 1} \tag{14}$$

where $\Omega = \left(\frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}\right)$. The sign in (14) is chosen so that $|\Gamma|<1$. With T determined from s-parameter using the network analyser, the propagation constant γ can be worked out from (12). Then $\alpha_f$ and $\beta_f$ are determined from (12) as they are real and the imaginary parts of propagation constant (γ).

## 5.5 Determination of collision frequency and electron density

The inverse of the real part of propagation constant determined from s-parameters is used graphically to determine collision frequency and electron density of the pine flame between the times AS1 and AS4 since ignition.

### *5.5.1 Collision frequency*

Inverting equation (10) gives;

$$\frac{1}{\alpha_f} = \frac{\varsigma\left(\omega^2 + \varphi_{\text{eff}}^2\right)}{\varphi_{\text{eff}}} \tag{15}$$

Where; $\varsigma = \frac{2c}{\omega_p^2}$; $\omega_p^2 = \left(\frac{Ne^2}{m\varepsilon_0}\right)$ and $\varepsilon_0$ are the plasma collision frequency and free space permittivity. A plot of $\frac{1}{\alpha_f}$ versus $\omega^2$ gives a linear function where $(\varsigma/\varphi_{\text{eff}})$ is the gradient (grad.) and $\varsigma\varphi_{\text{eff}}$ is the ordinate (ord.) at zero abscissa of the graph. Electron-neutral collision frequency $(\varphi_{\text{eff}})$ is calculated from grad. and ord. as:

$$\varphi_{\text{eff}} = \left(\frac{\text{ord.}}{\text{grad.}}\right)^{1/2} \tag{16}$$

### *5.5.2 Electron density*

Electron density in the flame is calculated from the relation:

$$N = \left(\frac{2cm\,.\varepsilon_0}{q_e^2}\right)\frac{1}{\sqrt{\text{grad.} \times \text{ord.}}} \tag{17}$$

# 6 Experimental results and discussions

## 6.1 Flame temperatures

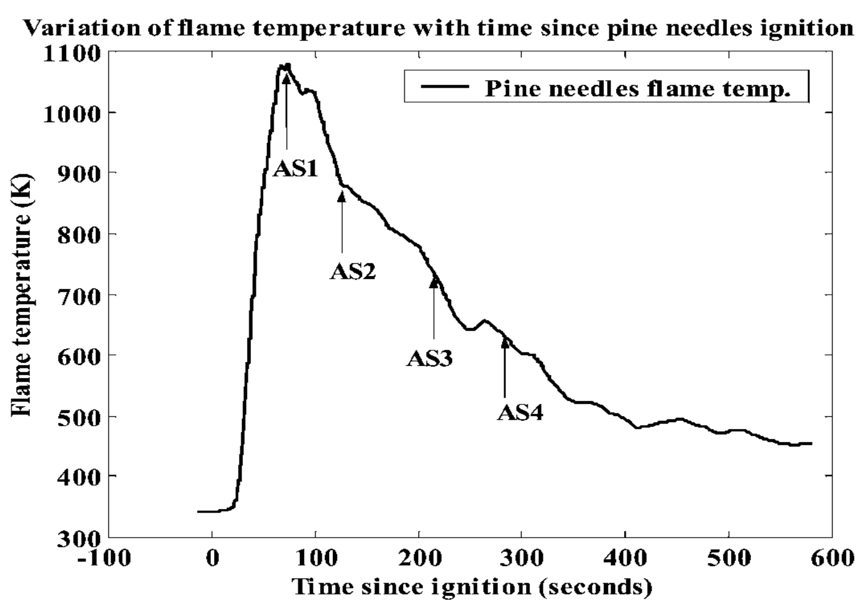
Flames up to 100 cm high were observed during the experiment as air entrained through the holes at the bottom of the hexagonal burner to facilitate continuous combustion. The flames due the combustion of pine litter took up to 6 mins to extinguish. It took 10 s for flames to fill the inner space of the burner. Fire plume temperatures at different height were logged in but those important for the experiment were those from pine litter surface. Pine litter surface temperatures during the experiment are shown in Fig. 2. The litter surface temperature rose rapidly to reach a maximum of 1081 K in 76 s. This was 4 s after the first set s-parameters (AS1) were logged in. At AS1, the temperature of the litter surface was 1075 K. After reaching the climax, the surface temperature dropped steeply, though not as quickly as it raised from ignition, to AS2, a second log in point where the pine litter flame filled the inner hollow of the burner. AS2 is at 135 s from ignition. At AS2, the pine litter surface temperature was observed to be 878 K.

Several s-parameter were logged in since AS2, but those selected for analysis were logged in at AS3 and AS4 corresponding to 217 and 274 s since ignition respectively. Surface temperature at AS3 and AS4 are 728 and 646 K respectively.

## 6.2 Microwave attenuation

Microwave propagation through the hottest part of the flames suffered a significant signal intensity loss. Before the fuel in the burner was set alight (no flame condition), VNA-burner system was checked for a systematic signal loss. An average systematic loss of the VNA-burner system was found to be 7.2 dB. Attenuation measurements at AS1 to AS3 for microwave frequencies (8–10.5 GHz) are shown in Fig. 3. The flame at AS1 was the most intense and it caused a signal loss of 5.68–3.70 dB for frequency range respectively. At AS2, 8–10 GHz microwaves incurred a signal loss of 3.17-1.94 dB respectively while the cooler flame at AS3 imposed signal intensity loss of 2.38-1.64 dB for the frequency range respectively. As it can be observed from Fig. 3, flame temperature plays a significant role in microwave absorption in the burner. A very hot flame imposes strong microwave absorption. High temperatures cause a significant ionization of incumbent flame particles. The effect could be amplified by the presence of alkali species in the flame, which is true for the combustion of vegetative matter. Plant matter contains up to 3.4% element potassium on dry weight basis. During combustion of plant matter, potassium species are released from a thermally crumbling plant structure and convectively drawn into the combustion zone of the fire. High temperature cause thermal dissociation of potassium

**Fig. 2** Pine litter surface fire temperature during the experiment.



species as they have low dissociation energies. Vodacek *et al.* [9] estimate that 10–20% of potassium in vegetation is ionized in fires. This makes vegetation fires a weakly ionized environment with the capability of causing significant microwave absorption at the most intense regions of the fire.

## 6.3 Electron density and collision frequency during flaming

At AS1, the gradient of the plot was $4.09\times10^{-22}$ (see Fig. 4) and the ordinate was observed to be $4.81\times10^{-1}$. The gradient and ordinate values gave electron density and collision frequency for the pine litter flame to be $1.35\times10^{16}$ m$^{-3}$ and $3.43\times10^{10}$ s$^{-1}$.

At AS2, the gradient and the ordinate for the pine litter flame was $7.25\times10^{-22}$ and $9.20\times10^{-1}$. The gradients and ordinate gave calculated electron density and collision frequency as $7.33\times10^{15}$ m$^{-3}$ and $3.56\times10^{10}$ s$^{-1}$. The gradient and ordinate for cooler flames at AS3 and AS4 gave electron density and collision frequency as: $5.41\times10^{15}$ m$^{-3}$ and $5.75\times10^{10}$ s$^{-1}$; and $5.13\times10^{15}$ m$^{-3}$ and $5.97\times10^{10}$ s$^{-1}$ respectively.

The general behaviour of electron density in the combustion of pine litter, thus from AS1 to AS4, was that it decayed exponentially with time from a near maximum to a low value of $5.13\times10^{15}$ m$^{-3}$(see Fig. 5). The measured data fitted exponential decay function of the first-order in the form: $N = N_0 + A\exp\left(\frac{-x}{t}\right)$, where No is near maximum electron concentration, A and × are flame dependent parameters. The variable t is time.

Electron-neutral collision frequency was observed to increase rapidly with the decrease in flame temperature (see Fig. 6). The influx of cool ambient air nitrogen dilutes combustion gas, which in effect increases neutral gas concentration in flame. This increases the rate of neutral collision with available electrons in the flame.

### *6.3.1 Errors in electron density and collision frequency estimation*

The electron density and collision frequency were determined by a graphical method. One of ways to determine the errors in the parameters is to use the gradient and ordinate values

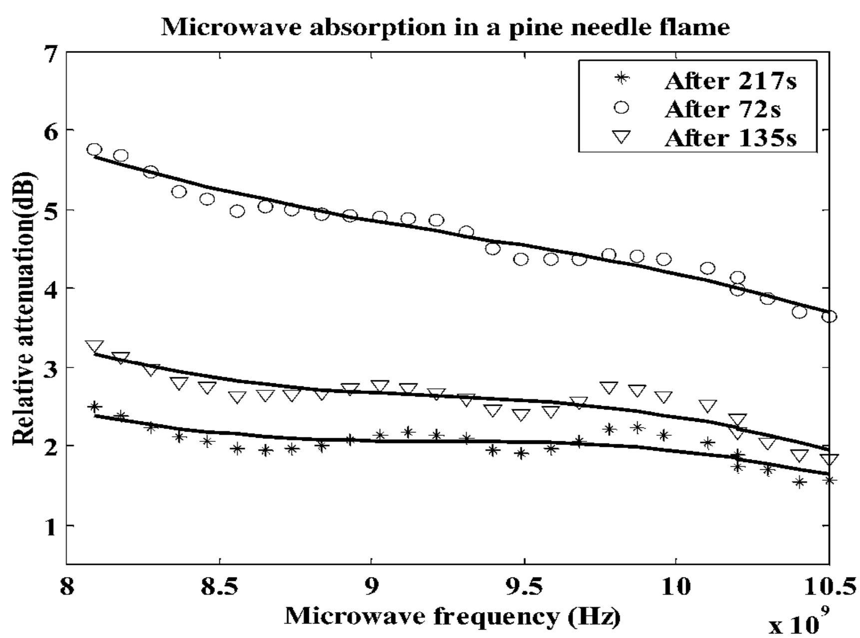



**Fig. 3** Variation of relative attenuation with propagation frequency.

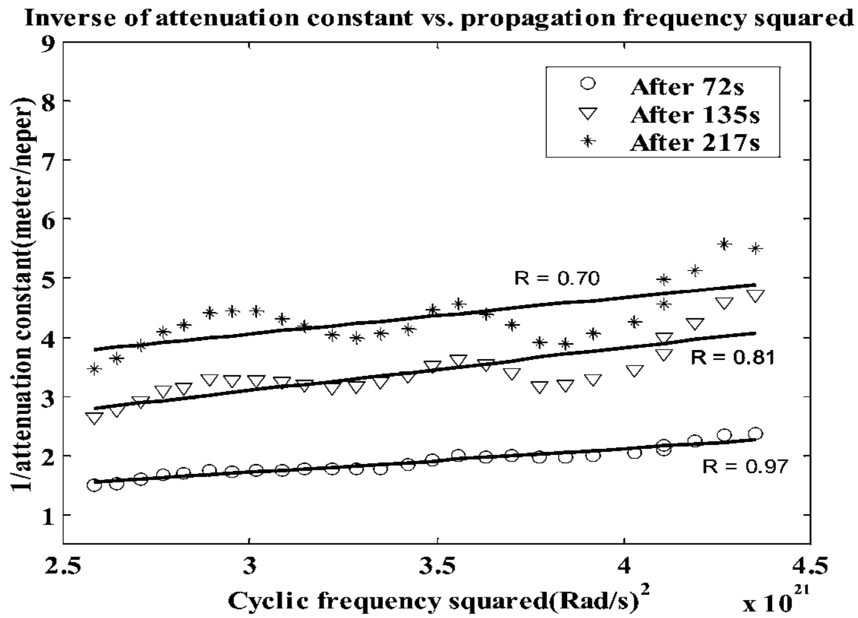



**Fig. 4** Variation of inverse of attenuation constant with propagation frequency squared.

and their associated errors e.g., in [21]. When using this method, error in the electron density ($\Delta$N) is given by the expression:

$$\Delta \mathrm{N} = \frac{\mathrm{N}}{2 \times \mathrm{grad} \times \mathrm{ord.}} \left\{ \frac{\Delta \mathrm{ord}}{\mathrm{ord}} + \frac{\Delta \mathrm{grad}}{\mathrm{grad}} \right\} \tag{18}$$

Similarly,

$$\Delta \varphi_{\mathrm{eff}} = \frac{\varphi_{\mathrm{eff}}}{2 \times \mathrm{grad} \times \mathrm{ord.}} \left\{ \frac{\Delta \mathrm{ord}}{\mathrm{ord}} + \frac{\Delta \mathrm{grad}}{\mathrm{grad}} \right\} \tag{19}$$

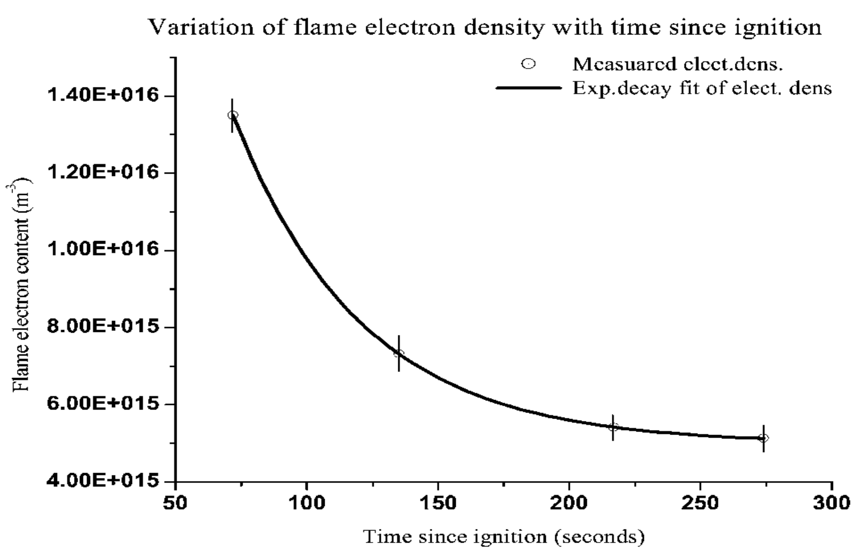
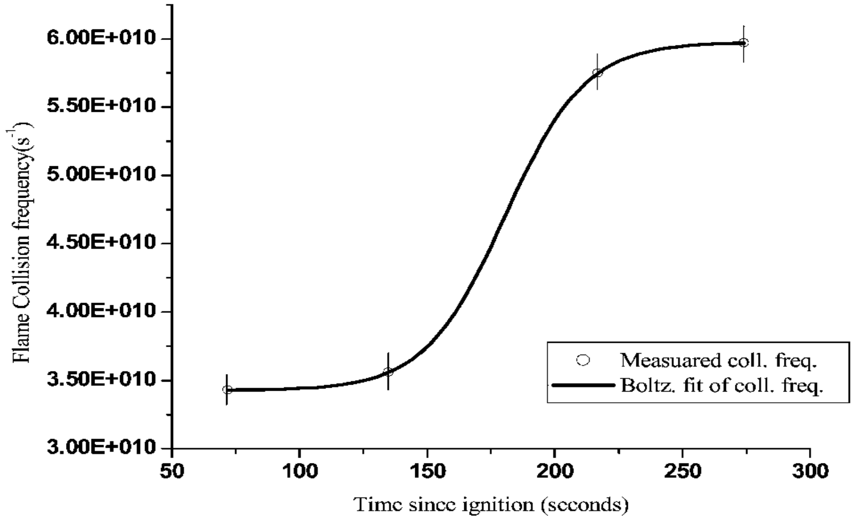



**Fig. 5** Variation of flame electron density with time since ignition.

**Fig. 6** Variation of flame collision frequency with time since ignition.




where Δgrad. is the difference between best and worst fits slopes and Δord. is the difference in the ordinate intercepts of the best and the worst fits. The errors are shown as error bars in Figs. 5 and 6. The errors for the time coordinates in figures are too small to show.

## 7 Conclusions

The electron density for the pine fire with maximum radiant heat up to about 62 $kWm^{-2}$ was in the range from $0.51–1.35\times10^{16}$ $m^{-3}$. The electron densities were lower than those produced from non vegetation fuel flames with much higher temperatures e.g. Belcher *et al.* [2] and Koretzky *et al.* [1]. Electron concentration in the flame depends on the type of fuel as well as its temperature because it is this combination that produces ionisable particles.

The collision frequency of the flames was in the range of $3.43–5.97\times10^{10}$ $s^{-1}$. The range is lower than electron-neutral collision frequency at normal air temperature. The collision frequency is directly related to the neutral gas density and medium temperature. At ambient air temperatures (288 K) electron-neutral collision frequency is about $2.3\times10^{12}$ $s^{-1}$(see e.g., in *[10]). In a constant air pressure environment, temperature influences number density of air *molecules. An increase in flame temperature results in a decrease in air density in the *combustion zone. It is for this reason that collision frequency has been observed to decrease *with the increase in fire temperature (see Fig. 6). For the pine litter fire, attenuation is however related in a complex way with both electron density and collision frequency, which are both related to electron content and flame temperature. From the experiment, 8–10.5 GHz microwaves experienced relative attenuation in the range 1.64–5.68 dB when propagating in a line-of-sight mode through flame.

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# CONDUCTION OF ELECTRICITY THROUGH GASES

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# CONDUCTION OF ELECTRICITY THROUGH GASES

BY

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SECOND EDITION

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# PREFACE.

I HAVE endeavoured in this work to develope the view that the conduction of electricity through gases is due to the presence in the gas of small particles charged with electricity, called ions, which under the influence of electric forces move from one part of the gas to another. My object has been to show how the various phenomena exhibited when electricity passes through gases can be coordinated by this conception rather than to attempt to give a complete account of the very numerous investigations which have been made on the electrical properties of gases; I have therefore confined myself for the most part to those phenomena which furnish results sufficiently precise to serve as a test of the truth of this theory. The book contains the subject-matter of lectures given at the Cavendish Laboratory where a good deal of attention has been paid to the subject and where a considerable number of physicists are working at it.

The study of the electrical properties of gases seems to offer the most promising field for investigating the Nature of Electricity and the Constitution of Matter, for thanks to the Kinetic Theory of Gases our conceptions of the processes other than electrical which occur in gases are much more vivid and definite than they are for liquids or solids; in consequence of this the subject has advanced very rapidly and I think it may now fairly be claimed that our knowledge of and insight into the processes going on when electricity passes through a gas is greater than it is in the case either of solids or liquids. The possession of a charge by the ions increases so much the ease with which they can be traced and their properties studied that, as the reader will see, we know far more about the ion than we do about the uncharged molecule.

With the discovery and study of Cathode rays, Röntgen rays and Radio-activity a new era has begun in Physics, in which the electrical properties of gases have played and will play a most important part; the bearing of these discoveries on the problems of the Constitution of Matter and the Nature of Electricity is in most intimate connection with the view we take of the processes which go on when electricity passes through a gas. I have endeavoured to show that the view taken in this volume is supported by a large amount of direct evidence and that it affords a direct and simple explanation of the electrical properties of gases.

The pressure of my other duties has caused this book to be a considerable time in passing through the press, and some important investigations have been published since the sheets relating to the subjects investigated were struck off. I have given a short account of these in a few Supplementary Notes.

My thanks are due to Mr C. T. R. Wilson, F.R.S., for the assistance he has given me by reading the proofs and I am indebted to Mr Hayles of the Cavendish Laboratory for the preparation of the diagrams.

J. J. THOMSON.

CAVENDISH LABORATORY, CAMBRIDGE.
*August*, 1903.

# PREFACE TO THE SECOND EDITION.

I HAVE made many additions to this edition and a considerable part of it has been rewritten, in the hope of introducing new material in a more logical and connected form than by merely adding new paragraphs to the old edition. This has increased the size of the book; on the other hand the publication, since the first edition of this book, of Rutherford's *Radio-activity* has enabled me to omit some matter fully treated by Rutherford. So many researches on Discharge through Gases have been made since the issue of the first edition that anything like a complete account of them is impossible within the space at my disposal. I have therefore limited myself to those which seemed most capable of testing the accuracy of the view of Electric Discharge advocated in this book.

The light which can be thrown by the study of the Electrical Phenomena occurring in Gases on many of the most interesting questions in Physics is now generally recognised, and the more the subject is studied the wider are seen to be its applications and the greater the opportunities for further research.

I take this opportunity of expressing the gratitude which all students of this subject must feel to the Société de Physique of Paris for the publication of the collection of original papers on Discharge through Gases in the volumes *Ions, Électrons, Corpuscles*, edited by MM. H. Abraham and P. Langevin.

J. J. THOMSON.

CAVENDISH LABORATORY, CAMBRIDGE.
*September*, 1906.

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# CHAPTER IX.

## IONISATION IN GASES FROM FLAMES.

**121.** It has been known for more than a century that gases from flames are conductors of electricity: a well-known application of this fact—the discharge of electricity from the surface of a non-conductor by passing a flame over it—was used by Volta in his experiments on Contact Electricity. We shall not attempt to give any historical account of the earlier experiments on this subject, because the conditions in these experiments were generally such that the interpretation of the results obtained is always exceedingly difficult and often ambiguous: the reason of this is very obvious—to investigate the electrical conditions of the flame wires are generally introduced, these become incandescent and so at once add to the electrical phenomena in the flame the very complicated effects we have been discussing in the last chapter.

The gases which come from the flame, even when they have got some distance away from it and have been cooled by the surrounding air, possess for some time considerable conductivity, and will discharge an insulated conductor placed within their reach. The conductivity can be entirely taken out of the gas by making it pass through a strong electric field, this field abstracts the ions from the gas, driving them against the electrodes so that when the gas emerges from the field, although its chemical composition is unaltered, its conducting power is gone. This result shows too that no uncharged radio-active substances, such as emanate from thorium and some other substances, are produced in the flame; these would not be taken out by the field, so that if they existed the conductivity of the gas would not be destroyed by the field. If not driven out of the gas by an electric field the ions are fairly long lived. Thus in some experiments Giese noticed that the gas retained appreciable conductivity 6 or 7 minutes after it had left the flame. The ions stick to any dust there may be in the air and then move very slowly so that their rate of recombination becomes exceedingly slow. McClelland* has shown that the velocity of the ions under a given electric force decreases very much as they recede from the flame; thus close to the flame the velocity under the force of a volt per centimetre was ·23 cm./sec., while some distance away from it the velocity was only ·04 cm./sec.

In order that a conductor should be discharged by a flame it is not necessary that it should be placed where the gases from the flame would naturally strike it—thus for example it will be discharged if placed underneath a Bunsen flame. The explanation of this is that the electric field due to the charged conductor drags out of the flame and up to the conductor ions of opposite sign to the charge.

This ionised gas is produced by flames of coal gas whether luminous or not, by the oxy-hydrogen flame, by the alcohol flame of a spirit lamp, by a flame of carbonic oxide; it is not however produced in very low temperature flames such as the pale lambent flame of ether. Thus to produce the ionised gas high temperature as well as chemical combination is required. That chemical combination alone is insufficient to produce ionisation is shown by the case of hydrogen and chlorine which do not conduct even when combining under ultra-violet light†. Braun‡ has shown that in the explosive wave produced in the combination of certain gases there is ionisation, but in this case there is also very high temperature.

In the coal-gas flame the part where the gas comes in contact with the air and where there is most combustion is positively electrified, while the interior of the flame is negatively electrified; this accounts for the effect produced by holding a negatively electrified body near the flame, the luminous part turns to the negative body, and if this is near, stretches out until it comes into contact with it; if the flame be placed between two

* McClelland, *Phil. Mag.* v. 46, p. 29, 1898.

† J. J. Thomson, *Proc. Camb. Phil. Soc.* xi. p. 90, 1901.

‡ Braun, *Zeitschrift für Physikalische Chemie*, xiii. p. 155, 1894.

oppositely charged plates the bright outer portion of the flame is attracted towards the negative plate while the inner portion moves, but less markedly, towards the positive plate. This effect is illustrated by Fig. 49 taken from a paper by Neureneuf*. In

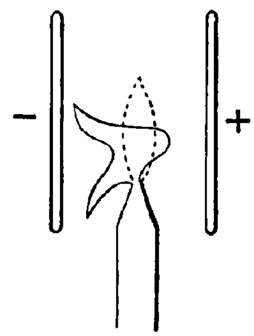



Fig. 49.

some experiments made by Holtz†, one of which is figured in Fig. 50, the flame was divided by the electric field between the

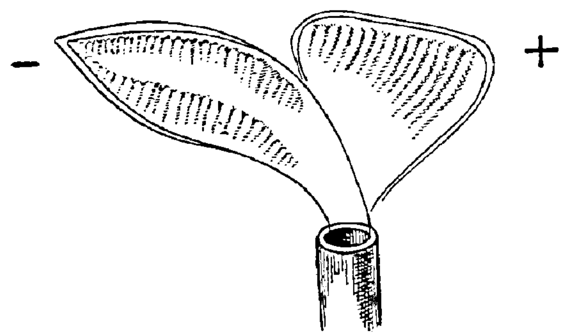



Fig 50.

plates into two sheets; the reader will find many other interesting experiments on the effect of an electric field on the shape of flames in the papers by Neureneuf and Holtz. It appears from these results that in the bright portion of the flame where combustion is taking place there is an excess of positive electricity, while in the unburnt coal gas there is an excess of negative, a fact discovered a long time ago by Pouillet‡. If the hydrogen and oxygen were ionised by the heat, then since negative ions of oxygen combine with positive ions of hydrogen to form water, the

* Neureneuf, *Annales de Chim. et de Phys.* v. 2, p. 473, 1874.

† Holtz, *Carl Répert.* xvii. p. 269, 1881.

‡ Pouillet, *Ann. de Chim. et de Phys.* xxxv. p. 410, 1827.

negative oxygen ions and the positive hydrogen ones would get used up, and there would be an excess of positive electricity in the oxygen and of negative in the hydrogen. It is possible too that at a temperature corresponding to that of vivid incandescence in a solid the molecules of a gas may like those of a solid give out the negative corpuscles, on this account there would be a tendency for the hotter parts of the flame to be positively, the colder negatively, electrified. When as in luminous flames we have small particles of solid carbon raised to the temperature of vivid incandescence the electrical effects are complicated by those due to incandescent solids which as we have seen in the last chapter are very considerable.

When two wires connected together through a sensitive galvanometer are placed in different parts of the flame currents flow through the galvanometer; suppose one of the wires is placed in the cool inner portion of the flame where there is an excess of negative electricity, while the other wire is placed at the outside of the flame where there is an excess of positive electricity, there will, neglecting any ionisation due to the wire, be a current from the hot outer portion of the flame to the cool inner portion through the galvanometer: the wire in the outer portion will however certainly be raised to incandescence, if its temperature keeps so low that only positive ions are produced at its surface, then there will on this account be a current of electricity from the hot to the cool part of the flame through the flame and thus in the opposite direction to the previous current. If however the wire got so hot that it emitted more negative than positive ions the effect of the incandescence of the wires would be to increase instead of diminishing the current due to the flame itself. Thus we see that these currents will vary in a complex way with the temperature. For an account of the currents which can thus be tapped from a flame and for other electrical properties of flames we must refer the reader to the papers of Erman*, Hankel†, Hittorf‡, Braun§, Herwig‖, and

* Erman, *Gilbert. Ann.* xi. p. 150, 1802; xxii. p. 14, 1806.

† Hankel, *Pogg. Ann.* lxxxi. p. 213, 1850; cviii. p. 146, 1859.

‡ Hittorf, *Pogg. Ann.* cxxxvi. p. 197, 1869; Jubelbd. p. 430, 1874.

§ Braun, *Pogg. Ann.* cliv. p. 481, 1875.

‖ Herwig, *Wied. Ann.* i. p. 516, 1877.

especially of Giese*, who was the first to suggest that the conduction of electricity through flames and hot gases was due to the motion of charged ions distributed through the gases: there is a very complete account of these researches in Wiedemann's *Elektricität*, Bd. IV. B, chap. 4.

*Conduction of electricity through flames.*

**122**. The passage of electricity through flames has been investigated by Arrhenius†, H. A. Wilson‡, Marx§, Starke||, Moreau¶, Stark**, Tufts††, and Tufts and Stark‡‡. The most important phenomena of flame conduction are as follows.

*Distribution of electric intensity between the electrodes.*

There is a very intense electric field close to the negative electrode and a weak uniform field between the electrodes, the field

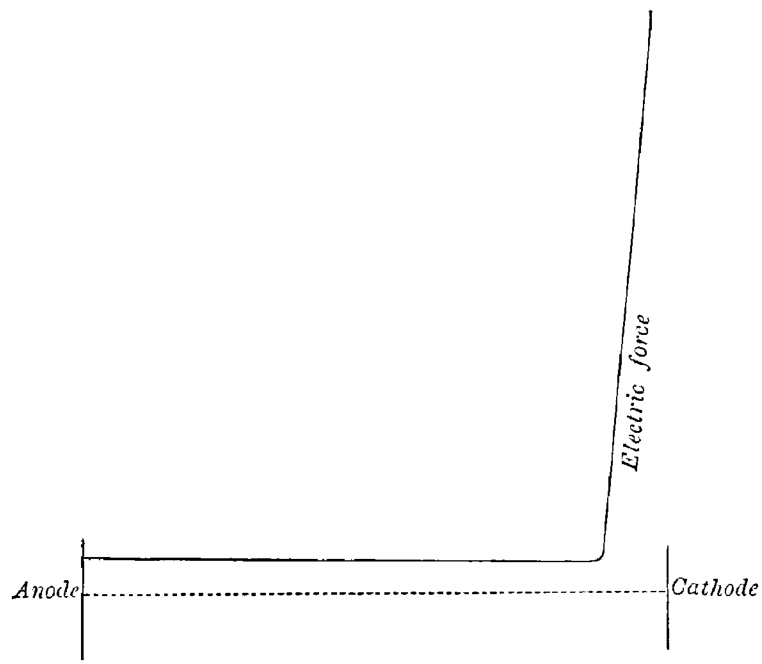



Fig. 51.

* Giese, *Wied. Ann.* xvii. pp. 1, 236, 519, 1882; xxxviii. p. 403, 1889.

† Arrhenius, *Wied. Ann.* xliii. 18, 1891.

‡ H. A. Wilson, *Phil. Trans.* A, 192, 499, 1899; *Proceedings Physical Society.*

§ Marx, *Ann. d. Phys.* ii. 768, 798, 1900; *Verh. d. D. Phys. Ges.* v. 441, 1903.

|| Starke, *Verh. d. D. Phys. Ges.* v. 364, 1903; vi. 33, 1904.

¶ Moreau, *Ann. de Chimie et de Physique*, vii. 30, p. 1, 1903.

** Stark, *Physik. Zeitschr.* v. 83, 1904.

†† Tufts, *Physik. Zeitschr.* v. 76, 1904.

‡‡ Tufts and Stark, *Physik. Zeitschr.* v. 248, 1904.

near the positive electrode although not nearly so intense as that close to the negative is stronger than that at some distance from either electrode. The distribution of electric intensity is of the type shown in Fig. 51.

Fig. 52 represents the distribution of electric potential measured by H. A. Wilson between electrodes 18 cm. apart in a long flame from a quartz tube burner. The difference of potential between the electrodes was 550 volts and it will be noticed that a drop of 450 volts occurs quite close to the cathode.

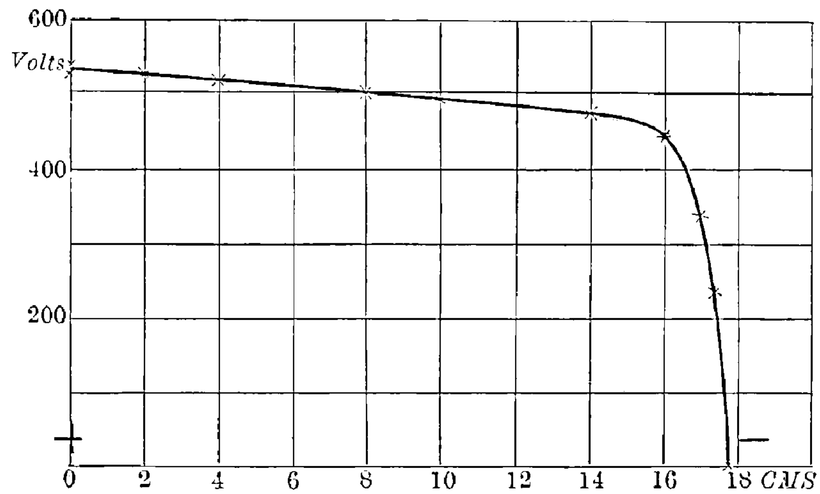



Fig. 52.

If $X$ is the electric intensity at a point $x$, $q$ the amount of ionisation per unit volume, $k_1$, $k_2$ the velocities of the positive and negative ions under unit force, $m$, $n$ the number of positive and negative ions per unit volume, we have by equation (7), p. 86,

$$\frac{d^2X^2}{dx^2} = 8\pi e(q - \alpha nm)\left(\frac{1}{k_1} + \frac{1}{k_2}\right).$$

Since $X$ is constant along the flame $\frac{d^2X^2}{dx^2}$ vanishes, hence

$$q = \alpha nm.$$

Thus the ionisation balances the recombination; as recombination of the ions is certainly taking place in the flame it follows that there must be ionisation throughout the flame. In the first edition of this book the view was taken that by far the greater part of the ionisation took place in the immediate neighbourhood of the glowing electrodes. Some of the results obtained by H. A. Wilson, especially the fact that even with large potential differences the current was almost independent of the distance between the electrodes, were readily explained on this view; while assuming that the large potential difference was able to saturate the current they were inconsistent with the existence of uniform ionisation throughout the flame, with such ionisation the saturation current would be proportional to the distance between the electrodes. It appears however from the preceding results that even when the potential difference is large the electric field is weak except close to the cathode, so that there is no approach to saturation throughout the flame. We investigated in Art. 48 the relation between the current and the potential difference when the velocity of the negative ion is very much greater than that of the positive; as this is the case in flames, we have by equation (7) of Art. 48

$$X^2 = \frac{\alpha i^2}{qe^2k_2^2} + \frac{\alpha i(i - i_0)}{qe^2k_1k_2} \epsilon^{-\frac{8\pi e^2 qk_2}{i\alpha}x} \quad \text{..............(1)},$$

where $i_0$ is the number of corpuscles coming from unit area of the incandescent cathode per second, $x$ is the distance from the cathode of the place where the electric intensity is $X$.

This equation represents a distribution of the electric intensity of the same kind as that found in flames, the first term on the right-hand side of the equation represents the uniform field, the second term the variable part near the cathode; since $k_1$, the velocity of the positive ion under unit force, is very small compared with $k_2$, the velocity of the negative ion, we see that unless $i_0$ is nearly equal to $i$ the electric force at the cathode when $x = 0$ will be large compared with that in the uniform part of the field.

If we compare this formula with the results of H. A. Wilson's* experiments we are led to the conclusion that so far from there being an excess of ionisation close to the cathode the ionisation is less there than in the body of the flame. Let us take as an example the case represented by the curve in Fig. 52. Here the electric force in the uniform part of the field was about 8 volts per cm., or, as the quantities in equation (1) are supposed to be expressed in electrostatic units, 8/300. The current between the

* H. A. Wilson, *Phil. Mag.* [6], 10, p. 476, 1905.

electrodes, which were discs 1 cm. in diameter, was $270 \times 8{\cdot}8 \times 10^{-9}$ amperes, so that the current per unit area in electrostatic units was $\frac{4}{\pi} \times 270 \times 8{\cdot}8 \times 3$. Thus we have

$$\frac{8}{300} = \left\{\frac{\alpha}{qe^2}\right\}^{\frac{1}{2}} \frac{1}{k_2} \frac{4}{\pi} 270 \times 8{\cdot}8 \times 3,$$

so that
$$\left(\frac{\alpha}{qe^2}\right)^{\frac{1}{2}} \frac{1}{k_2} = \frac{\pi}{4 \times 27 \times 10^4}$$

approximately.

The index of the exponential term is $\frac{8\pi e^2 q k_2}{i\alpha} x$; substituting the values of $i$ and $\alpha/qe^2$, we find that this is equal to $\frac{324 \times 10^6}{k_2} x$.

Now Wilson has shown that the velocity of the negative ion under a force of a volt per centimetre is about 1000 cm./sec.; $k_2$ is the velocity under unit electrostatic force, *i.e.* 300 volts per centimetre, *i.e.* $k_2$ is about $3 \times 10^5$. Substituting this value for $k_2$ we find that the exponential term is $\epsilon^{-1080x}$, with this value of the exponential term the field would become practically uniform at a distance not exceeding a very small fraction of a millimetre from the cathode. An inspection of Fig. 52 shows that the variable part of the field extends to quite 1 cm. from the cathode, a result quite inconsistent with its representation by the term $\epsilon^{-1080x}$. We have assumed that the $q$ occurring in the exponential term is equal to that in the constant term, if however the ionisation is variable from point to point this will not be the case, the $q$ occurring in the exponential term refers to the ionisation near the cathode, if this is less than the $q$ in the body of the flame the index of the exponential term will be less than the value we have calculated. Now the electrode will conduct heat from the flame and will therefore cool it. The process of ionisation is however analogous to the dissociation of a diatomic gas into atoms, and the expression for the amount of this dissociation contains a factor $e^{-\frac{a}{\theta}}$ where $\theta$ is the absolute temperature, so that this factor varies very rapidly with the temperature. Thus a comparatively slight cooling of the gas near the cathode would produce a great diminution in $q$, this diminution in $q$ would diminish the index in the exponential term in equation (1) and thus increase the thickness of the variable part of the electric field.

We have seen on page 97 that equation (1) leads to the following relation between $V$ the potential difference between the plates, $i$ the current through unit area and $l$ the distance between the electrodes:

$$V = \frac{il}{k_2}\left\{\frac{\alpha}{qe^2}\right\}^{\frac{1}{2}} + \frac{i\sqrt{i(i-i_0)}}{k_1^{\frac{1}{2}}k_2^{\frac{3}{2}}}\frac{1}{8\pi}\left(\frac{\alpha}{qe^2}\right)^{\frac{3}{2}} \quad \text{.........(2)}.$$

When $i_0$ is small compared with $i$, this equation becomes

$$V = \frac{il}{k_2}\left(\frac{\alpha}{qe^2}\right)^{\frac{1}{2}} + \frac{i^2}{8\pi k_1^{\frac{1}{2}}k_2^{\frac{3}{2}}}\left(\frac{\alpha}{qe^2}\right)^{\frac{3}{2}} \quad \text{..............(3)}.$$

The first term represents the fall of potential in the body of the flame, this is proportional to the current; the second term represents the drop of potential at the cathode, this is proportional to the square of the current. H. A. Wilson has shown that the relation between the potential difference and the current can be expressed with great accuracy by an equation of the type

$$V = Ai + Bi^2.$$

*Conductivity of Gases containing Salt Vapours.*

**123.** When the vapours of salts are introduced into a flame the conductivity between metallic terminals is very greatly increased, and the electrical properties are simpler and more regular than in pure flames; the laws of the flow of electricity through these salt-laden flames have been investigated by Arrhenius* and H. A. Wilson†. The method—devised by Arrhenius and adopted by Wilson—of introducing the salt into the flame was as follows: a dilute solution of the salt was sprayed into exceedingly fine drops by a Gouy sprayer, the spray got well mixed with the coal gas on its way to the burner, and in the flame the water evaporated and the salt vaporised. The amount of salt supplied to the flame in unit time was estimated by determining

* Arrhenius, *Wied. Ann.* xlii. p. 18, 1891.

† H. A. Wilson, *Phil. Trans.* A, 192, p. 499, 1899.

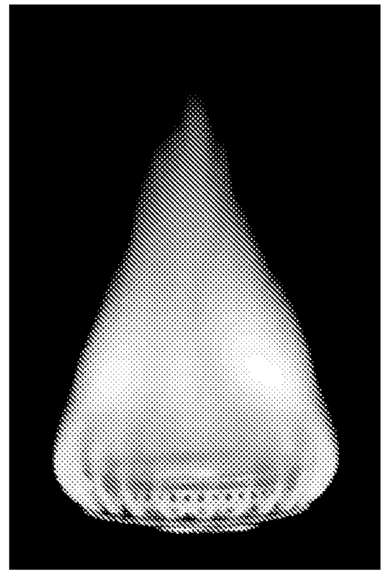
# Plasma and Flames – The Burning Question

***Do flames contain plasma?***

Phrased one way or another, this is a frequently asked question.

**The Short Answer:** Some do; some don't.

**The Medium Answer:** Whether a plasma exists in a flame depends on the material being burned and the temperature. The temperature in a flame varies greatly from one region to another. Depending on the material being burned, the temperature can range from a few hundred degrees Celcius in one region to thousands of degrees elsewhere. Furthermore, the nature of the burning material and the temperatures at different locations within a flame determine the kinds of atoms and molecules that are present.


A natural gas stovetop flame.

In a cool gas, the atoms are generally electrically neutral; each atom has a positively charged nucleus surrounded by a number of negatively charged electrons that exactly balance the positive charge. But if the gas temperature is high enough, particle collisions can remove some electrons from atoms, resulting in a mixture of freely moving electrons and the atoms from which they were stripped. Those atoms, which are left with an excess positive charge, are called "ions," and those particles as well as the gas are said to be "ionized." All regions of a flame will contain at least some charged particles and, therefore, will be ionized. The types of atoms and molecules present and their temperature determine how many of them become ionized. But does this ionization within the flame constitute a plasma?

A plasma is an ionized gas. However, not all ionized gases are plasmas. In order for an ionized region of a flame to be plasma, it must contain enough charged particles for that region to exhibit unique electrical properties of plasma, which are distinctly different from properties of other states of matter. This leads to . . .

**The Long Answer:** To be plasma, a region must contain enough negative and positive charged particles for them to interact with each other in groups, rather than individually as they do in very weakly-ionized gases. Effects that result from collections of charged particles interacting with each other are called "collective effects." Thus, the key criterion for an ionized gas to be a plasma is that there are enough charged particles to exhibit collective effects.

There are many kinds of collective effects. The most important one for defining a plasma is the generation of internal electric fields that oppose and cancel externally-applied fields. That is, plasmas can shield themselves from externally-applied electric fields.

Say there is a collection of positive and negative charges in a gas, and an electric field is applied to the group. The positive charges will be pushed by that field in one direction and the negative charges in the opposite direction. But as the two charged groups separate, they will themselves produce an electric field between them that is in the opposite direction from the applied field. If there are enough charged particles, small charge separations can create internal electric fields that are large enough to totally cancel out the applied field between them. The externally-applied field is then prevented from fully penetrating into the collection of charged particles. If a collection of charged particles can shield itself from externally-applied fields in this way, it is a plasma.

The distance that an externally-applied electric field can penetrate into a collection of charged particles is called the "Debye length" (named after the Dutch scientist Peter J. W. Debye, 1884-1966). The Debye length becomes smaller as

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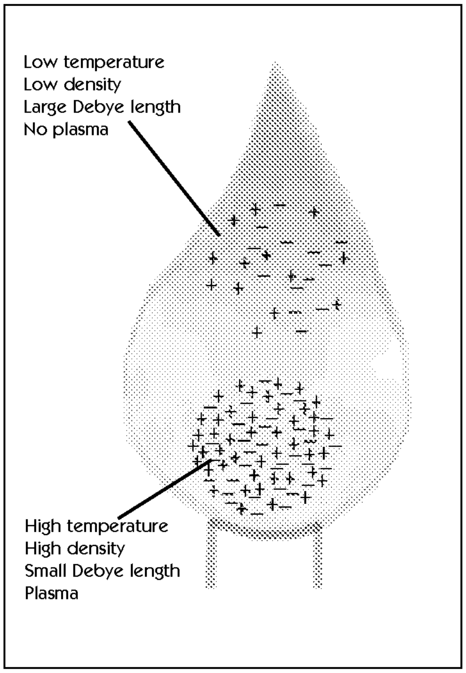



If a flame contains plasma, the plasma would be located where the charged-particle density is high enough for the Debye length to be small compared with the size of the high-density region.

the density of charged particles increases. To restate the main criterion for an ionized gas to be a plasma: A group of charged particles is a plasma if the Debye length is smaller than the group's smallest dimension. Thus, when the Debye length is much smaller than a flame, that flame very likely contains plasma. (A technical point: For the idea of Debye length to be meaningful, there must be a relatively large number of charged particles in a volume of a sphere with radius equal to the Debye length.)

Since the density of charged particles increases as temperature increases, a high-temperature region in a flame may contain enough charged particles to be a plasma. Lower-temperature flames contain no significantly ionized regions and no plasma.

An example of a flame with relatively low temperatures is the flame of a household wax candle. The maximum temperature is less than 1,500 degrees Celsius, too low for much ionization to occur. However, some flames are much hotter than that. For example, in some burning mixtures of acetylene (made up of hydrogen and carbon) and oxygen, at a pressure of one atmosphere, the peak temperature in a flame has been measured to exceed 3,100 degrees Celsius. Calculations for a particular mixture of those gases indicate an electron density high enough for the Debye length to be only about 0.01 millimeters. (The calculated density satisfies the requirement that there are many charged particles in a spherical volume with radius equal to the Debye length.) Since the Debye length is much smaller than a flame, such a flame would be expected to contain plasma.

**The Future Answer:** At present, little detailed information is available for determining if a flame contains plasma. What we need are measurements and/or mathematical calculations of charged particle densities at specific locations in a flame. Since flame properties vary greatly from one region to another, considerable effort is required to obtain the needed data.

In some cases, charged particle densities can be calculated from measured temperatures. Temperatures in some flames have been measured accurately, but not in the detail required for determining plasma properties in particular regions. Although temperatures in some flames can be estimated by their color, that method is far from reliable. Indeed, some flames do not produce much visible light at all. For example, a pure hydrogen flame is nearly invisible. (This is a concern for hydrogen leaks at oil refineries, and will be for filling stations in a future hydrogen economy.)

Detailed mathematical calculations of temperatures and charged-particle densities in small regions of a flame are complex, since many processes are at work. Those calculations involve chemical processes, gas dynamics, heat transfer, and the production of visible and non-visible light -- all in a gas with strongly varying properties.

Historically, long before the word "plasma" was conceived and first published in 1928, experiments were carried out on electrical properties of flames. Technical journal articles can be found extending back to the early 1800s. However, although flames have been studied for a long time, we still have a long way to go to understand them in the detail required to establish the presence or absence of plasma.


Text: Gerald Rogoff; Editor: Paul Rivenberg
Acknowledgements: C. Struck for charged-particle density calculations, T. Eagar for comments on flames.
Images: Stan Fellerman; Flame illustration/Mary Pat McNally

# Plasma Fundamentals and Applications


By: Dr. I.J. Van der Walt

Senior Scientist

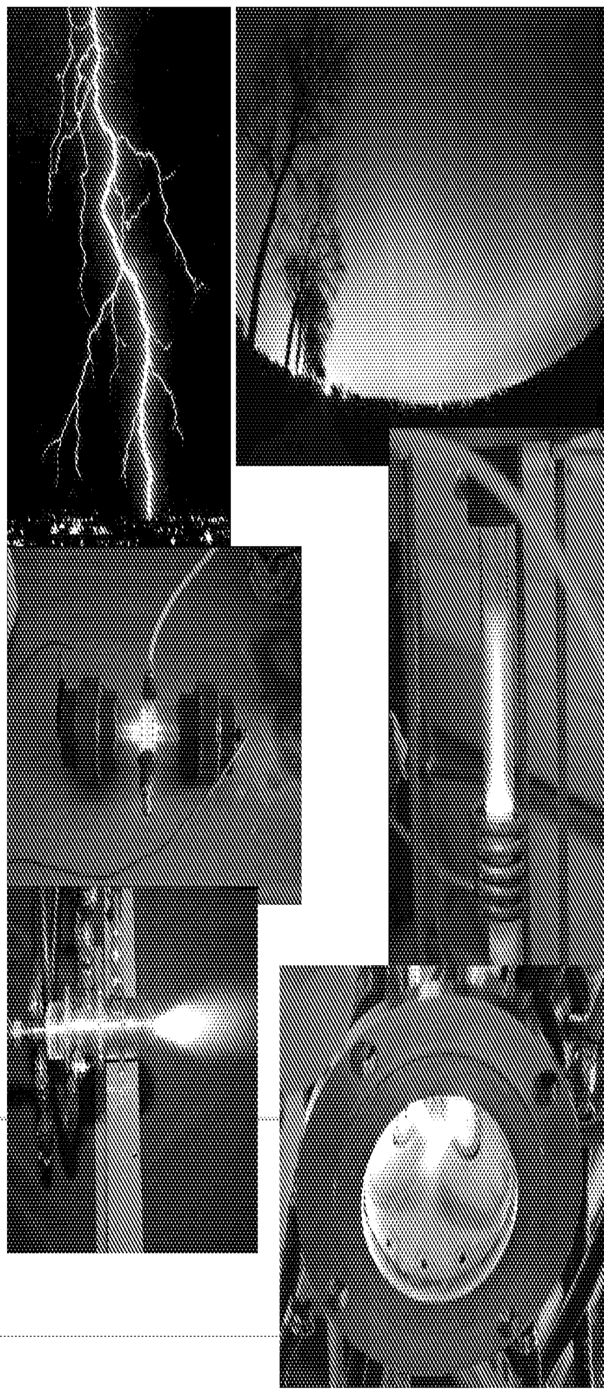
Necsa

necsa

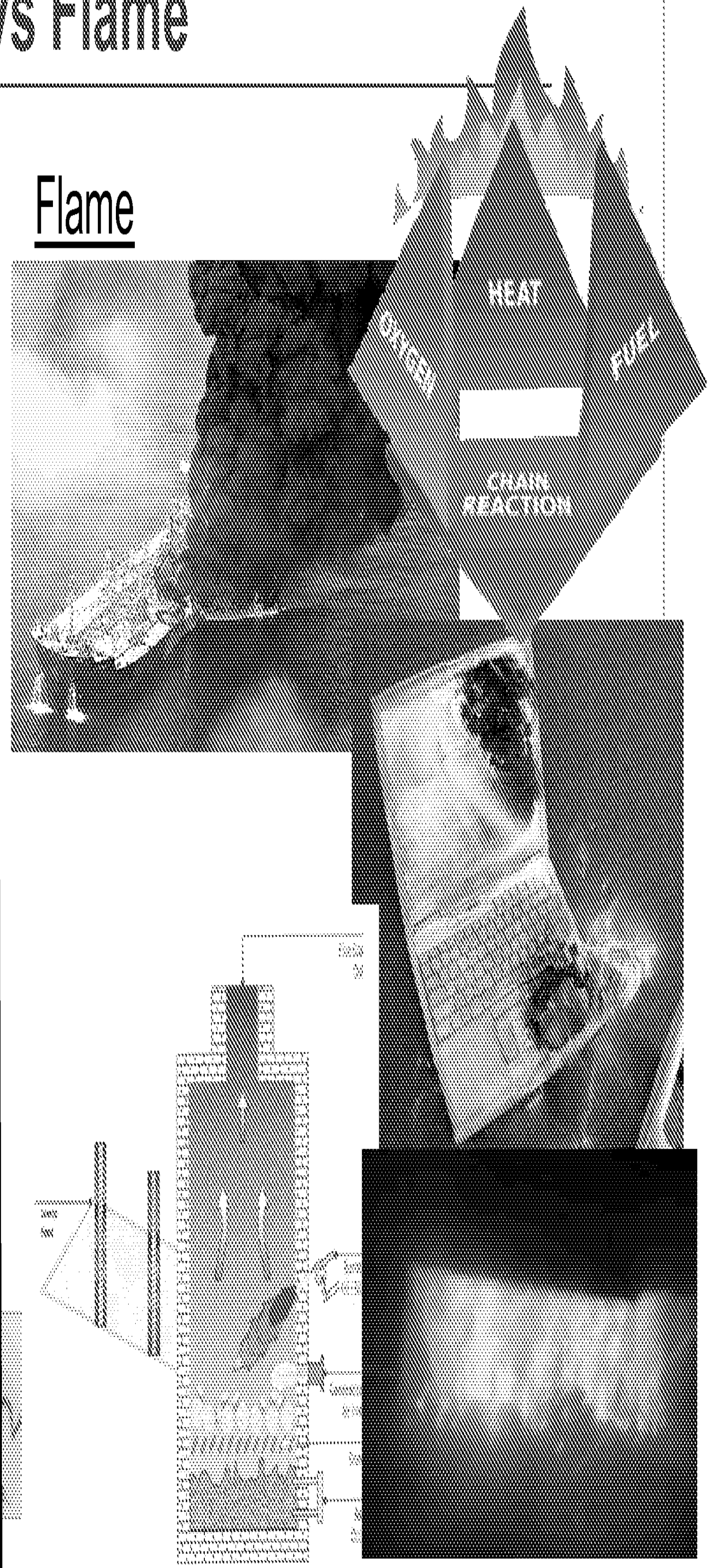
# A Natural Occurring Plasma

# Plasma vs Flame

## Plasma



## Flame



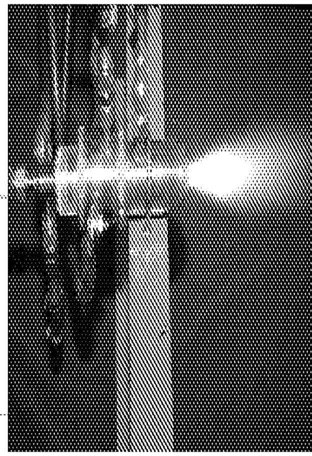
# Plasma vs Flame

<u>Plasma</u>

- 1 500 – 20 000 °C
- No $O_2$ necessary
- Ionisation process
- Electricity is constant energy source
- Small concentrated heat

<u>Flame</u>

- 450 – 2 000 °C
- $O_2$ necessary
- Oxidation process
- Initiation energy needed before exothermic reaction
- Big flames



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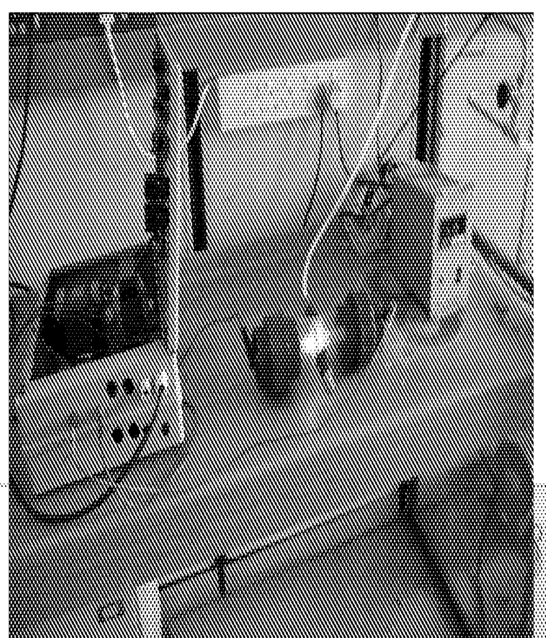
# Plasma vs Flame

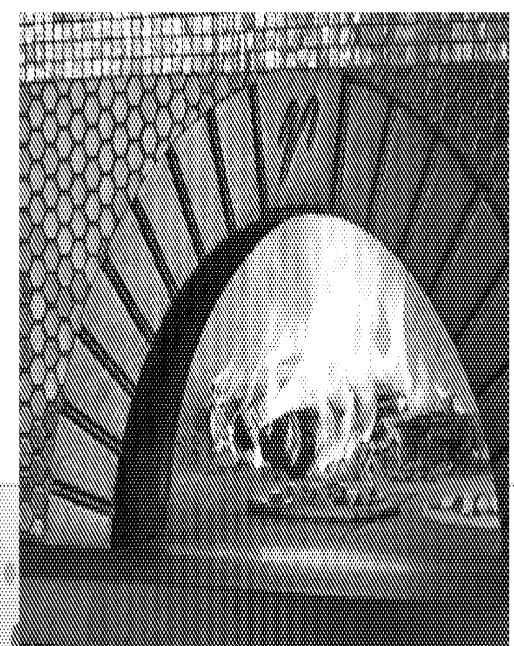
**Plasma**

- Endothermic
- $N_2 + E \rightarrow 2N + \Delta$



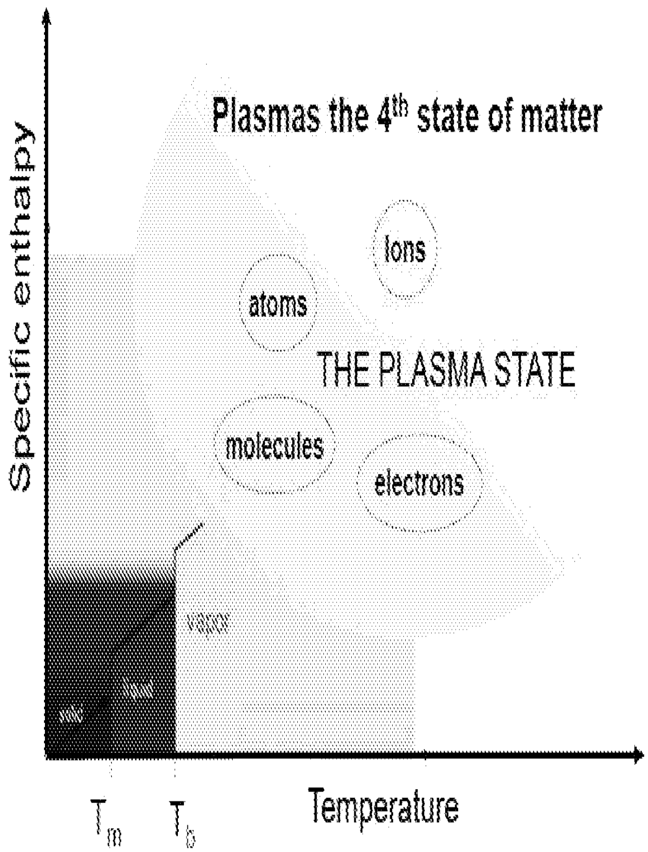
**Flame**

- Exothermic
- $C_2H_6 + 2.5O_2 + \Delta \rightarrow CO_2 + C + 3H_2O$



# What is a Plasma

- Fourth state of matter
- Mixture of electrons, ions and neutral particles;
- Exited state species to ground state responsible for luminosity
- Negative and positive species balance each other
- Photons emitted by electrons "bremstrahlung"

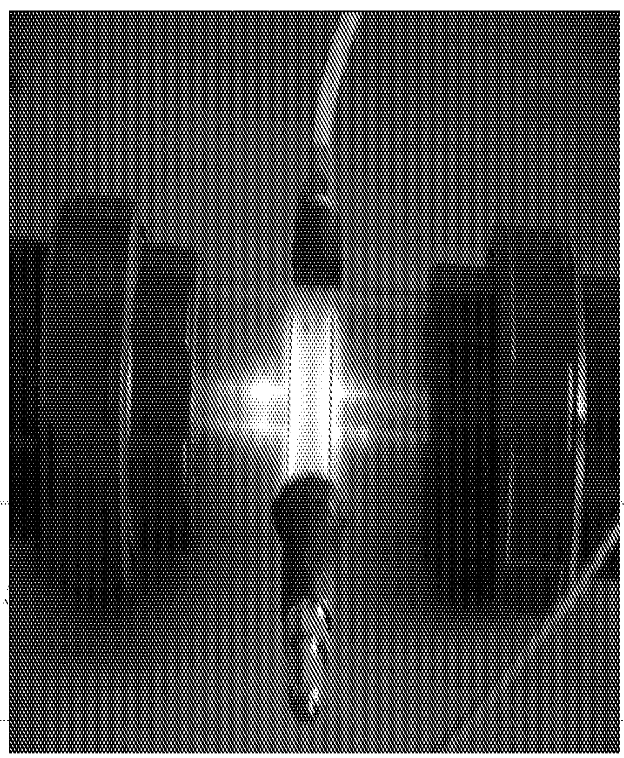




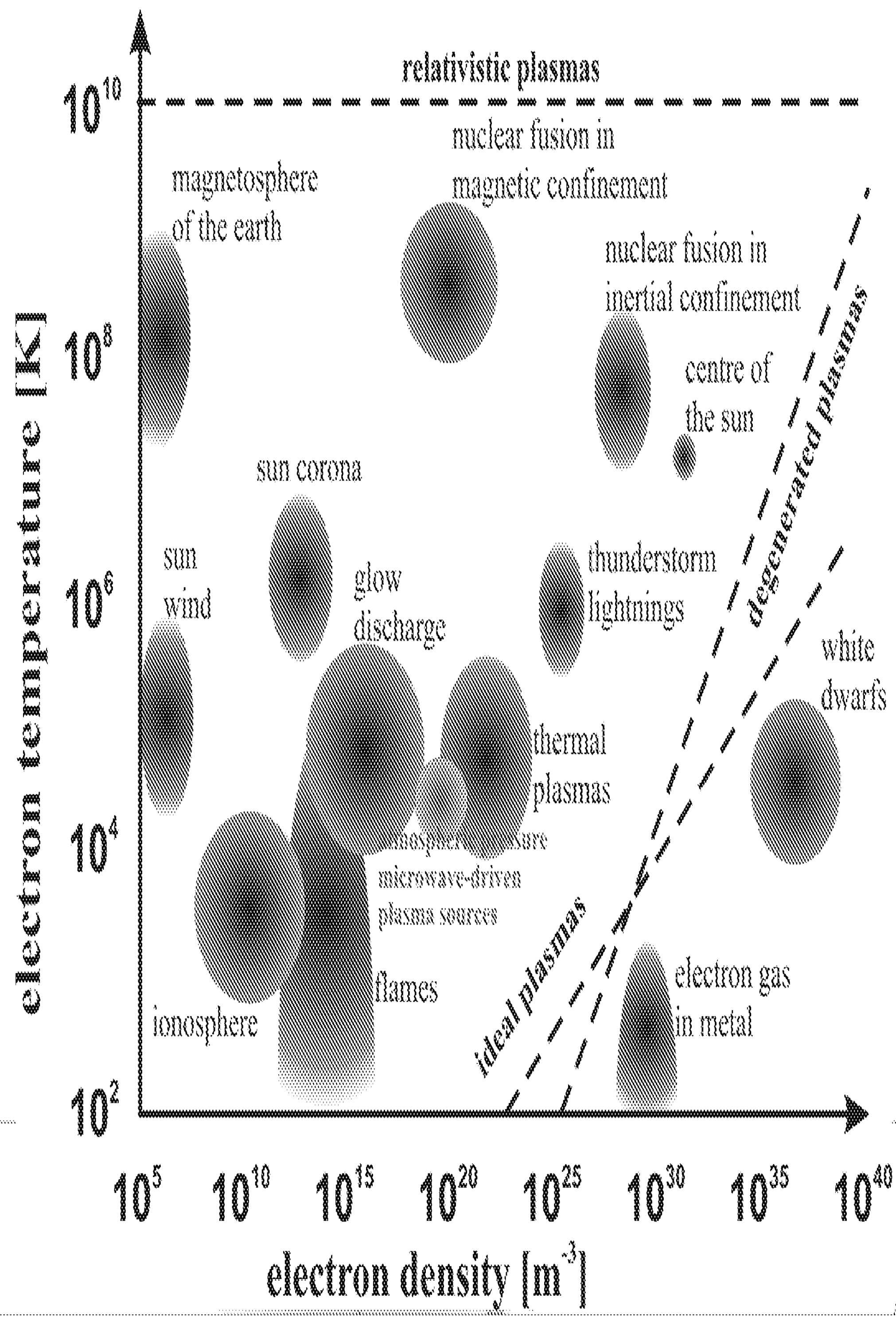

M.I. Boulos, P. Fauchais, E. Pfender, Thermal Plasmas: Fundamentals and Applications, Vol 1, Plenum Press, 1994.

# What is a Plasma

- Plasmas are:
  - Electrically conductive;
  - Not a flame!!!;
  - Classified according to ē T and ē ρ;
  - Classified according to the difference between ē T and ion T

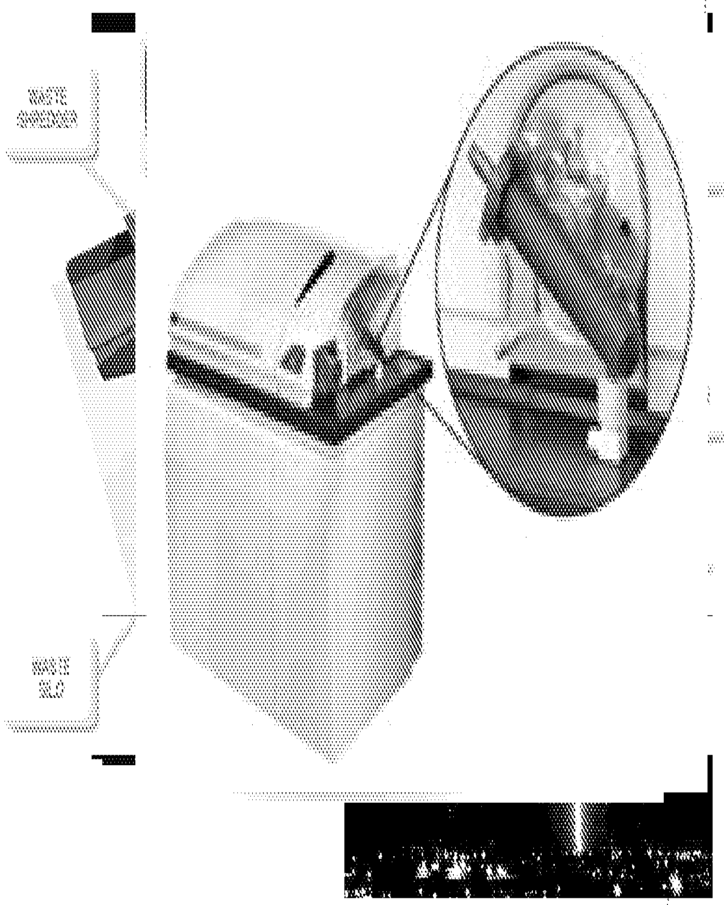


# Plasmas Classification

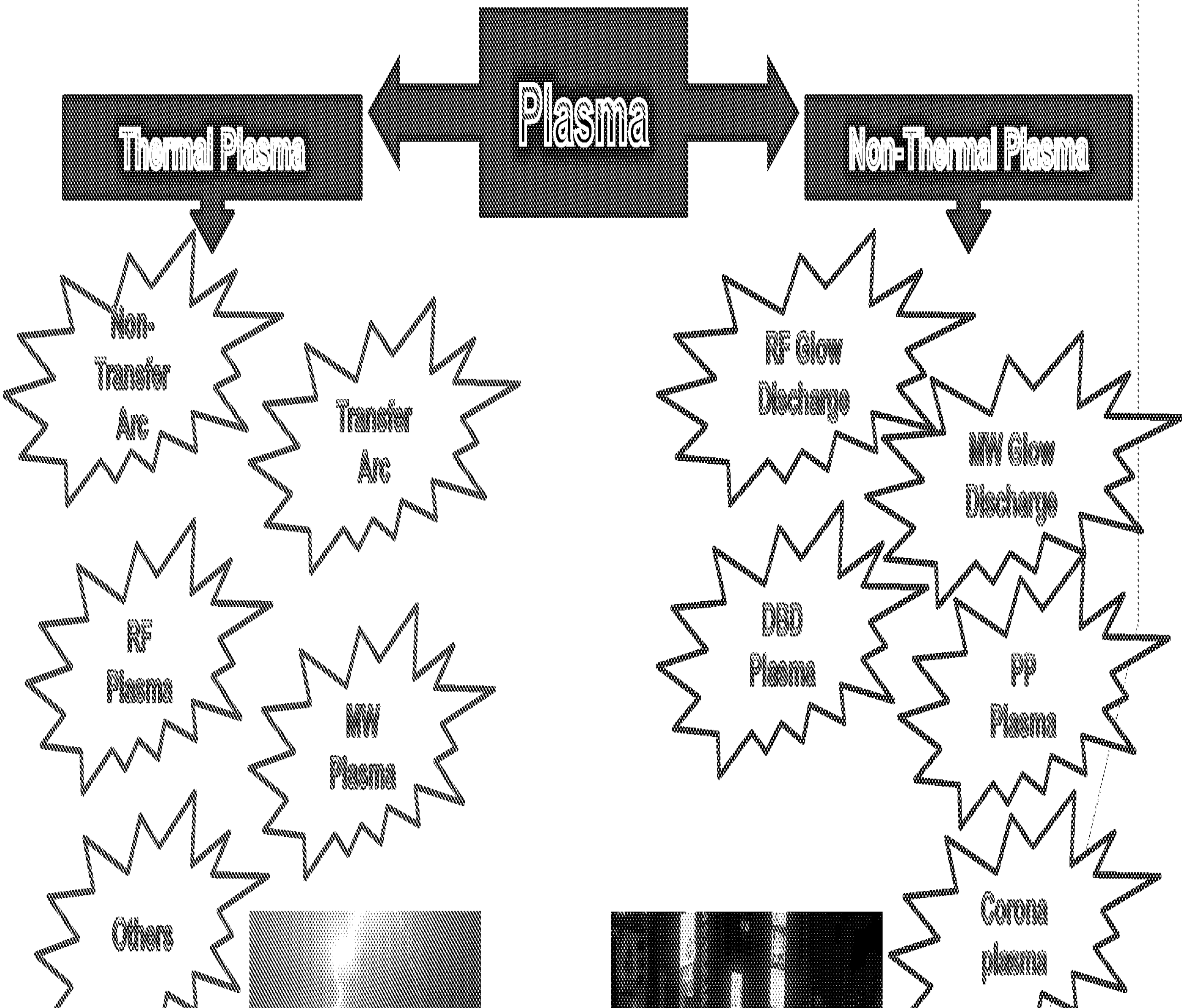


# Different Examples of plasmas

- Lightning
- Auroras
- Fluorescent lamps
- Arc welding
- Melting furnaces
- Household waste destruction
- Plasma TV by means of DBD
- Photo copy machine lights
- Proxima lights
- Analytical instruments

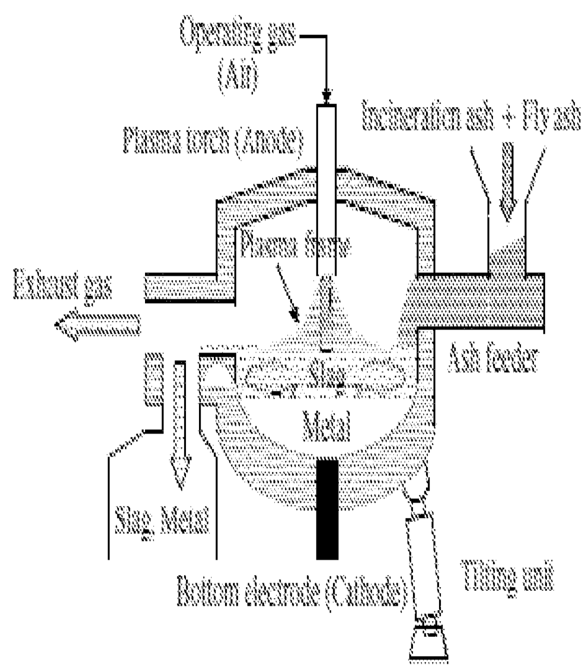


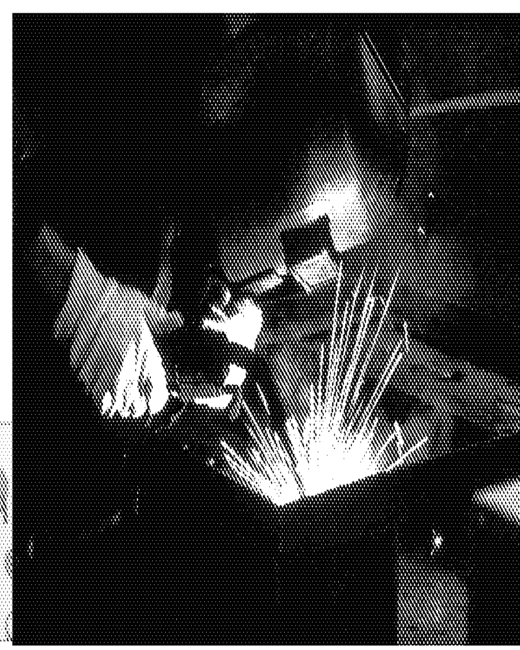
# Types of Plasmas




# Thermal Plasmas: Transfer Arc Plasma

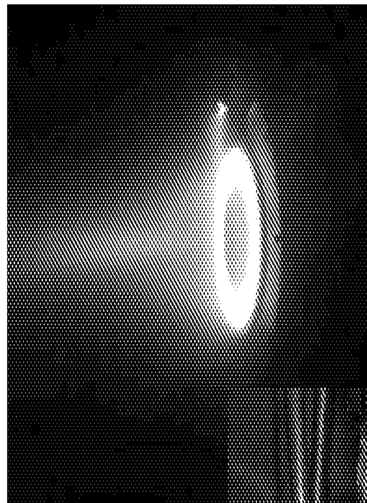
- Useable electrodes
- Effective energy transfer
- Some contamination from electrodes
- Conventional metal melting method

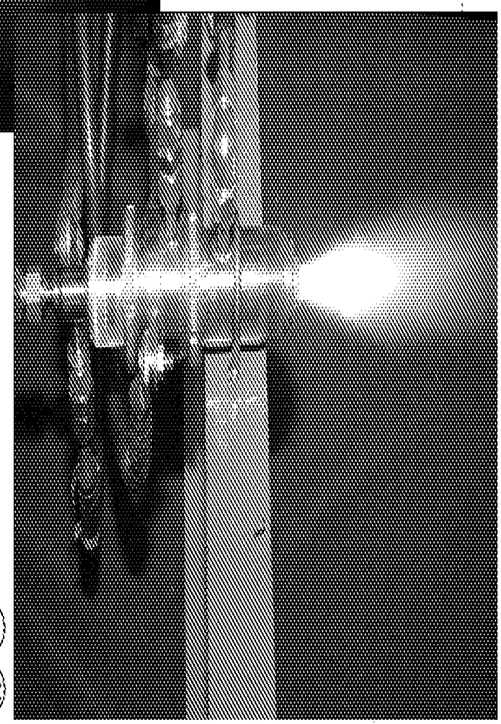


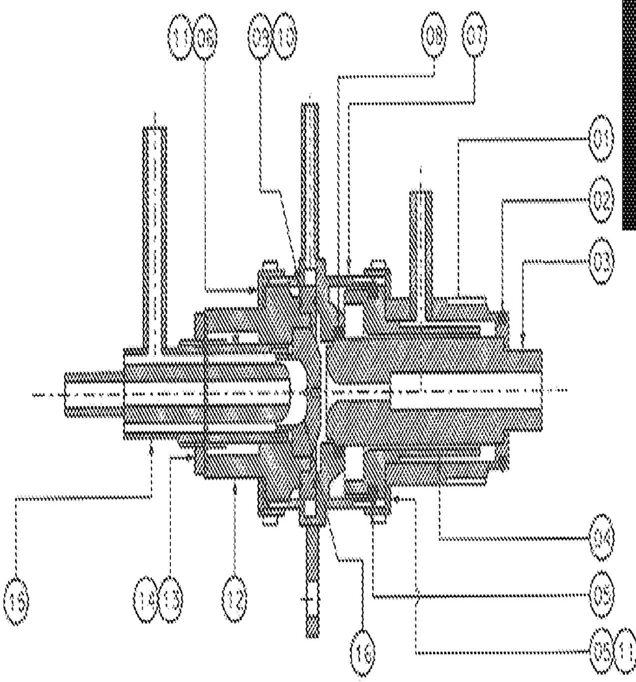



# Thermal Plasmas: Non-transfer Arc Plasma

- Non-useable water cooled electrodes
- Energy transfer in the tail flame
- Used in:
  - Plasma spraying
  - Mineral beneficiation
  - Waste destruction







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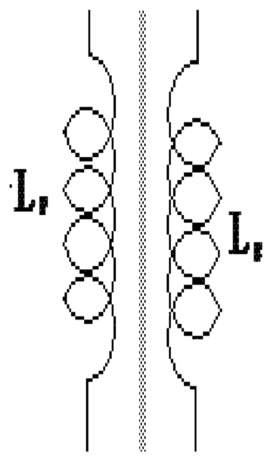
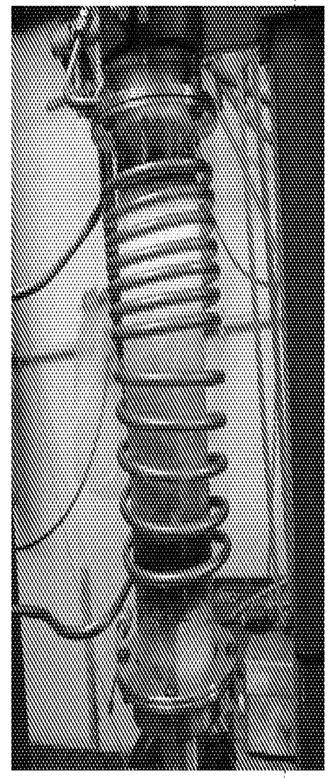
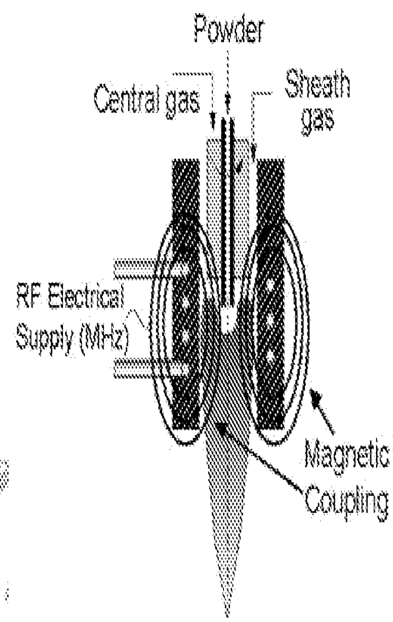
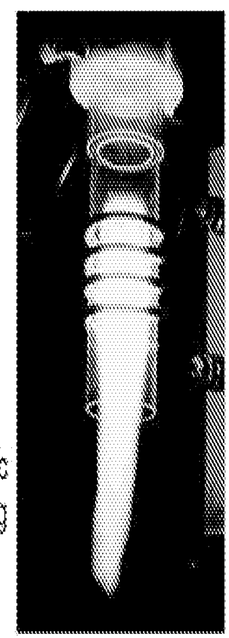
# Thermal Plasmas: Radio Frequency Plasma

- No electrodes
- Plasma by induction at 13.56 MHz
- Used in:
  - Plasma spraying
  - Analytical instrumentation
  - Waste destruction
  - Nano particle production



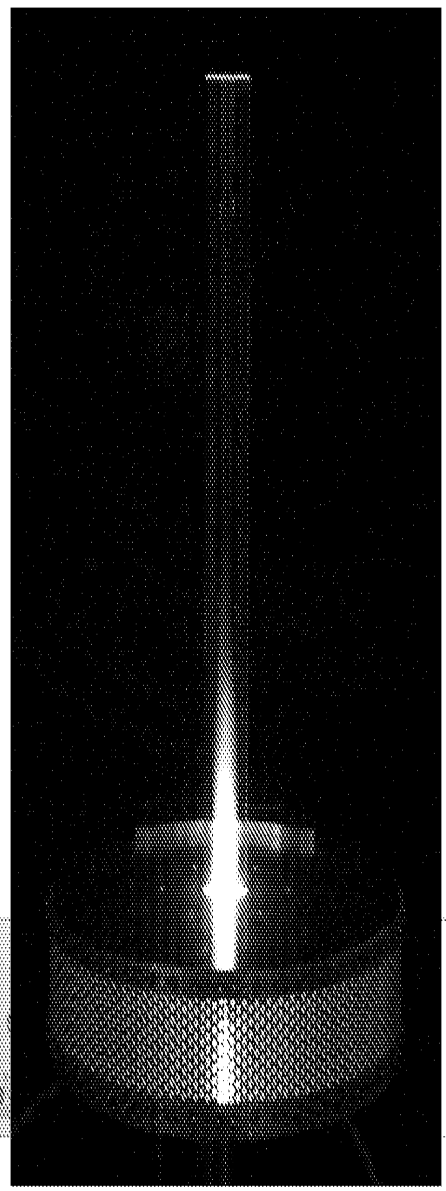



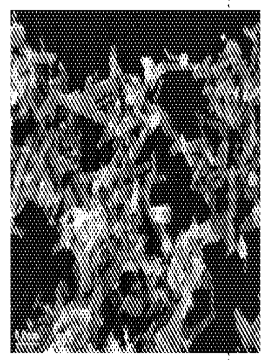


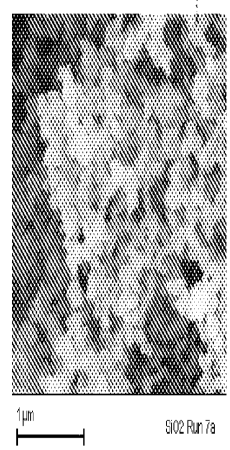



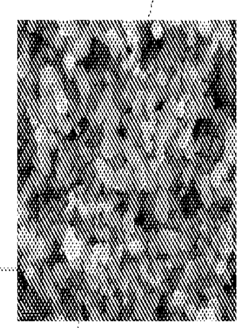
# Thermal Plasmas: Micro Wave Plasma

- No electrodes, no coils
- Plasma by MW generation at 2.45 GHz
- Used in:
  - Off gas treatment
  - Nano particle production
  - Surface etching
  - Chemical vapour deposition



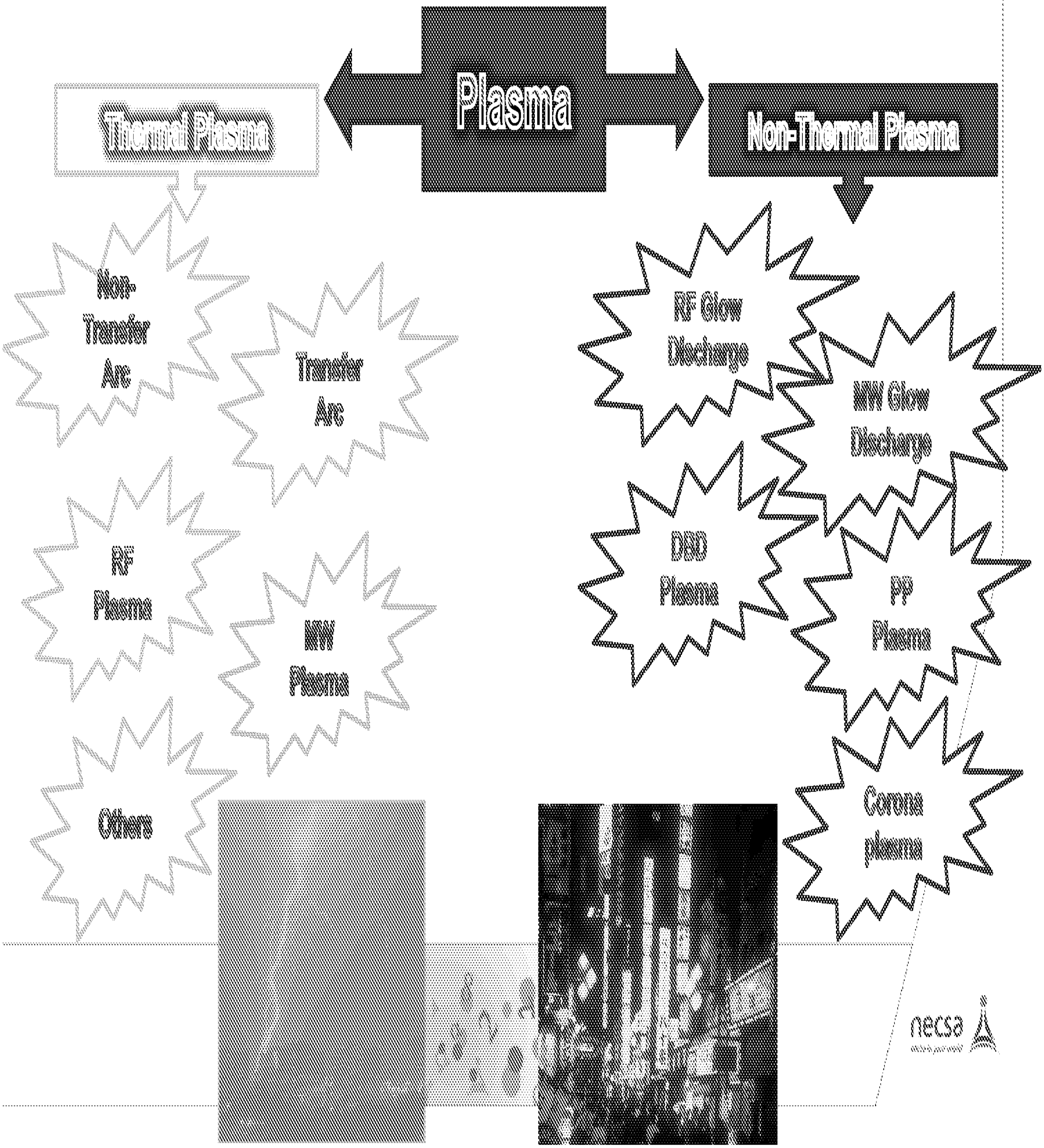




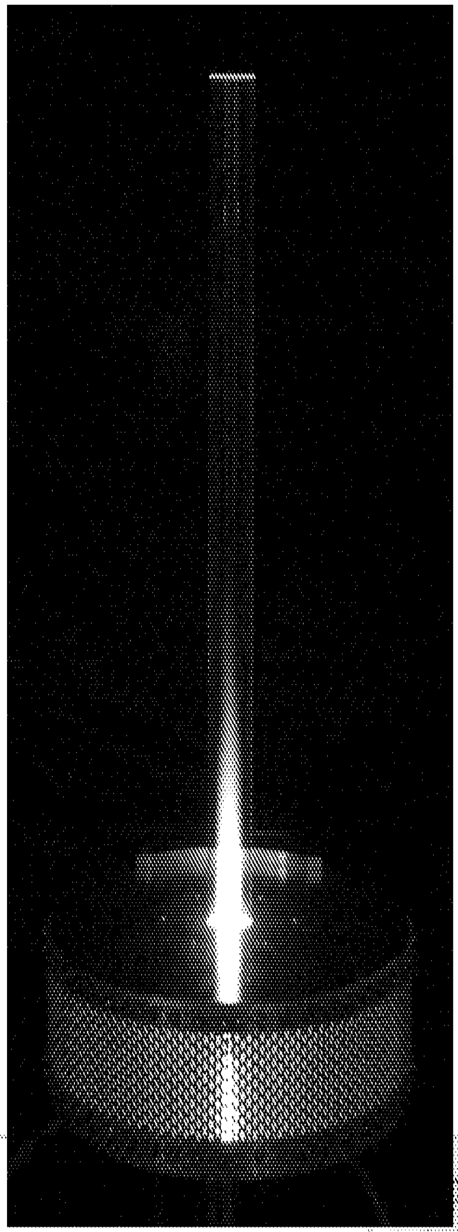



Courtesy of Marieta Leins
Stuttgart University

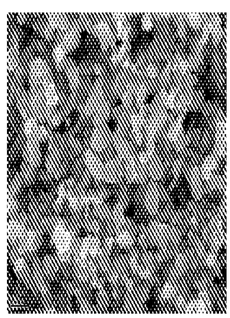
# Types of Plasmas

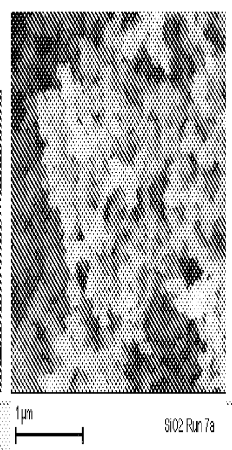


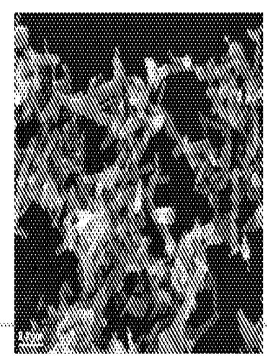
# Non-Thermal Plasmas: Micro Wave



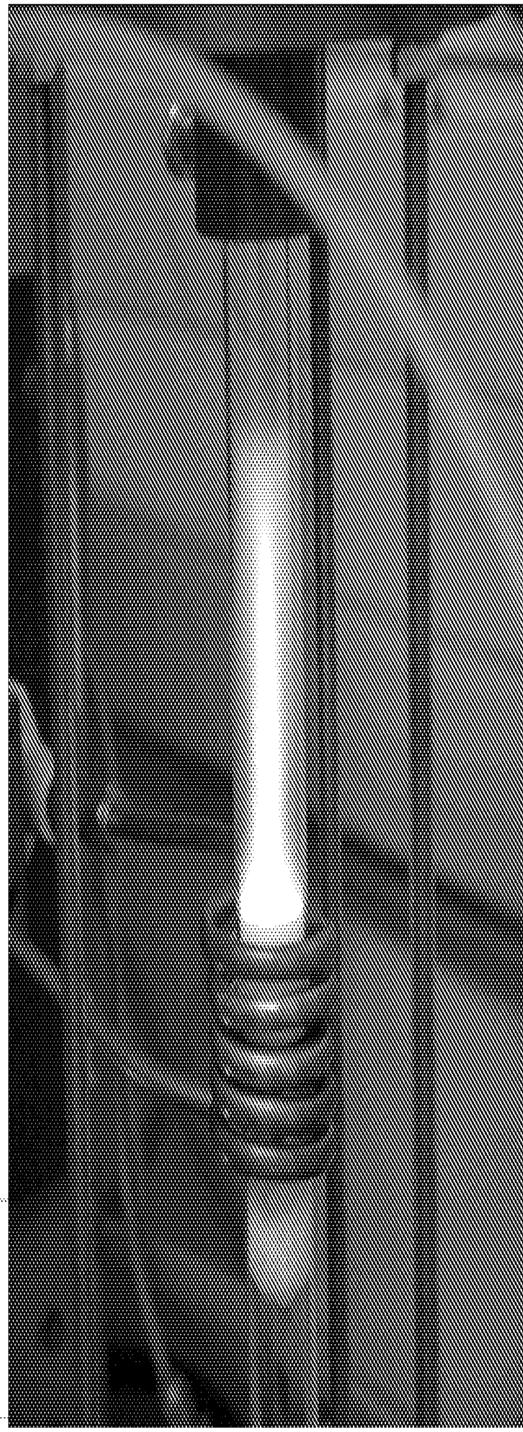
- No electrodes, no coils, low pressure
- Plasma by MW generation at 2.45 GHz
- Used in:
  - Nano particle production
  - Artificial diamond growth
  - Chemical vapour deposition





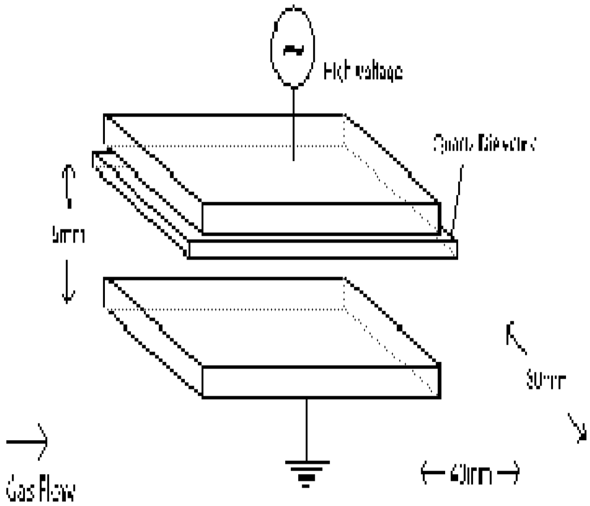



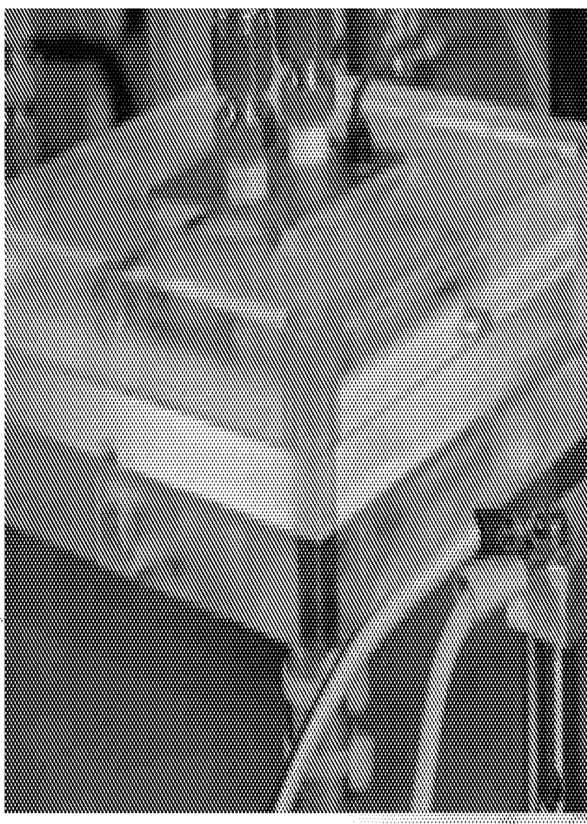
# Non-Thermal Plasmas: RF Glow Discharge



- No electrodes, low pressure
- Plasma by RF Induction at 13.56 MHz
- Used in:
  - Surface modification
  - Surface etching
  - Chemical vapour deposition
  - Lighting

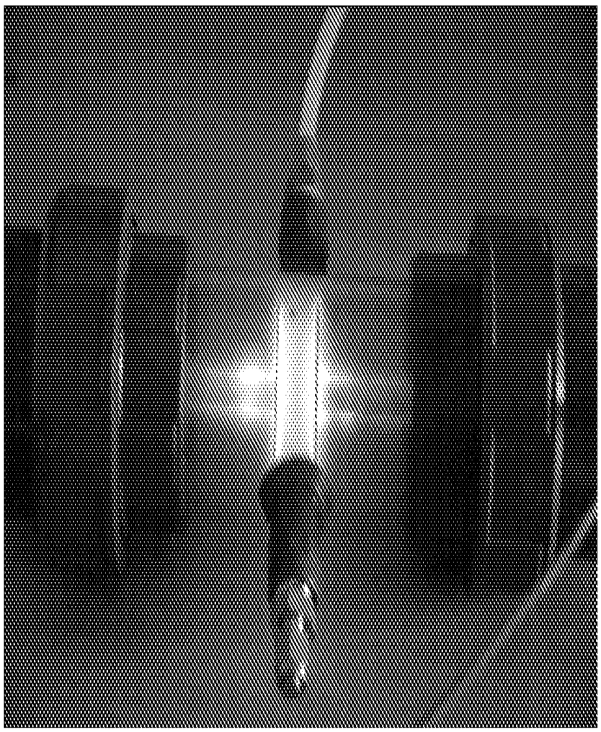
# Non-Thermal Plasmas: Dielectric Barrier Discharge

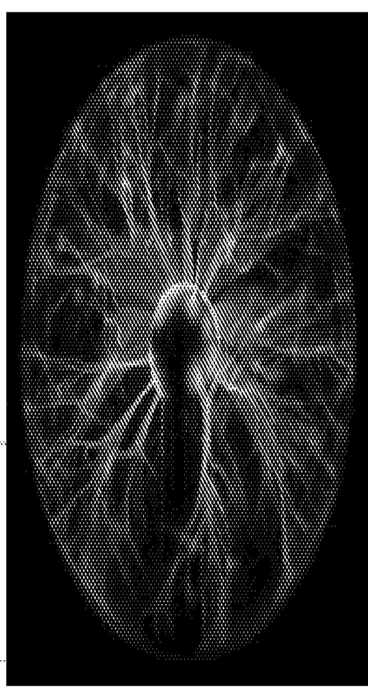


- 2 electrodes separated by a dielectric layer at ambient pressure
- Plasma by dielectric barrier discharge at 1 - 100 MHz
- Used in:
  - Ozone ($O_3$) production

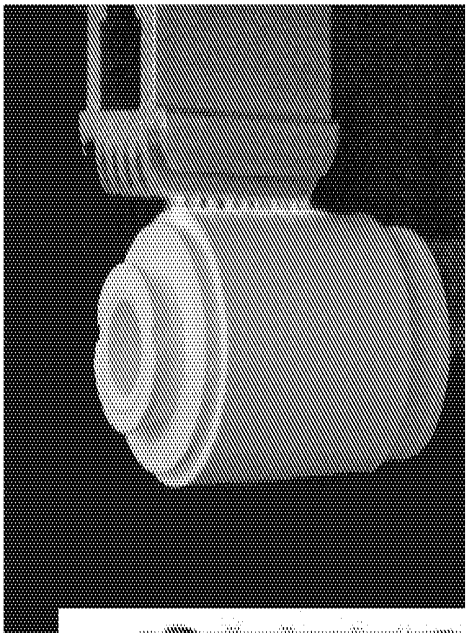
# Non-Thermal Plasmas: Pulsed Power Plasma





- 2 electrodes at ambient pressure
- Nano second thermal plasma 10 – 100 kHz
- Used in:
  - Off gas treatment

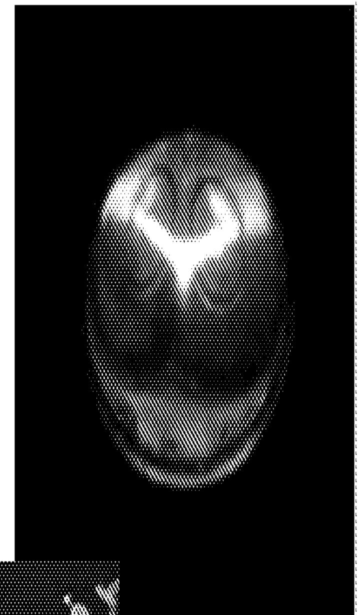
# Non-Thermal Plasmas: Corona Discharge

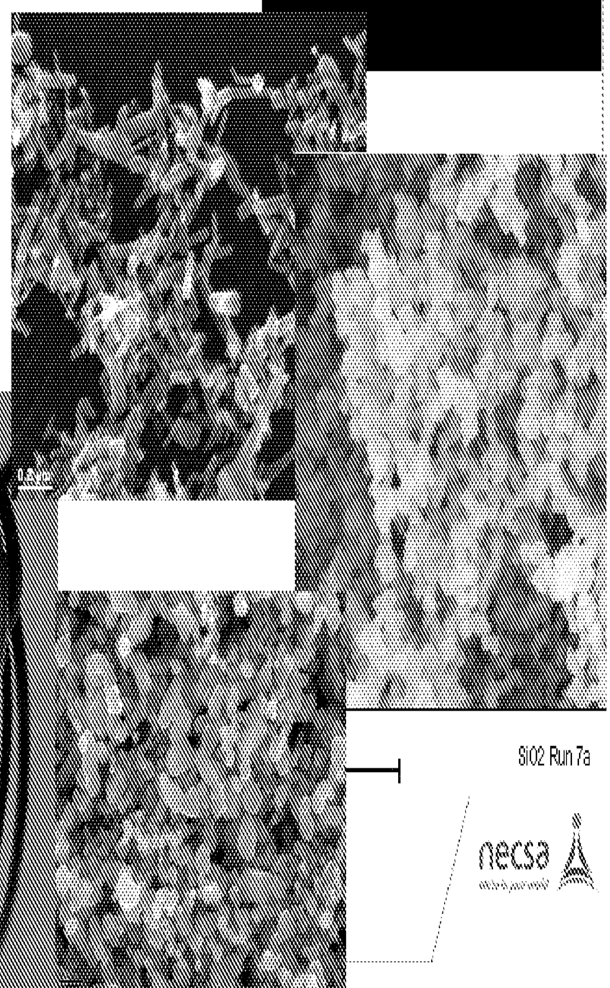


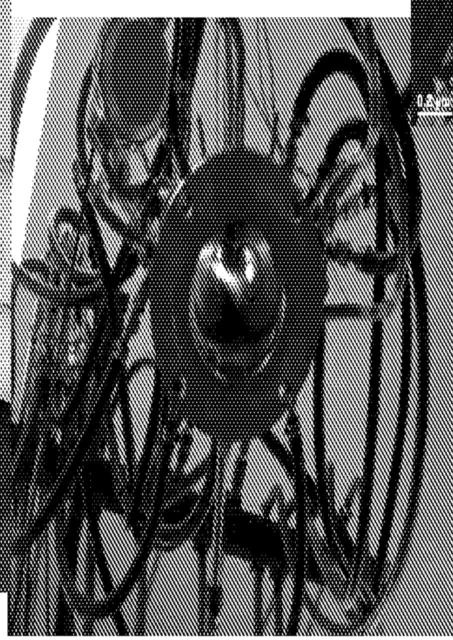
- 2 electrodes at ambient pressure
- Nano second thermal plasma 10 – 100 kHz
- Used in:
  - Off gas treatment
  - Ozone production
  - Surface activation

# Plasma Chemistry

- Chemistry with inert chemicals like C, $ZrO_2$, $SiO_2$, $TiO_2$, $Al_2O_3$, ZnO, etc.
- Chemistry with inert chemicals like $CF_4$, $N_2$, Ar, etc.
- Manufacturing of nano particles.



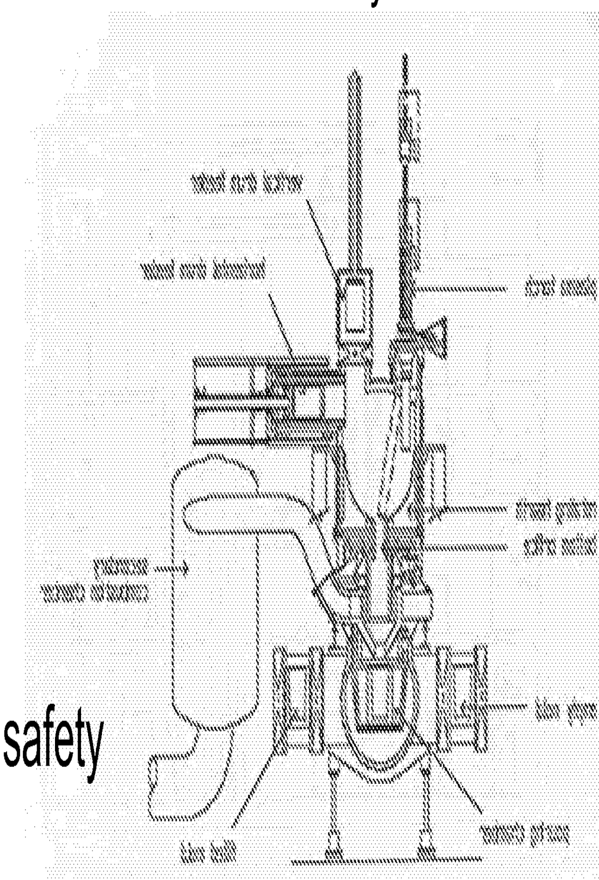


# Plasma Nuclear Application

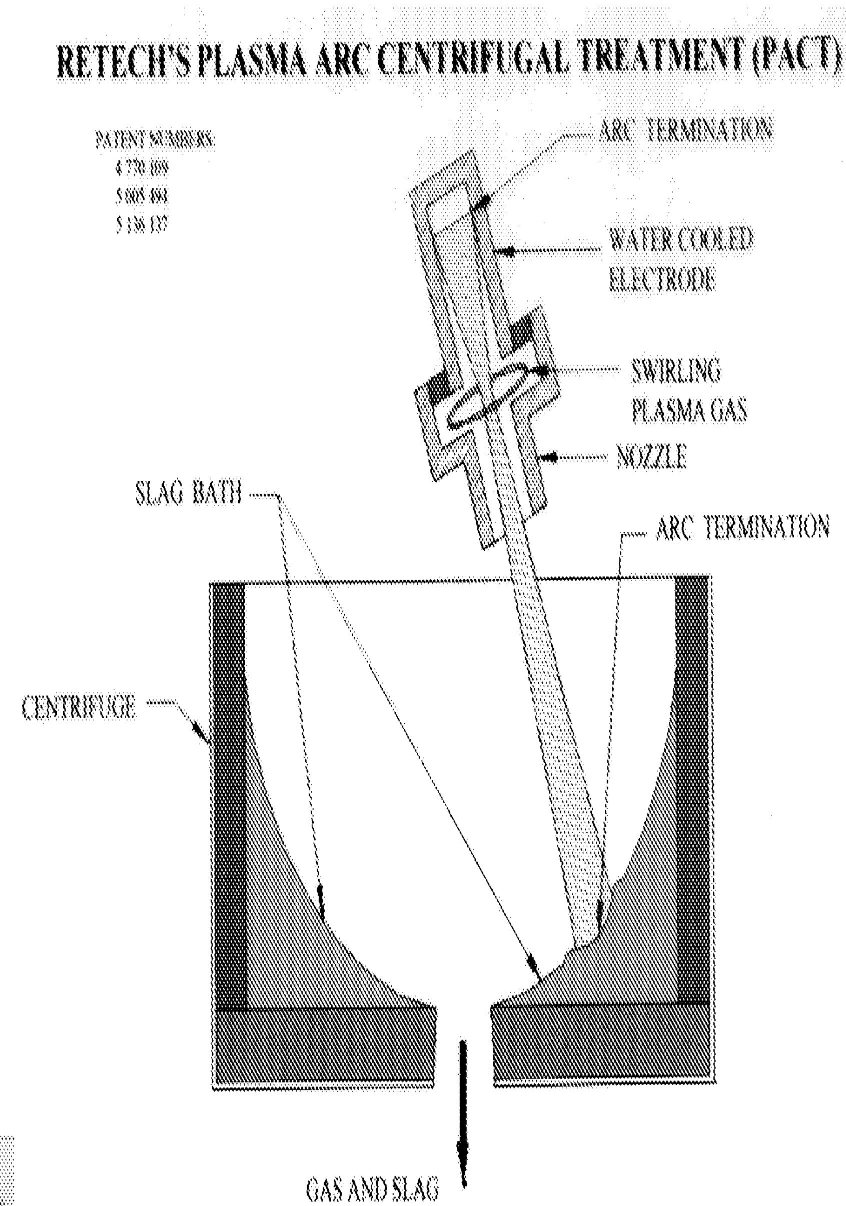
- Low level nuclear waste treatment
- Volume reduction (>90 %)
- Uranium recovery
- Vitrification
- Treat the whole drum
- No sorting
- Increased chemical and radiological safety
- Technology is mature
- Technology is applied on nuclear sites
- Small footprint

Plasmarc system



# Plasma Nuclear Application

- Different suppliers in the world
  - Retech scientific
  - Europlasma
  - Tetronics
  - Scanarc
  - Nukem
  - Westinghouse
  - Phoenix Solutions



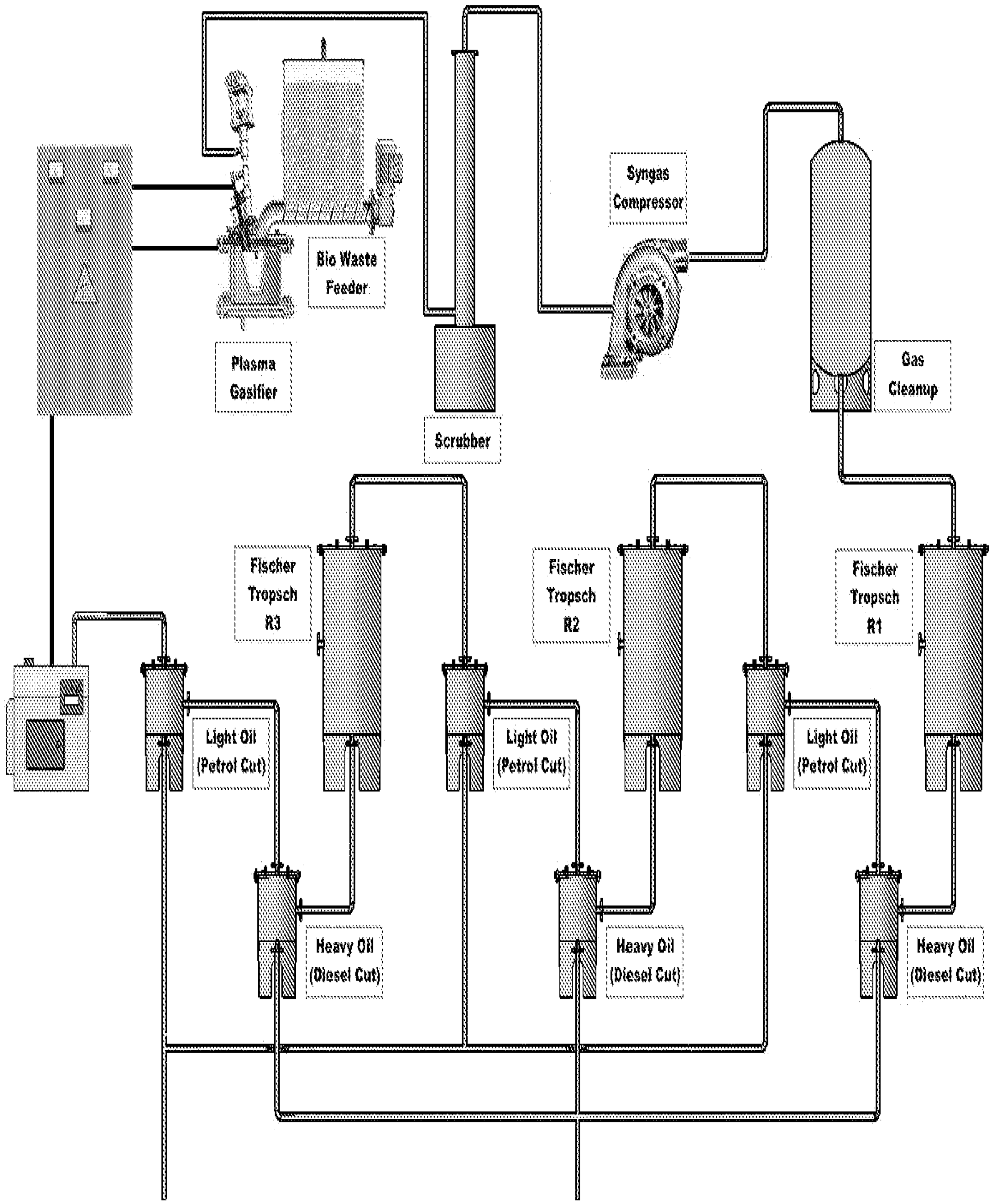
# Plasma Nuclear Application

## Necsa demonstration plasma nuclear waste volume reduction

# Benefit

- **Benefit to the greater South Africa**
  - Solution to serious municipal waste problems;
  - Solution to medical waste problems;
  - Solution to various other waste problems;
  - Takes pressure off fuel supply to remote areas;
  - Takes pressure off electricity supply to remote areas;
  - Promotes the decrease of the carbon footprint;
  - Opportunity for renewable energy supply;
  - Job creation;
  - Trade waste for electricity.

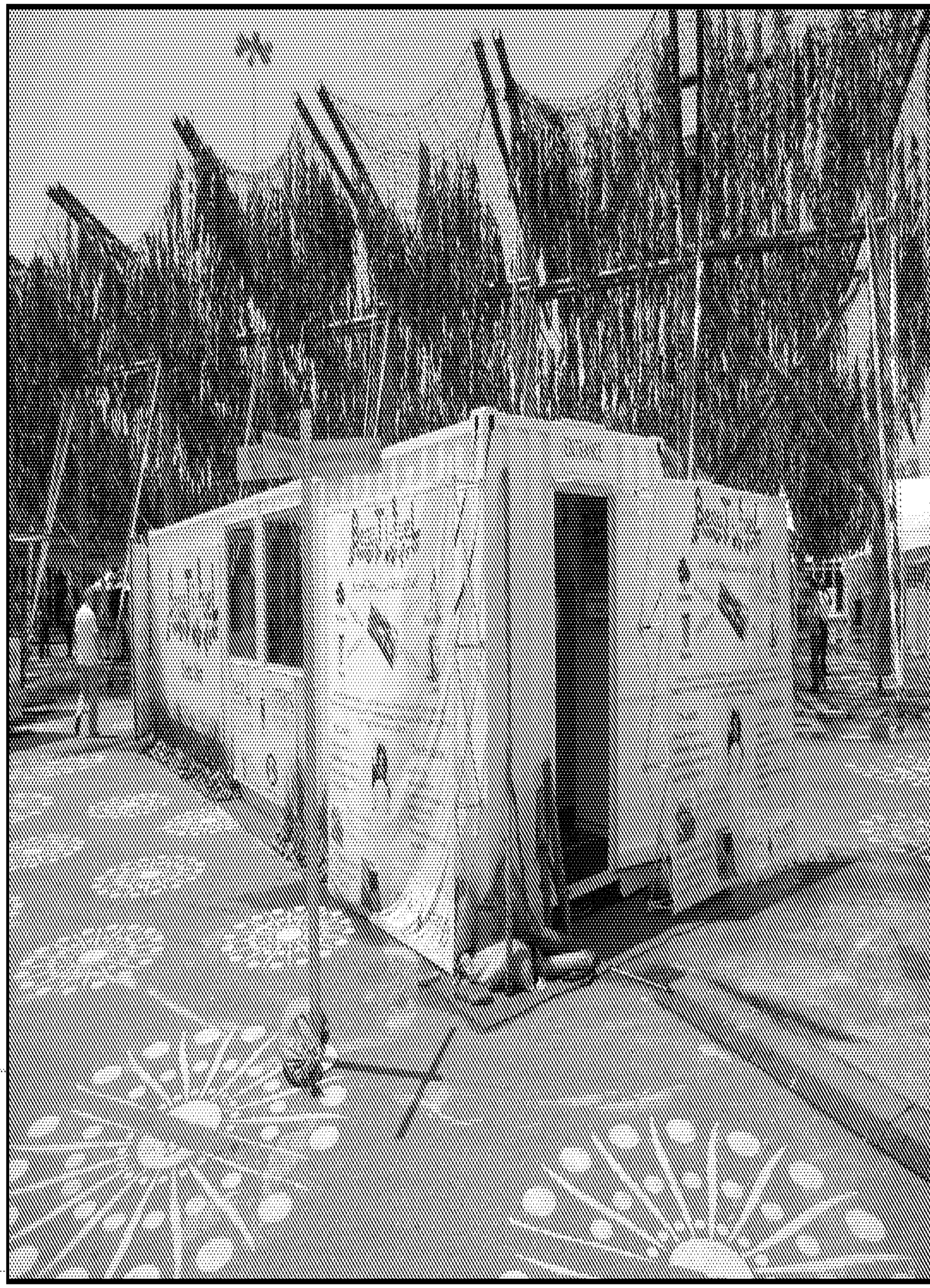
# BeauTi-fueL™



Syngas Compressor
Bio Waste Feeder
Plasma Gasifier
Scrubber
Gas Cleanup
Fischer Tropsch R3
Fischer Tropsch R2
Fischer Tropsch R1
Light Oil (Petrol Cut)
Light Oil (Petrol Cut)
Light Oil (Petrol Cut)
Heavy Oil (Diesel Cut)
Heavy Oil (Diesel Cut)
Heavy Oil (Diesel Cut)

# BeauTi-fueL™

http://www.rchelicam.co.za/preview/CCR_Expo/Climate_Smart_CTN_Outside.html



# BeauTi-fueL™

# Waste-to-Energy Application sectors

- Product capabilities

| | Electricity only | Electricity and fuel | Unit size (tpd) |
|---|---|---|---|
| Municipal land fill sites | | X | 100 – 200 |
| De-localised municipal waste sites | X | | 1 – 10 |
| Farming plant waste | | X | 1 – 3 |
| Farming animal manure waste | | X | 1 – 3 |
| Renewable feedstock | | X | 100 – 200 |
| Tyre waste | | X | 10 – 50 |
| Medical waste | X | | 1 |
| Toxic waste | X | | 1 |
| Nuclear waste | X | | 10 |

# Technical data

- Up-scaling modular systems (50 % accuracy)

| Plant | 1 | 10 | 50 | 100 |
|---|---|---|---|---|
| Feed quantity | ~2 - 3 tpd | ~10 - 15 tpd | ~50 - 70 tpd | ~100 – 150 tpd |
| Plasma size | 30 kW | 150 kW | 500 kW | 1000 kW |
| Availability | 2012 | 2013 | 2015 | 2017 |
| Estimated Development Cost | R10 mil | R25 mil | R60 mil | R125 mil |
| Electricity only or | 150 kW | 750 kW | 3.75 MW | 7.5 MW |
| Diesel and Electricity | 2 bbl<br>50 kW | 10 bbl<br>250 kW | 50 bbl<br>1.25 MW | 100 bbl<br>2.5 MW |

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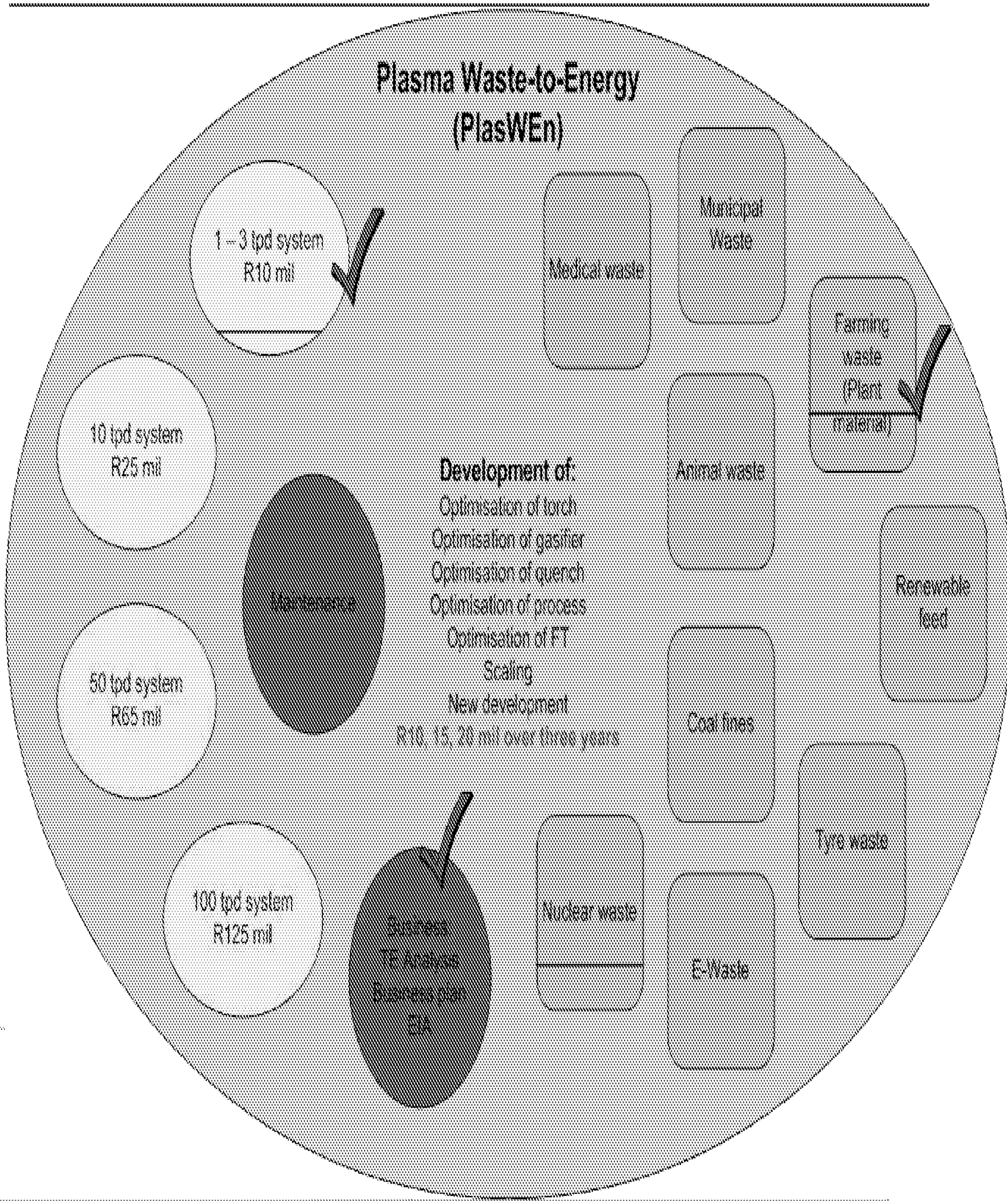
# Funding



Plasma Waste-to-Energy (PlasWEn)
1 – 3 tpd system R10 mil
10 tpd system R25 mil
50 tpd system R65 mil
100 tpd system R125 mil
Maintenance
Business TE Analysis Business plan EIA
Development of:
Optimisation of torch
Optimisation of gasifier
Optimisation of quench
Optimisation of process
Optimisation of FT
Scaling
New development
R10, 15, 20 mil over three years
Medical waste
Municipal Waste
Farming waste (Plant material)
Animal waste
Renewable feed
Coal fines
Tyre waste
Nuclear waste
E-Waste

# Thank You!!!

# An Introduction to Combustion

## *Concepts and Applications*

**Third Edition**

**Stephen R. Turns**
*Propulsion Engineering Research Center*
*and*
*Department of Mechanical and Nuclear Engineering*
*The Pennsylvania State University*

**McGraw Hill Education (India) Private Limited**
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**AN INTRODUCTION TO COMBUSTION: CONCEPTS AND APPLICATIONS, THIRD EDITION**



Second reprint 2013
**RZZYCRZORYLQB**



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From experimental measurements, the rate at which the fuel is consumed can be expressed as

$$\frac{d[X_F]}{dt} = -k_G(T)[X_F]^n[X_{Ox}]^m, \tag{4.2}$$

where the notation $[X_i]$ is used to denote the molar concentration (kmol/m$^3$ in SI units or gmol/cm$^3$ in CGS units) of the $i$th species in the mixture. Equation 4.2 states that the rate of disappearance of the fuel is proportional to each of the reactants raised to a power. The constant of proportionality, $k_G$, is called the **global rate coefficient,** and, in general, is not constant, but rather is a strong function of temperature. The minus sign indicates that the fuel concentration decreases with time. The exponents $n$ and $m$ relate to the **reaction order.** Equation 4.2 says that the reaction is $n$th order with respect to the fuel, $m$th order with respect to the oxidizer, and $(n + m)$th order overall. For global reactions, $n$ and $m$ are not necessarily integers and arise from curvefitting experimental data. Later, we will see that for elementary reactions, reaction orders will always be integers. In general, a particular global expression in the form of Eqn. 4.2 holds only over a limited range of temperatures and pressures, and may depend on the details of the apparatus used to define the rate parameters. For example, different expressions for $k_G(T)$ and different values for $n$ and $m$ must be applied to cover a wide range of temperatures.

The use of global reactions to express the chemistry in a specific problem is frequently a "black box" approach. Although this approach may be useful in solving some problems, it does not provide a basis for understanding what is actually happening chemically in a system. For example, it is totally unrealistic to believe that $a$ oxidizer molecules simultaneously collide with a single fuel molecule to form $b$ product molecules, since this would require breaking several bonds and subsequently forming many new bonds. In reality, many sequential processes can occur involving many **intermediate species.** For example, consider the global reaction

$$2H_2 + O_2 \rightarrow 2H_2O. \tag{4.3}$$

To effect this global conversion of hydrogen and oxygen to water, the following **elementary reactions** are important:

$$H_2 + O_2 \rightarrow HO_2 + H, \tag{4.4}$$

$$H + O_2 \rightarrow OH + O, \tag{4.5}$$

$$OH + H_2 \rightarrow H_2O + H, \tag{4.6}$$

$$H + O_2 + M \rightarrow HO_2 + M, \tag{4.7}$$

among others.

In this partial mechanism for hydrogen combustion, we see from reaction 4.4 that when oxygen and hydrogen molecules collide and react, they do not yield water, but, instead, form the intermediate species $HO_2$, the hydroperoxy radical, and a hydrogen atom, H, another radical. **Radicals** or **free radicals** are reactive molecules, or atoms, that have unpaired electrons. To form $HO_2$ from $H_2$ and $O_2$, only one bond is broken and one bond formed. Alternatively, one might consider that $H_2$ and $O_2$ would react to form two hydroxyl radicals (OH); however, such a reaction is unlikely since it requires the breaking of two bonds and the creation of two new bonds. The hydrogen atom created in reaction 4.4 then reacts with $O_2$ to form two additional radicals, OH and O (reaction 4.5). It is the subsequent reaction (4.6) of the hydroxyl radical (OH) with molecular hydrogen that forms water. To have a complete picture of the combustion of $H_2$ and $O_2$, more than 20 elementary reactions can be considered [1, 2]. These we consider in Chapter 5. The collection of elementary reactions necessary to describe an overall reaction is called a reaction **mechanism.** Reaction mechanisms may involve only a few steps (i.e., elementary reactions) or as many as several hundred. A field of active research involves selecting the minimum number of elementary steps necessary to describe a particular global reaction.

# ELEMENTARY REACTION RATES

## Bimolecular Reactions and Collision Theory

Most elementary reactions of interest in combustion are **bimolecular;** that is, two molecules collide and react to form two different molecules. For an arbitrary bimolecular reaction, this is expressed as

$$A + B \rightarrow C + D. \tag{4.8}$$

Reactions 4.4–4.6 are examples of bimolecular elementary reactions.

The rate at which the reaction proceeds is directly proportional to the concentrations (kmol/m$^3$) of the two reactant species, i.e.,

$$\frac{d[A]}{dt} = -k_{bimolec}[A][B]. \tag{4.9}$$

All elementary bimolecular reactions are overall second order, being first order with respect to each of the reacting species. The rate coefficient, $k_{bimolec}$, again is a function of temperature, but unlike the global rate coefficient, this rate coefficient has a theoretical basis. The SI units for $k_{bimolec}$ are m$^3$/kmol-s; however, much of the chemistry and combustion literature still uses CGS units.

Molecular collision theory can be used to provide insight into the form of Eqn. 4.9 and to suggest the temperature dependence of the bimolecular rate coefficient. As we will see, the collision theory for bimolecular reactions has many shortcomings; nevertheless, the approach is important for historical reasons and provides a way to visualize bimolecular reactions. In our discussion of molecular transport in Chapter 3, we introduced the concepts of wall collision frequency, mean molecular speed, and mean free path (Eqn. 3.10). These same concepts are important in our discussion of molecular collision rates. To determine the collision frequency of a pair of molecules, we start with the simpler case of a single molecule of diameter $\sigma$ traveling with constant speed $v$ and experiencing collisions with identical, but

**Table 5.3** Chemical kinetic studies targeting real fuel combustion

| Target Fuel | Surrogate Blend[1] | Reference | Comment |
|---|---|---|---|
| Natural gas | Methane ($CH_4$)<br>Ethane ($C_2H_6$)<br>Propane ($C_3H_8$) | Dagaut [11] | — |
| Kerosene (Jet A-1) | *n*-Decane ($C_{10}H_{22}$) | Dagaut [11] | Single-component model fuel |
| Kerosene (Jet A-1) | 74% *n*-Decane ($C_{10}H_{22}$)<br>15% *n*-Propylbenzene<br>11% *n*-Propylcyclohexane | Dagaut [11] | 207 species and 1,592 reactions |
| Diesel fuel | 36.5% *n*-Hexadecane ($C_{16}H_{24}$)<br>24.5% Isooctane ($C_8H_{18}$)<br>20.4% *n*-Propylcyclohexane<br>18.2% *n*-Propylbenzene | Dagaut [11] | 298 species and 2,352 reactions |
| JP-8 (Jet fuel) | 10% Isooctane<br>20% Methylcyclohexane ($C_7H_{14}$)<br>15% *m*-Xylene ($C_8H_{10}$)<br>30% *n*-Dodecane ($C_7H_{14}$)<br>5% Tetralin ($C_7H_{14}$)<br>20% Tetradecane ($C_{14}H_{30}$) | Cooke *et al.* [12]<br>Violi *et al.* [13]<br>Ranzi *et al.* [14]<br>Ranzi *et al.* [15]<br>Ranzi *et al.* [16] | 221 species and 5,032 reactions |
| Gasoline | Isooctane (neat) ($C_8H_{18}$)<br>Isooctane ($C_8H_{18}$) – *n*-Heptane ($C_7H_{16}$) | Curran *et al.* [17]<br>Curran *et al.* [18] | Single-component model fuel and two-component surrogates; 860–990 species and 3,600–4,060 reactions |
| Gasoline | 63–69% (liq. vol.) Isooctane ($C_8H_{18}$)<br>14–20% (liq. vol.) Toluene ($C_7H_8$)<br>17% (liq. vol.) *n*-Heptane ($C_7H_{16}$)<br>and<br>62% (liq. vol.) Isooctane ($C_8H_{18}$)<br>20% (liq. vol.) Ethanol ($C_2H_5OH$)<br>18% (liq. vol.) *n*-Heptane ($C_7H_{16}$)<br>and<br>45% (liq. vol.) Toluene ($C_7H_8$)<br>25% (liq. vol.) Isooctane ($C_8H_{18}$)<br>20% (liq. vol.) *n*-Heptane ($C_7H_{16}$)<br>10% (liq. vol.) Diisobutylene ($C_8H_{16}$) | Andrae *et al.* [19]<br>Andrae [20] | Octane numbers of blends match standard European gasoline. |
| Biodiesel | Methyl decaoate ($C_{10}H_{22}O_2$, i.e., $CH_3(CH_2)_8COOCH_3$) | Herbinet *et al.* [21] | 3,012 species and 8,820 reactions |

[1]Compositions given in mole percent unless otherwise noted.

# METHANE COMBUSTION

## Complex Mechanism

Because of its unique tetrahedral molecular structure with large C–H bond energies, methane exhibits some unique combustion characteristics. For example, it has a high ignition temperature, low flame speed, and low reactivity in photochemical smog chemistry compared to other hydrocarbons.

Methane chemical kinetics are perhaps the most widely researched and, hence, most well understood. Kaufman [22], in a review of combustion kinetics indicated that the methane combustion mechanism evolved in the period 1970–1982 from less than 15 elementary steps with 12 species to 75 elementary steps, plus the 75 reverse reactions, with 25 species. More recently, several research groups have collaborated in the creation of an optimized methane kinetic mechanism [23]. This mechanism, designated GRI Mech, is based on the optimization techniques of Frenklach *et al.* [24]. GRI Mech [23] is available on the Internet and is continually updated. Version 3.0, shown in Table 5.4, considers 325 elementary reactions involving 53 species. Many of these steps we have seen before as part of the $H_2$ and CO oxidation mechanisms.

To make some sense of this complex system, we present reaction pathway analyses for both high-temperature and low-temperature combustion of $CH_4$ with air in a well-stirred reactor [25] using GRI Mech 2.11. A detailed discussion of the well-stirred reactor is presented in Chapter 6; however, for our purposes here, we need only recognize that reactions take place in a homogeneous, isothermal environment. The choice of a well-stirred reactor eliminates the need to account for a spatial distribution of species as would be encountered in a flame, for example.

**Table 5.4** Complex methane combustion mechanism (GRI Mech 3.0) [23]

| | | Forward Rate Coefficient[a] | | |
|---|---|---|---|---|
| **No.** | **Reaction** | ***A*** | ***b*** | ***E*** |
| ***C–H–O Reactions*** | | | | |
| 1 | $O + O + M \rightarrow O_2 + M$ | 1.20E + 17 | −1.0 | 0.0 |
| 2 | $O + H + M \rightarrow OH + M$ | 5.00E + 17 | −1.0 | 0.0 |
| 3 | $O + H_2 \rightarrow H + OH$ | 3.87E + 04 | 2.7 | 6,260 |
| 4 | $O + HO_2 \rightarrow OH + O_2$ | 2.00E + 13 | 0.0 | 0.0 |
| 5 | $O + H_2O_2 \rightarrow OH + HO_2$ | 9.63E + 06 | 2.0 | 4,000 |
| 6 | $O + CH \rightarrow H + CO$ | 5.70E + 13 | 0.0 | 0.0 |
| 7 | $O + CH_2 \rightarrow H + HCO$ | 8.00E + 13 | 0.0 | 0.0 |
| 8[b] | $O + CH_2(S) \rightarrow H_2 + CO$ | 1.50E + 13 | 0.0 | 0.0 |
| 9[b] | $O + CH_2(S) \rightarrow H + HCO$ | 1.50E + 13 | 0.0 | 0.0 |
| 10 | $O + CH_3 \rightarrow H + CH_2O$ | 5.06E + 13 | 0.0 | 0.0 |
| 11 | $O + CH_4 \rightarrow OH + CH_3$ | 1.02E + 09 | 1.5 | 8,600 |
| 12 | $O + CO + M \rightarrow CO_2 + M$ | 1.8E + 10 | 0.0 | 2,385 |
| 13 | $O + HCO \rightarrow OH + CO$ | 3.00E + 13 | 0.0 | 0.0 |
| 14 | $O + HCO \rightarrow H + CO_2$ | 3.00E + 13 | 0.0 | 0.0 |
| 15 | $O + CH_2O \rightarrow OH + HCO$ | 3.90E + 13 | 0.0 | 3,540 |
| 16 | $O + CH_2OH \rightarrow OH + CH_2O$ | 1.00E + 13 | 0.0 | 0.0 |
| 17 | $O + CH_3O \rightarrow OH + CH_2O$ | 1.00E + 13 | 0.0 | 0.0 |
| 18 | $O + CH_3OH \rightarrow OH + CH_2OH$ | 3.88E + 05 | 2.5 | 3,100 |
| 19 | $O + CH_3OH \rightarrow OH + CH_3O$ | 1.30E + 05 | 2.5 | 5,000 |
| 20 | $O + C_2H \rightarrow CH + CO$ | 5.00E + 13 | 0.0 | 0.0 |
| 21 | $O + C_2H_2 \rightarrow H + HCCO$ | 1.35E + 07 | 2.0 | 1,900 |
| 22 | $O + C_2H_2 \rightarrow OH + C_2H$ | 4.60E + 19 | −1.4 | 28,950 |
| 23 | $O + C_2H_2 \rightarrow CO + CH_2$ | 9.64E + 06 | 2.0 | 1,900 |
| 24 | $O + C_2H_3 \rightarrow H + CH_2CO$ | 3.00E + 13 | 0.0 | 0.0 |

Table 5.4 (continued)

| No. | Reaction | Forward Rate Coefficient[a] A | b | E |
|---|---|---|---|---|
| *C–H–O Reactions (continued)* | | | | |
| 25 | $O + C_2H_4 \rightarrow CH_3 + HCO$ | 1.25E + 07 | 1.83 | 220 |
| 26 | $O + C_2H_5 \rightarrow CH_3 + CH_2O$ | 2.24E + 13 | 0.0 | 0.0 |
| 27 | $O + C_2H_6 \rightarrow OH + C_2H_5$ | 8.98E + 07 | 1.9 | 5,690 |
| 28 | $O + HCCO \rightarrow H + CO + CO$ | 1.00E + 14 | 0.0 | 0.0 |
| 29 | $O + CH_2CO \rightarrow OH + HCCO$ | 1.00E + 13 | 0.0 | 8,000 |
| 30 | $O + CH_2CO \rightarrow CH_2 + CO_2$ | 1.75E + 12 | 0.0 | 1,350 |
| 31 | $O_2 + CO \rightarrow O + CO_2$ | 2.50E + 12 | 0.0 | 47,800 |
| 32 | $O_2 + CH_2O \rightarrow HO_2 + HCO$ | 1.00E + 14 | 0.0 | 40,000 |
| 33 | $H + O_2 + M \rightarrow HO_2 + M$ | 2.80E + 18 | −0.9 | 0.0 |
| 34 | $H + O_2 + O_2 \rightarrow HO_2 + O_2$ | 2.08E + 19 | −1.2 | 0.0 |
| 35 | $H + O_2 + H_2O \rightarrow HO_2 + H_2O$ | 1.13E + 19 | −0.8 | 0.0 |
| 36 | $H + O_2 + N_2 \rightarrow HO_2 + N_2$ | 2.60E + 19 | −1.2 | 0.0 |
| 37 | $H + O_2 + Ar \rightarrow HO_2 + Ar$ | 7.00E + 17 | −0.8 | 0.0 |
| 38 | $H + O_2 \rightarrow O + OH$ | 2.65E + 16 | −0.7 | 17,041 |
| 39 | $H + H + M \rightarrow H_2 + M$ | 1.00E + 18 | −1.0 | 0.0 |
| 40 | $H + H + H_2 \rightarrow H_2 + H_2$ | 9.00E + 16 | −0.6 | 0.0 |
| 41 | $H + H + H_2O \rightarrow H_2 + H_2O$ | 6.00E + 19 | −1.2 | 0.0 |
| 42 | $H + H + CO_2 \rightarrow H_2 + CO_2$ | 5.50E + 20 | −2.0 | 0.0 |
| 43 | $H + OH + M \rightarrow H_2O + M$ | 2.20E + 22 | −2.0 | 0.0 |
| 44 | $H + HO_2 \rightarrow O + H_2O$ | 3.97E + 12 | 0.0 | 671 |
| 45 | $H + HO_2 \rightarrow O_2 + H_2$ | 4.48E + 13 | 0.0 | 1,068 |
| 46 | $H + HO_2 \rightarrow OH + OH$ | 8.4E + 13 | 0.0 | 635 |
| 47 | $H + H_2O_2 \rightarrow HO_2 + H_2$ | 1.21E + 07 | 2.0 | 5,200 |
| 48 | $H + H_2O_2 \rightarrow OH + H_2O$ | 1.00E + 13 | 0.0 | 3,600 |
| 49 | $H + CH \rightarrow C + H_2$ | 1.65E + 14 | 0.0 | 0.0 |
| 50 | $H + CH_2 (+ M) \rightarrow CH_3 (+ M)$ | | pressure dependent | |
| 51[b] | $H + CH_2(S) \rightarrow CH + H_2$ | 3.00E + 13 | 0.0 | 0.0 |
| 52 | $H + CH_3 (+ M) \rightarrow CH_4 (+ M)$ | | pressure dependent | |
| 53 | $H + CH_4 \rightarrow CH_3 + H_2$ | 6.60E + 08 | 1.6 | 10,840 |
| 54 | $H + HCO (+ M) \rightarrow CH_2O (+ M)$ | | pressure dependent | |
| 55 | $H + HCO \rightarrow H_2 + CO$ | 7.34E + 13 | 0.0 | 0.0 |
| 56 | $H + CH_2O (+ M) \rightarrow CH_2OH (+ M)$ | | pressure dependent | |
| 57 | $H + CH_2O (+ M) \rightarrow CH_3O (+ M)$ | | pressure dependent | |
| 58 | $H + CH_2O \rightarrow HCO + H_2$ | 5.74E + 07 | 1.9 | 2,742 |
| 59 | $H + CH_2OH (+ M) \rightarrow CH_3OH (+ M)$ | | pressure dependent | |
| 60 | $H + CH_2OH \rightarrow H_2 + CH_2O$ | 2.00E + 13 | 0.0 | 0.0 |
| 61 | $H + CH_2OH \rightarrow OH + CH_3$ | 1.65E + 11 | 0.7 | −284 |
| 62[b] | $H + CH_2OH \rightarrow CH_2(S) + H_2O$ | 3.28E + 13 | −0.1 | 610 |
| 63 | $H + CH_3O (+ M) \rightarrow CH_3OH (+ M)$ | | pressure dependent | |
| 64[b] | $H + CH_2OH \rightarrow CH_2(S) + H_2O$ | 4.15E + 07 | 1.6 | 1,924 |
| 65 | $H + CH_3O \rightarrow H_2 + CH_2O$ | 2.00E + 13 | 0.0 | 0.0 |
| 66 | $H + CH_3O \rightarrow OH + CH_3$ | 1.50E + 12 | 0.5 | −110 |
| 67[b] | $H + CH_3O \rightarrow CH_2(S) + H_2O$ | 2.62E + 14 | −0.2 | 1,070 |
| 68 | $H + CH_3OH \rightarrow CH_2OH + H_2$ | 1.70E + 07 | 2.1 | 4,870 |
| 69 | $H + CH_3OH \rightarrow CH_3O + H_2$ | 4.20E + 06 | 2.1 | 4,870 |
| 70 | $H + C_2H (+ M) \rightarrow C_2H_2 (+ M)$ | | pressure dependent | |

**Table 5.4** (continued)

| No. | Reaction | Forward Rate Coefficient[a] A | b | E |
|---|---|---|---|---|
| ***C–H–O Reactions (continued)*** | | | | |
| 71 | $H + C_2H_2 (+ M) \rightarrow C_2H_3 (+ M)$ | | pressure dependent | |
| 72 | $H + C_2H_3 (+ M) \rightarrow C_2H_4 (+ M)$ | | pressure dependent | |
| 73 | $H + C_2H_3 \rightarrow H_2 + C_2H_2$ | 3.00E + 13 | 0.0 | 0.0 |
| 74 | $H + C_2H_4 (+ M) \rightarrow C_2H_5 (+ M)$ | | pressure dependent | |
| 75 | $H + C_2H_4 \rightarrow C_2H_3 + H_2$ | 1.32E + 06 | 2.5 | 12,240 |
| 76 | $H + C_2H_5 (+ M) \rightarrow C_2H_6 (+ M)$ | | pressure dependent | |
| 77 | $H + C_2H_5 \rightarrow C_2H_4 + H_2$ | 2.00E + 12 | 0.0 | 0.0 |
| 78 | $H + C_2H_6 \rightarrow C_2H_5 + H_2$ | 1.15E + 08 | 1.9 | 7,530 |
| 79[b] | $H + HCCO \rightarrow CH_2(S) + CO$ | 1.00E + 14 | 0.0 | 0.0 |
| 80 | $H + CH_2CO \rightarrow HCCO + H_2$ | 5.00E + 13 | 0.0 | 8,000 |
| 81 | $H + CH_2CO \rightarrow CH_3 + CO$ | 1.13E + 13 | 0.0 | 3,428 |
| 82 | $H + HCCOH \rightarrow H + CH_2CO$ | 1.00E + 13 | 0.0 | 0.0 |
| 83 | $H_2 + CO (+ M) \rightarrow CH_2O (+ M)$ | | pressure dependent | |
| 84 | $OH + H_2 \rightarrow H + H_2O$ | 2.16E + 08 | 1.5 | 3,430 |
| 85 | $OH + OH (+ M) \rightarrow H_2O_2 (+ M)$ | | pressure dependent | |
| 86 | $OH + OH \rightarrow O + H_2O$ | 3.57E + 04 | 2.4 | −2,110 |
| 87 | $OH + HO_2 \rightarrow O_2 + H_2O$ | 1.45E + 13 | 0.0 | −500 |
| 88 | $OH + H_2O_2 \rightarrow HO_2 + H_2O$ | 2.00E + 12 | 0.0 | 427 |
| 89 | $OH + H_2O_2 \rightarrow HO_2 + H_2O$ | 1.70E + 18 | 0.0 | 29,410 |
| 90 | $OH + C \rightarrow H + CO$ | 5.00E + 13 | 0.0 | 0.0 |
| 91 | $OH + CH \rightarrow H + HCO$ | 3.00E + 13 | 0.0 | 0.0 |
| 92 | $OH + CH_2 \rightarrow H + CH_2O$ | 2.00E + 13 | 0.0 | 0.0 |
| 93 | $OH + CH_2 \rightarrow CH + H_2O$ | 1.13E + 07 | 2.0 | 3,000 |
| 94[b] | $OH + CH_2(S) \rightarrow H + CH_2O$ | 3.00E + 13 | 0.0 | 0.0 |
| 95 | $OH + CH_3 (+ M) \rightarrow CH_3OH (+ M)$ | | pressure dependent | |
| 96 | $OH + CH_3 \rightarrow CH_2 + H_2O$ | 5.60E + 07 | 1.6 | 5,420 |
| 97[b] | $OH + CH_3 \rightarrow CH_2(S) + H_2O$ | 6.44E + 17 | −1.3 | 1,417 |
| 98 | $OH + CH_4 \rightarrow CH_3 + H_2O$ | 1.00E + 08 | 1.6 | 3,120 |
| 99 | $OH + CO \rightarrow H + CO_2$ | 4.76E + 07 | 1.2 | 70 |
| 100 | $OH + HCO \rightarrow H_2O + CO$ | 5.00E + 13 | 0.0 | 0.0 |
| 101 | $OH + CH_2O \rightarrow HCO + H_2O$ | 3.43E + 09 | 1.2 | −447 |
| 102 | $OH + CH_2OH \rightarrow H_2O + CH_2O$ | 5.00E + 12 | 0.0 | 0.0 |
| 103 | $OH + CH_3O \rightarrow H_2O + CH_2O$ | 5.00E + 12 | 0.0 | 0.0 |
| 104 | $OH + CH_3OH \rightarrow CH_2OH + H_2O$ | 1.44E + 06 | 2.0 | −840 |
| 105 | $OH + CH_3OH \rightarrow CH_3O + H_2O$ | 6.30E + 06 | 2.0 | 1,500 |
| 106 | $OH + C_2H \rightarrow H + HCCO$ | 2.00E + 13 | 0.0 | 0.0 |
| 107 | $OH + C_2H_2 \rightarrow H + CH_2CO$ | 2.18E − 04 | 4.5 | −1,000 |
| 108 | $OH + C_2H_2 \rightarrow H + HCCOH$ | 5.04E + 05 | 2.3 | 13,500 |
| 109 | $OH + C_2H_2 \rightarrow C_2H + H_2O$ | 3.37E + 07 | 2.0 | 14,000 |
| 110 | $OH + C_2H_2 \rightarrow CH_3 + CO$ | 4.83E − 04 | 4.0 | −2,000 |
| 111 | $OH + C_2H_3 \rightarrow H_2O + C_2H_2$ | 5.00E + 12 | 0.0 | 0.0 |
| 112 | $OH + C_2H_4 \rightarrow C_2H_3 + H_2O$ | 3.60E + 06 | 2.0 | 2,500 |
| 113 | $OH + C_2H_6 \rightarrow C_2H_5 + H_2O$ | 3.54E + 06 | 2.1 | 870 |
| 114 | $OH + CH_2CO \rightarrow HCCO + H_2O$ | 7.50E + 12 | 0.0 | 2,000 |
| 115 | $HO_2 + HO_2 \rightarrow O_2 + H_2O_2$ | 1.30E + 11 | 0.0 | −1,630 |
| 116 | $HO_2 + HO_2 \rightarrow O_2 + H_2O_2$ | 4.20E + 14 | 0.0 | 12,000 |

**Table 5.4** (continued)

| No. | Reaction | Forward Rate Coefficient[a] *A* | *b* | *E* |
|---|---|---|---|---|
| *C–H–O Reactions (continued)* | | | | |
| 117 | $HO_2 + CH_2 \rightarrow OH + CH_2O$ | 2.00E + 13 | 0.0 | 0.0 |
| 118 | $HO_2 + CH_3 \rightarrow O_2 + CH_4$ | 1.00E + 12 | 0.0 | 0.0 |
| 119 | $HO_2 + CH_3 \rightarrow OH + CH_3O$ | 3.78E + 13 | 0.0 | 0.0 |
| 120 | $HO_2 + CO \rightarrow OH + CO_2$ | 1.50E + 14 | 0.0 | 23,600 |
| 121 | $HO_2 + CH_2O \rightarrow HCO + H_2O_2$ | 5.60E + 06 | 2.0 | 12,000 |
| 122 | $C + O_2 \rightarrow O + CO$ | 5.80E + 13 | 0.0 | 576 |
| 123 | $C + CH_2 \rightarrow H + C_2H$ | 5.00E + 13 | 0.0 | 0.0 |
| 124 | $C + CH_3 \rightarrow H + C_2H_2$ | 5.00E + 13 | 0.0 | 0.0 |
| 125 | $CH + O_2 \rightarrow O + HCO$ | 6.71E + 13 | 0.0 | 0.0 |
| 126 | $CH + H_2 \rightarrow H + CH_2$ | 1.08E + 14 | 0.0 | 3,110 |
| 127 | $CH + H_2O \rightarrow H + CH_2O$ | 5.71E + 12 | 0.0 | −755 |
| 128 | $CH + CH_2 \rightarrow H + C_2H_2$ | 4.00E + 13 | 0.0 | 0.0 |
| 129 | $CH + CH_3 \rightarrow H + C_2H_3$ | 3.00E + 13 | 0.0 | 0.0 |
| 130 | $CH + CH_4 \rightarrow H + C_2H_4$ | 6.00E + 13 | 0.0 | 0.0 |
| 131 | $CH + CO (+M) \rightarrow HCCO (+M)$ | | pressure dependent | |
| 132 | $CH + CO_2 \rightarrow HCO + CO$ | 1.90E + 14 | 0.0 | 15,792 |
| 133 | $CH + CH_2O \rightarrow H + CH_2CO$ | 9.46E + 13 | 0.0 | −515 |
| 134 | $CH + HCCO \rightarrow CO + C_2H_2$ | 5.00E + 13 | 0.0 | 0.0 |
| 135 | $CH_2 + O_2 \rightarrow OH + HCO$ | 5.00E + 12 | 0.0 | 1,500 |
| 136 | $CH_2 + H_2 \rightarrow H + CH_3$ | 5.00E + 05 | 2.0 | 7,230 |
| 137 | $CH_2 + CH_2 \rightarrow H_2 + C_2H_2$ | 1.60E + 15 | 0.0 | 11,944 |
| 138 | $CH_2 + CH_3 \rightarrow H + C_2H_4$ | 4.00E + 13 | 0.0 | 0.0 |
| 139 | $CH_2 + CH_4 \rightarrow CH_3 + CH_3$ | 2.46E + 06 | 2.0 | 8,270 |
| 140 | $CH_2 + CO (+M) \rightarrow CH_2CO (+M)$ | | pressure dependent | |
| 141 | $CH_2 + HCCO \rightarrow C_2H_3 + CO$ | 3.00E + 13 | 0.0 | 0.0 |
| 142[b] | $CH_2(S) + N_2 \rightarrow CH_2 + N_2$ | 1.50E + 13 | 0.0 | 600 |
| 143[b] | $CH_2(S) + Ar \rightarrow CH_2 + Ar$ | 9.00E + 12 | 0.0 | 600 |
| 144[b] | $CH_2(S) + O_2 \rightarrow H + OH + CO$ | 2.80E + 13 | 0.0 | 0.0 |
| 145[b] | $CH_2(S) + O_2 \rightarrow CO + H_2O$ | 1.20E + 13 | 0.0 | 0.0 |
| 146[b] | $CH_2(S) + H_2 \rightarrow CH_3 + H$ | 7.00E + 13 | 0.0 | 0.0 |
| 147[b] | $CH_2(S) + H_2O (+M) \rightarrow CH_3OH (+M)$ | | pressure dependent | |
| 148[b] | $CH_2(S) + H_2O \rightarrow CH_2 + H_2O$ | 3.00E + 13 | 0.0 | 0.0 |
| 149[b] | $CH_2(S) + CH_3 \rightarrow H + C_2H_4$ | 1.20E + 13 | 0.0 | −570 |
| 150[b] | $CH_2(S) + CH_4 \rightarrow CH_3 + CH_3$ | 1.60E + 13 | 0.0 | −570 |
| 151[b] | $CH_2(S) + CO \rightarrow CH_2 + CO$ | 9.00E + 12 | 0.0 | 0.0 |
| 152[b] | $CH_2(S) + CO_2 \rightarrow CH_2 + CO_2$ | 7.00E + 12 | 0.0 | 0.0 |
| 153[b] | $CH_2(S) + CO_2 \rightarrow CO + CH_2O$ | 1.40E + 13 | 0.0 | 0.0 |
| 154[b] | $CH_2(S) + C_2H_6 \rightarrow CH_3 + C_2H_5$ | 4.00E + 13 | 0.0 | −550 |
| 155 | $CH_3 + O_2 \rightarrow O + CH_3O$ | 3.56E + 13 | 0.0 | 30,480 |
| 156 | $CH_3 + O_2 \rightarrow OH + CH_2O$ | 2.31E + 12 | 0.0 | 20,315 |
| 157 | $CH_3 + H_2O_2 \rightarrow HO_2 + CH_4$ | 2.45E + 04 | 2.47 | 5,180 |
| 158 | $CH_3 + CH_3 (+M) \rightarrow C_2H_6 (+M)$ | | pressure dependent | |
| 159 | $CH_3 + CH_3 \rightarrow H + C_2H_5$ | 6.48E + 12 | 0.1 | 10,600 |
| 160 | $CH_3 + HCO \rightarrow CH_4 + CO$ | 2.65E + 13 | 0.0 | 0.0 |
| 161 | $CH_3 + CH_2O \rightarrow HCO + CH_4$ | 3.32E + 03 | 2.8 | 5,860 |

**Table 5.4** (continued)

| No. | Reaction | Forward Rate Coefficient[a] A | b | E |
|---|---|---|---|---|
| ***C–H–O Reactions (continued)*** | | | | |
| 162 | $CH_3 + CH_3OH \rightarrow CH_2OH + CH_4$ | 3.00E + 07 | 1.5 | 9,940 |
| 163 | $CH_3 + CH_3OH \rightarrow CH_3O + CH_4$ | 1.00E + 07 | 1.5 | 9,940 |
| 164 | $CH_3 + C_2H_4 \rightarrow C_2H_3 + CH_4$ | 2.27E + 05 | 2.0 | 9,200 |
| 165 | $CH_3 + C_2H_6 \rightarrow C_2H_5 + CH_4$ | 6.14E + 06 | 1.7 | 10,450 |
| 166 | $HCO + H_2O \rightarrow H + CO + H_2O$ | 1.55E + 18 | −1.0 | 17,000 |
| 167 | $HCO + M \rightarrow H + CO + M$ | 1.87E + 17 | −1.0 | 17,000 |
| 168 | $HCO + O_2 \rightarrow HO_2 + CO$ | 1.35E + 13 | 0.0 | 400 |
| 169 | $CH_2OH + O_2 \rightarrow HO_2 + CH_2O$ | 1.80E + 13 | 0.0 | 900 |
| 170 | $CH_3O + O_2 \rightarrow HO_2 + CH_2O$ | 4.28E − 13 | 7.6 | −3,530 |
| 171 | $C_2H + O_2 \rightarrow HCO + CO$ | 1.00E + 13 | 0.0 | −755 |
| 172 | $C_2H + H_2 \rightarrow H + C_2H_2$ | 5.68E + 10 | 0.9 | 1,993 |
| 173 | $C_2H_3 + O_2 \rightarrow HCO + CH_2O$ | 4.58E + 16 | −1.4 | 1,015 |
| 174 | $C_2H_4\ (+M) \rightarrow H_2 + C_2H_2\ (+M)$ | | pressure dependent | |
| 175 | $C_2H_5 + O_2 \rightarrow HO_2 + C_2H_4$ | 8.40E + 11 | 0.0 | 3,875 |
| 176 | $HCCO + O_2 \rightarrow OH + CO + CO$ | 3.20E + 12 | 0.0 | 854 |
| 177 | $HCCO + HCCO \rightarrow CO + CO + C_2H_2$ | 1.00E + 13 | 0.0 | 0.0 |
| ***N-Containing Reactions*** | | | | |
| 178 | $N + NO \rightarrow N_2 + O$ | 2.70E + 13 | 0.0 | 355 |
| 179 | $N + O_2 \rightarrow NO + O$ | 9.00E + 09 | 1.0 | 6,500 |
| 180 | $N + OH \rightarrow NO + H$ | 3.36E + 13 | 0.0 | 385 |
| 181 | $N_2O + O \rightarrow N_2 + O_2$ | 1.40E + 12 | 0.0 | 10,810 |
| 182 | $N_2O + O \rightarrow NO + NO$ | 2.90E + 13 | 0.0 | 23,150 |
| 183 | $N_2O + H \rightarrow N_2 + OH$ | 3.87E + 14 | 0.0 | 18,880 |
| 184 | $N_2O + OH \rightarrow N_2 + HO_2$ | 2.00E + 12 | 0.0 | 21,060 |
| 185 | $N_2O\ (+M) \rightarrow N_2 + O\ (+M)$ | | pressure dependent | |
| 186 | $HO_2 + NO \rightarrow NO_2 + OH$ | 2.11E + 12 | 0.0 | −480 |
| 187 | $NO + O + M \rightarrow NO_2 + M$ | 1.06E + 20 | −1.4 | 0.0 |
| 188 | $NO_2 + O \rightarrow NO + O_2$ | 3.90E + 12 | 0.0 | −240 |
| 189 | $NO_2 + H \rightarrow NO + OH$ | 1.32E + 14 | 0.0 | 360 |
| 190 | $NH + O \rightarrow NO + H$ | 4.00E + 13 | 0.0 | 0.0 |
| 191 | $NH + H \rightarrow N + H_2$ | 3.20E + 13 | 0.0 | 330 |
| 192 | $NH + OH \rightarrow HNO + H$ | 2.00E + 13 | 0.0 | 0.0 |
| 193 | $NH + OH \rightarrow N + H_2O$ | 2.00E + 09 | 1.2 | 0.0 |
| 194 | $NH + O_2 \rightarrow HNO + O$ | 4.61E + 05 | 2.0 | 6,500 |
| 195 | $NH + O_2 \rightarrow NO + OH$ | 1.28E + 06 | 1.5 | 100 |
| 196 | $NH + N \rightarrow N_2 + H$ | 1.50E + 13 | 0.0 | 0.0 |
| 197 | $NH + H_2O \rightarrow HNO + H_2$ | 2.00E + 13 | 0.0 | 13,850 |
| 198 | $NH + NO \rightarrow N_2 + OH$ | 2.16E + 13 | −0.2 | 0.0 |
| 199 | $NH + NO \rightarrow N_2O + H$ | 3.65E + 14 | −0.5 | 0.0 |
| 200 | $NH_2 + O \rightarrow OH + NH$ | 3.00E + 12 | 0.0 | 0.0 |

**Table 5.4** (continued)

| No. | Reaction | Forward Rate Coefficient[a] A | b | E |
|---|---|---|---|---|
| *N-Containing Reactions (continued)* | | | | |
| 201 | $NH_2 + O \rightarrow H + HNO$ | 3.9E + 13 | 0.0 | 0.0 |
| 202 | $NH_2 + H \rightarrow NH + H_2$ | 4.00E + 13 | 0.0 | 3,650 |
| 203 | $NH_2 + OH \rightarrow NH + H_2O$ | 9.00E + 07 | 1.5 | −460 |
| 204 | $NNH \rightarrow N_2 + H$ | 3.30E + 08 | 0.0 | 0.0 |
| 205 | $NNH + M \rightarrow N_2 + H + M$ | 1.30E + 14 | −0.1 | 4,980 |
| 206 | $NNH + O_2 \rightarrow HO_2 + N_2$ | 5.00E + 12 | 0.0 | 0.0 |
| 207 | $NNH + O \rightarrow OH + N_2$ | 2.50E + 13 | 0.0 | 0.0 |
| 208 | $NNH + O \rightarrow NH + NO$ | 7.00E + 13 | 0.0 | 0.0 |
| 209 | $NNH + H \rightarrow H_2 + N_2$ | 5.00E + 13 | 0.0 | 0.0 |
| 210 | $NNH + OH \rightarrow H_2O + N_2$ | 2.00E + 13 | 0.0 | 0.0 |
| 211 | $NNH + CH_3 \rightarrow CH_4 + N_2$ | 2.50E + 13 | 0.0 | 0.0 |
| 212 | $H + NO + M \rightarrow HNO + M$ | 4.48E + 19 | −1.3 | 740 |
| 213 | $HNO + O \rightarrow NO + OH$ | 2.50E + 13 | 0.0 | 0.0 |
| 214 | $HNO + H \rightarrow H_2 + NO$ | 9.00E + 11 | 0.7 | 660 |
| 215 | $HNO + OH \rightarrow NO + H_2O$ | 1.30E + 07 | 1.9 | −950 |
| 216 | $HNO + O_2 \rightarrow HO_2 + NO$ | 1.00E + 13 | 0.0 | 13,000 |
| 217 | $CN + O \rightarrow CO + N$ | 7.70E + 13 | 0.0 | 0.0 |
| 218 | $CN + OH \rightarrow NCO + H$ | 4.00E + 13 | 0.0 | 0.0 |
| 219 | $CN + H_2O \rightarrow HCN + OH$ | 8.00E + 12 | 0.0 | 7,460 |
| 220 | $CN + O_2 \rightarrow NCO + O$ | 6.14E + 12 | 0.0 | −440 |
| 221 | $CN + H_2 \rightarrow HCN + H$ | 2.95E + 05 | 2.5 | 2,240 |
| 222 | $NCO + O \rightarrow NO + CO$ | 2.35E + 13 | 0.0 | 0.0 |
| 223 | $NCO + H \rightarrow NH + CO$ | 5.40E + 13 | 0.0 | 0.0 |
| 224 | $NCO + OH \rightarrow NO + H + CO$ | 2.50E + 12 | 0.0 | 0.0 |
| 225 | $NCO + N \rightarrow N_2 + CO$ | 2.00E + 13 | 0.0 | 0.0 |
| 226 | $NCO + O_2 \rightarrow NO + CO_2$ | 2.00E + 12 | 0.0 | 20,000 |
| 227 | $NCO + M \rightarrow N + CO + M$ | 3.10E + 14 | 0.0 | 54,050 |
| 228 | $NCO + NO \rightarrow N_2O + CO$ | 1.90E + 17 | −1.5 | 740 |
| 229 | $NCO + NO \rightarrow N_2 + CO_2$ | 3.80E + 18 | −2.0 | 800 |
| 230 | $HCN + M \rightarrow H + CN + M$ | 1.04E + 29 | −3.3 | 126,600 |
| 231 | $HCN + O \rightarrow NCO + H$ | 2.03E + 04 | 2.6 | 4,980 |
| 232 | $HCN + O \rightarrow NH + CO$ | 5.07E + 03 | 2.6 | 4,980 |
| 233 | $HCN + O \rightarrow CN + OH$ | 3.91E + 09 | 1.6 | 26,600 |
| 234 | $HCN + OH \rightarrow HOCN + H$ | 1.10E + 06 | 2.0 | 13,370 |
| 235 | $HCN + OH \rightarrow HNCO + H$ | 4.40E + 03 | 2.3 | 6,400 |
| 236 | $HCN + OH \rightarrow NH_2 + CO$ | 1.60E + 02 | 2.6 | 9,000 |
| 237 | $H + HCN + M \rightarrow H_2CN + M$ | | pressure dependent | |
| 238 | $H_2CN + N \rightarrow N_2 + CH_2$ | 6.00E + 13 | 0.0 | 400 |
| 239 | $C + N_2 \rightarrow CN + N$ | 6.30E + 13 | 0.0 | 46,020 |
| 240 | $CH + N_2 \rightarrow HCN + N$ | 3.12E + 09 | 0.9 | 20,130 |
| 241 | $CH + N_2 (+M) \rightarrow HCNN (+M)$ | | pressure dependent | |
| 242 | $CH_2 + N_2 \rightarrow HCN + NH$ | 1.00E + 13 | 0.0 | 74,000 |
| 243[b] | $CH_2(S) + N_2 \rightarrow NH + HCN$ | 1.00E + 11 | 0.0 | 65,000 |

**Table 5.4** (continued)

| | | Forward Rate Coefficient[a] | | |
|---|---|---|---|---|
| **No.** | **Reaction** | ***A*** | ***b*** | ***E*** |
| ***N-Containing Reactions (continued)*** | | | | |
| 244 | $C + NO \rightarrow CN + O$ | 1.90E + 13 | 0.0 | 0.0 |
| 245 | $C + NO \rightarrow CO + N$ | 2.90E + 13 | 0.0 | 0.0 |
| 246 | $CH + NO \rightarrow HCN + O$ | 4.10E + 13 | 0.0 | 0.0 |
| 247 | $CH + NO \rightarrow H + NCO$ | 1.62E + 13 | 0.0 | 0.0 |
| 248 | $CH + NO \rightarrow N + HCO$ | 2.46E + 13 | 0.0 | 0.0 |
| 249 | $CH_2 + NO \rightarrow H + HNCO$ | 3.10E + 17 | −1.4 | 1,270 |
| 250 | $CH_2 + NO \rightarrow OH + HCN$ | 2.90E + 14 | −0.7 | 760 |
| 251 | $CH_2 + NO \rightarrow H + HCNO$ | 3.80E + 13 | −0.4 | 580 |
| 252[b] | $CH_2(S) + NO \rightarrow H + HNCO$ | 3.10E + 17 | −1.4 | 1,270 |
| 253[b] | $CH_2(S) + NO \rightarrow OH + HCN$ | 2.90E + 14 | −0.7 | 760 |
| 254[b] | $CH_2(S) + NO \rightarrow H + HCNO$ | 3.80E + 13 | −0.4 | 580 |
| 255 | $CH_3 + NO \rightarrow HCN + H_2O$ | 9.60E + 13 | 0.0 | 28,800 |
| 256 | $CH_3 + NO \rightarrow H_2CN + OH$ | 1.00E + 12 | 0.0 | 21,750 |
| 257 | $HCNN + O \rightarrow CO + H + N_2$ | 2.20E + 13 | 0.0 | 0.0 |
| 258 | $HCNN + O \rightarrow HCN + NO$ | 2.00E + 12 | 0.0 | 0.0 |
| 259 | $HCNN + O_2 \rightarrow O + HCO + N_2$ | 1.20E + 13 | 0.0 | 0.0 |
| 260 | $HCNN + OH \rightarrow H + HCO + N_2$ | 1.20E + 13 | 0.0 | 0.0 |
| 261 | $HCNN + H \rightarrow CH_2 + N_2$ | 1.00E + 14 | 0.0 | 0.0 |
| 262 | $HNCO + O \rightarrow NH + CO_2$ | 9.80E + 07 | 1.4 | 8,500 |
| 263 | $HNCO + O \rightarrow HNO + CO$ | 1.50E + 08 | 1.6 | 44,000 |
| 264 | $HNCO + O \rightarrow NCO + OH$ | 2.20E + 06 | 2.1 | 11,400 |
| 265 | $HNCO + H \rightarrow NH_2 + CO$ | 2.25E + 07 | 1.7 | 3,800 |
| 266 | $HNCO + H \rightarrow H_2 + NCO$ | 1.05E + 05 | 2.5 | 13,300 |
| 267 | $HNCO + OH \rightarrow NCO + H_2O$ | 3.30E + 07 | 1.5 | 3,600 |
| 268 | $HNCO + OH \rightarrow NH_2 + CO_2$ | 3.30E + 06 | 1.5 | 3,600 |
| 269 | $HNCO + M \rightarrow NH + CO + M$ | 1.18E + 16 | 0.0 | 84,720 |
| 270 | $HCNO + H \rightarrow H + HNCO$ | 2.10E + 15 | −0.7 | 2,850 |
| 271 | $HCNO + H \rightarrow OH + HCN$ | 2.70E + 11 | 0.2 | 2,120 |
| 272 | $HCNO + H \rightarrow NH_2 + CO$ | 1.70E + 14 | −0.8 | 2,890 |
| 273 | $HOCN + H \rightarrow H + HNCO$ | 2.00E + 07 | 2.0 | 2,000 |
| 274 | $HCCO + NO \rightarrow HCNO + CO$ | 9.00E + 12 | 0.0 | 0.0 |
| 275 | $CH_3 + N \rightarrow H_2CN + H$ | 6.10E + 14 | −0.3 | 290 |
| 276 | $CH_3 + N \rightarrow HCN + H_2$ | 3.70E + 12 | 0.1 | −90 |
| 277 | $NH_3 + H \rightarrow NH_2 + H_2$ | 5.40E + 05 | 2.4 | 9,915 |
| 278 | $NH_3 + OH \rightarrow NH_2 + H_2O$ | 5.00E + 07 | 1.6 | 955 |
| 279 | $NH_3 + O \rightarrow NH_2 + OH$ | 9.40E + 06 | 1.9 | 6,460 |
| ***Reactions Added in Update from Version 2.11 to Version 3.0*** | | | | |
| 280 | $NH + CO_2 \rightarrow HNO + CO$ | 1.00E + 13 | 0.0 | 14,350 |
| 281 | $CN + NO_2 \rightarrow NCO + NO$ | 6.16E + 15 | −0.8 | 345 |
| 282 | $NCO + NO_2 \rightarrow N_2O + CO_2$ | 3.25E + 12 | 0.0 | −705 |
| 283 | $N + CO_2 \rightarrow NO + CO$ | 3.00E + 12 | 0.0 | 11,300 |
| 284 | $O + CH_3 \rightarrow H + H_2 + CO$ | 3.37E + 13 | 0.0 | 0.0 |
| 285 | $O + C_2H_4 \rightarrow CH_2CHO$ | 6.70E + 06 | 1.8 | 220 |
| 286 | $O + C_2H_5 \rightarrow H + CH_3CHO$ | 1.10E + 14 | 0.0 | 0.0 |

**Table 5.4** (continued)

| No. | Reaction | Forward Rate Coefficient[a] *A* | *b* | *E* |
|---|---|---|---|---|
| ***Reactions Added in Update from Version 2.11 to Version 3.0 (continued)*** | | | | |
| 287 | $OH + HO_2 \rightarrow O_2 + H_2O$ | 5.00E + 15 | 0.0 | 17,330 |
| 288 | $OH + CH_3 \rightarrow H_2 + CH_2O$ | 8.00E + 09 | 0.5 | −1,755 |
| 289 | $CH + H_2 + M \rightarrow CH_3 + M$ | | pressure dependent | |
| 290 | $CH_2 + O_2 \rightarrow H + H + CO_2$ | 5.80E + 12 | 0.0 | 1,500 |
| 291 | $CH_2 + O_2 \rightarrow O + CH_2O$ | 2.40E + 12 | 0.0 | 1,500 |
| 292 | $CH_2 + CH_2 \rightarrow H + H + C_2H_2$ | 2.00E + 14 | 0.0 | 10,989 |
| 293[b] | $CH_2(S) + H_2O \rightarrow H_2 + CH_2O$ | 6.82E + 10 | 0.2 | −935 |
| 294 | $C_2H_3 + O_2 \rightarrow O + CH_2CHO$ | 3.03E + 11 | 0.3 | 11 |
| 295 | $C_2H_3 + O_2 \rightarrow HO_2 + C_2H_2$ | 1.34E + 06 | 1.6 | −384 |
| 296 | $O + CH_3CHO \rightarrow OH + CH_2CHO$ | 2.92E + 12 | 0.0 | 1,808 |
| 297 | $O + CH_3CHO \rightarrow OH + CH_3 + CO$ | 2.92E + 12 | 0.0 | 1,808 |
| 298 | $O_2 + CH_3CHO \rightarrow HO_2 + CH_3 + CO$ | 3.01E + 13 | 0.0 | 39,150 |
| 299 | $H + CH_3CHO \rightarrow CH_2CHO + H_2$ | 2.05E + 09 | 1.2 | 2,405 |
| 300 | $H + CH_3CHO \rightarrow CH_3 + H_2 + CO$ | 2.05E + 09 | 1.2 | 2,405 |
| 301 | $OH + CH_3CHO \rightarrow CH_3 + H_2O + CO$ | 2.34E + 10 | 0.7 | −1,113 |
| 302 | $HO_2 + CH_3CHO \rightarrow CH_3 + H_2O_2 + CO$ | 3.01E + 12 | 0.0 | 11,923 |
| 303 | $CH_3 + CH_3CHO \rightarrow CH_3 + CH_4 + CO$ | 2.72E + 06 | 1.8 | 5,920 |
| 304 | $H + CH_2CO + M \rightarrow CH_2CHO + M$ | | pressure dependent | |
| 305 | $O + CH_2CHO \rightarrow H + CH_2 + CO_2$ | 1.50E + 14 | 0.0 | 0.0 |
| 306 | $O_2 + CH_2CHO \rightarrow OH + CO + CH_2O$ | 1.81E + 10 | 0.0 | 0.0 |
| 307 | $O_2 + CH_2CHO \rightarrow OH + HCO + HCO$ | 2.35E + 10 | 0.0 | 0.0 |
| 308 | $H + CH_2CHO \rightarrow CH_3 + HCO$ | 2.20E + 13 | 0.0 | 0.0 |
| 309 | $H + CH_2CHO \rightarrow CH_2CO + H_2$ | 1.10E + 13 | 0.0 | 0.0 |
| 310 | $OH + CH_2CHO \rightarrow H_2O + CH_2CO$ | 1.20E + 13 | 0.0 | 0.0 |
| 311 | $OH + CH_2CHO \rightarrow HCO + CH_2OH$ | 3.01E + 13 | 0.0 | 0.0 |
| 312 | $CH_3 + C_2H_5 + M \rightarrow C_3H_8 + M$ | | pressure dependent | |
| 313 | $O + C_3H_8 \rightarrow OH + C_3H_7$ | 1.93E + 05 | 2.7 | 3,716 |
| 314 | $H + C_3H_8 \rightarrow C_3H_7 + H_2$ | 1.32E + 06 | 2.5 | 6,756 |
| 315 | $OH + C_3H_8 \rightarrow C_3H_7 + H_2O$ | 3.16E + 07 | 1.8 | 934 |
| 316 | $C_3H_7 + H_2O_2 \rightarrow HO_2 + C_3H_8$ | 3.78E + 02 | 2.7 | 1,500 |
| 317 | $CH_3 + C_3H_8 \rightarrow C_3H_7 + CH_4$ | 9.03E − 01 | 3.6 | 7,154 |
| 318 | $CH_3 + C_2H_4 + M \rightarrow C_3H_7 + M$ | | pressure dependent | |
| 319 | $O + C_3H_7 \rightarrow C_2H_5 + CH_2O$ | 9.64E + 13 | 0.0 | 0.0 |
| 320 | $H + C_3H_7 + M \rightarrow C_3H_8 + M$ | | pressure dependent | |
| 321 | $H + C_3H_7 \rightarrow CH_3 + C_2H_5$ | 4.06E + 06 | 2.2 | 890 |
| 322 | $OH + C_3H_7 \rightarrow C_2H_5 + CH_2OH$ | 2.41E + 13 | 0.0 | 0.0 |
| 323 | $HO_2 + C_3H_7 \rightarrow O_2 + C_3H_8$ | 2.55E + 10 | 0.3 | −943 |
| 324 | $HO_2 + C_3H_7 \rightarrow OH + C_2H_5 + CH_2O$ | 2.41E + 13 | 0.0 | 0.0 |
| 325 | $CH_3 + C_3H_7 \rightarrow C_2H_5 + C_2H_5$ | 1.93E + 13 | −0.3 | 0.0 |

[a]The forward rate coefficient $k = AT^b \exp(-E/RT)$. $R$ is the universal gas constant, $T$ is the temperature in K. The units of $A$ involve gmol/cm$^3$ and s, and those of $E$, cal/gmol.

[b]$CH_2(S)$ designates the singlet state of $CH_2$.

chapter

# 8

# Laminar Premixed Flames

## OVERVIEW

In previous chapters, we introduced the concepts of mass transfer (Chapter 3) and chemical kinetics (Chapters 4 and 5) and linked them with familiar thermodynamic and heat transfer concepts in Chapters 6 and 7. Understanding premixed laminar flames requires us to utilize all of these concepts. Our development in Chapter 7 of the one-dimensional conservation equations for a reacting flow will be the starting point for analyzing laminar flames.

Laminar premixed flames, frequently in conjunction with diffusion flames, have application in many residential, commercial, and industrial devices and processes. Examples include gas ranges and ovens, heating appliances, and Bunsen burners. An advanced cooktop burner for a gas range is illustrated in Fig. 8.1. Laminar, premixed, natural-gas flames also are frequently employed in the manufacturing of glass products. As suggested by the examples given above, laminar premixed flames are by themselves important; but, perhaps more importantly, understanding laminar flames is a necessary prerequisite to the study of turbulent flames. In both laminar and turbulent flows, the same physical processes are active, and many turbulent flame theories are based on an underlying laminar flame structure. In this chapter, we will qualitatively describe the essential characteristics of laminar premixed flames and develop a simplified analysis of these flames that allows us to see what factors influence the laminar flame speed and the flame thickness. A detailed analysis using state-of-the-art methods will illustrate the power of numerical simulations in understanding flame structure. We will also examine experimental data that illustrate how equivalence ratio, temperature, pressure, and fuel type affect flame speed and flame thickness. Flame speed is emphasized because it is this property that dictates flame shape and important flame-stability characteristics, such as blowoff and flashback. The chapter concludes with discussion of flammability limits and ignition and extinction phenomena.

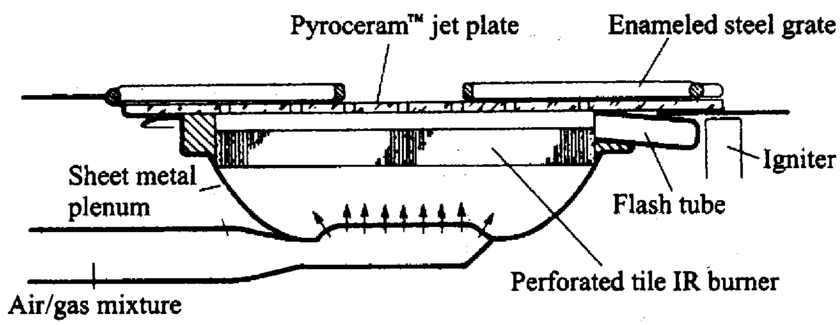


**Figure 8.1** Advanced residential cooktop burner for gas ranges.
SOURCE: Courtesy of the Gas Research Institute.

# PHYSICAL DESCRIPTION

## Definition

Before proceeding, it is useful to define what we mean by a flame. A **flame** is a self-sustaining propagation of a localized combustion zone at subsonic velocities. There are several key words in this definition. First, we require a flame to be localized; that is, the flame occupies only a small portion of the combustible mixture at any one time. This is in contrast to the various homogeneous reactors we studied in Chapter 6, where reaction was assumed to occur uniformly throughout the reaction vessel. The second key word is subsonic. A discrete combustion wave that travels subsonically is termed a **deflagration.** It is also possible for combustion waves to propagate at supersonic velocities. Such a wave is called a **detonation.** The fundamental propagation mechanisms are different in deflagrations and detonations, and, because of this, these are distinct phenomena. Detonations are discussed in Chapter 16.

## Principal Characteristics

The temperature profile through a flame is perhaps its most important characteristic. Figure 8.2 illustrates a typical flame temperature profile, together with other essential flame features.

To understand this figure, we need to establish a reference frame for our coordinate system. A flame may be freely propagating, as occurs when a flame is initiated in a tube containing a combustible gas mixture. The appropriate coordinate system would be fixed to the propagating combustion wave. An observer riding with the flame would experience the unburned mixture approaching at the **flame speed,** $S_L$. This is equivalent to a flat flame stabilized on a burner. Here, the flame is stationary relative to the laboratory reference frame and, once again, the reactants enter the flame with a velocity equal to the flame propagation velocity, $S_L$. In both examples, we assume that the flame is one dimensional and that the unburned gas enters the flame in a direction normal to the flame sheet. Since a flame creates hot products, the product density is less than the reactant density. Continuity thus requires that the burned gas velocity be greater than the velocity of the unburned gas:

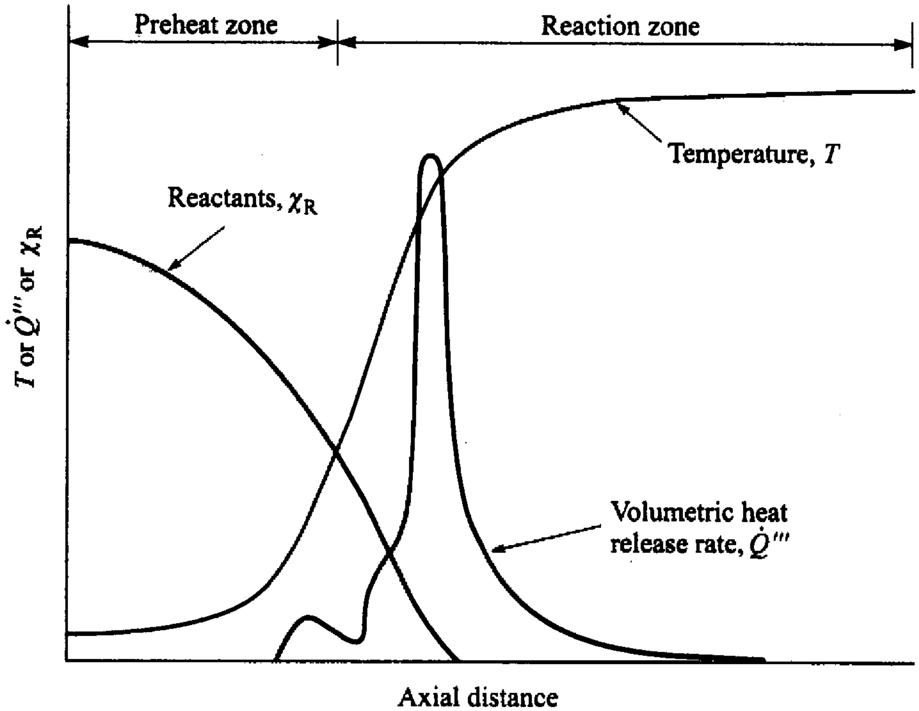


**Figure 8.2** Laminar flame structure. Temperature and heat-release-rate profiles based on experiments of Friedman and Burke [1].

$$\rho_u S_L A \equiv \rho_u v_u A = \rho_b v_b A, \tag{8.1}$$

where the subscripts $u$ and $b$ refer to the unburned and burned gases, respectively. For a typical hydrocarbon–air flame at atmospheric pressure, the density ratio is approximately seven. Thus, there is considerable acceleration of the gas flow across the flame.

It is convenient to divide a flame into two zones: the **preheat zone,** where little heat is released; and the **reaction zone,** where the bulk of the chemical energy is released. At atmospheric pressure, the flame thickness is quite thin, on the order of a millimeter. It is useful to divide the reaction zone further into a thin region of very fast chemistry followed by a much wider region of slow chemistry. The destruction of the fuel molecules and the creation of many intermediate species occur in the fast-chemistry region. This region is dominated by bimolecular reactions. At atmospheric pressure, the fast-reaction zone is quite thin, typically less than a millimeter. Because this zone is thin, temperature gradients and species concentration gradients are very large. These gradients provide the driving forces that cause the flame to be self-sustaining: the diffusion of heat and radical species from the reaction zone to the preheat zone. In the secondary reaction zone, the chemistry is dominated by three-body radical recombination reactions, which are much slower than typical bimolecular reactions, and the final burnout of CO via $CO + OH \rightarrow CO_2 + H$. This secondary reaction zone may extend several millimeters in a 1-atm flame. Later in this chapter, we present a more detailed description of flame structure illustrating these ideas. Additional information may also be found in Fristrom [2].

Hydrocarbon flames are also characterized by their visible radiation. With an excess of air, the fast-reaction zone appears blue. This blue radiation results from excited CH radicals in the high-temperature zone. When the air is decreased to less than stoichiometric proportions, the zone appears blue-green, now as a result of radiation from excited $C_2$. In both flames, OH radicals also contribute to the visible radiation, and to a lesser degree, chemiluminescence from the reaction $CO + O \rightarrow CO_2 + h\nu$ [3]. If the flame is made richer still, soot will form, with its consequent blackbody continuum radiation. Although the soot radiation has its maximum intensity in the infrared (recall Wien's law?), the spectral sensitivity of the human eye causes us to see a bright yellow (nearly white) to dull orange emission, depending on the flame temperature. References [4] and [5] provide a wealth of information on radiation from flames.

## Typical Laboratory Flames

The Bunsen-burner flame provides an interesting example of laminar premixed flames with which most students have some familiarity and that can be easily used in classroom demonstrations. Figure 8.3a schematically illustrates a Bunsen burner and the flame it produces. A jet of fuel at the base induces a flow of air through the variable area port, and the air and fuel mix as they flow up through the tube. The typical Bunsen-burner flame is a dual flame: a fuel-rich premixed inner flame surrounded by a diffusion flame. The secondary diffusion flame results when the carbon monoxide and hydrogen products from the rich inner flame encounter the ambient air. The shape of the flame is determined by the combined effects of the velocity profile and heat losses to the tube wall. For the flame to remain stationary, the flame speed must equal the speed of the normal component of unburned gas at each location, as illustrated in the vector diagram in Fig. 8.3b. Thus,

$$S_L = v_u \sin \alpha, \tag{8.2}$$

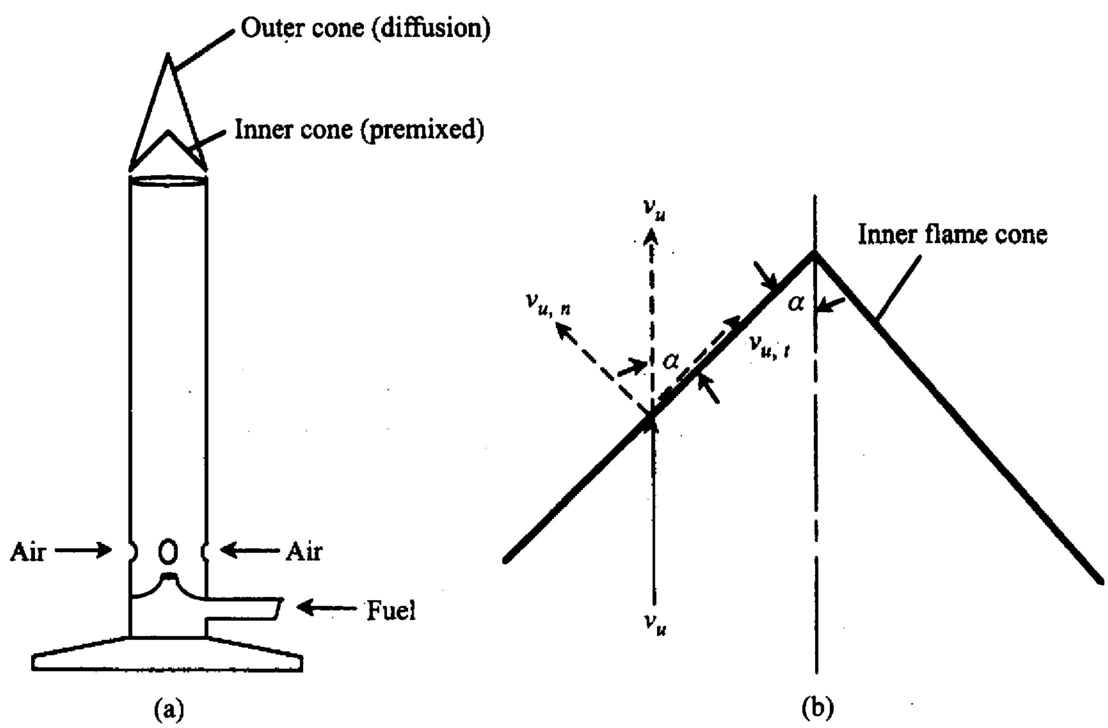


**Figure 8.3** (a) Bunsen-burner schematic. (b) Laminar flame speed equals normal component of unburned gas velocity, $v_{u,n}$.

where $S_L$ is the laminar burning velocity. This principle causes the essential conical character of the flame.

One-dimensional flat flames are frequently studied in the laboratory and are also used in some radiant heating burners (Fig. 8.4). Figure 8.5 illustrates the laboratory

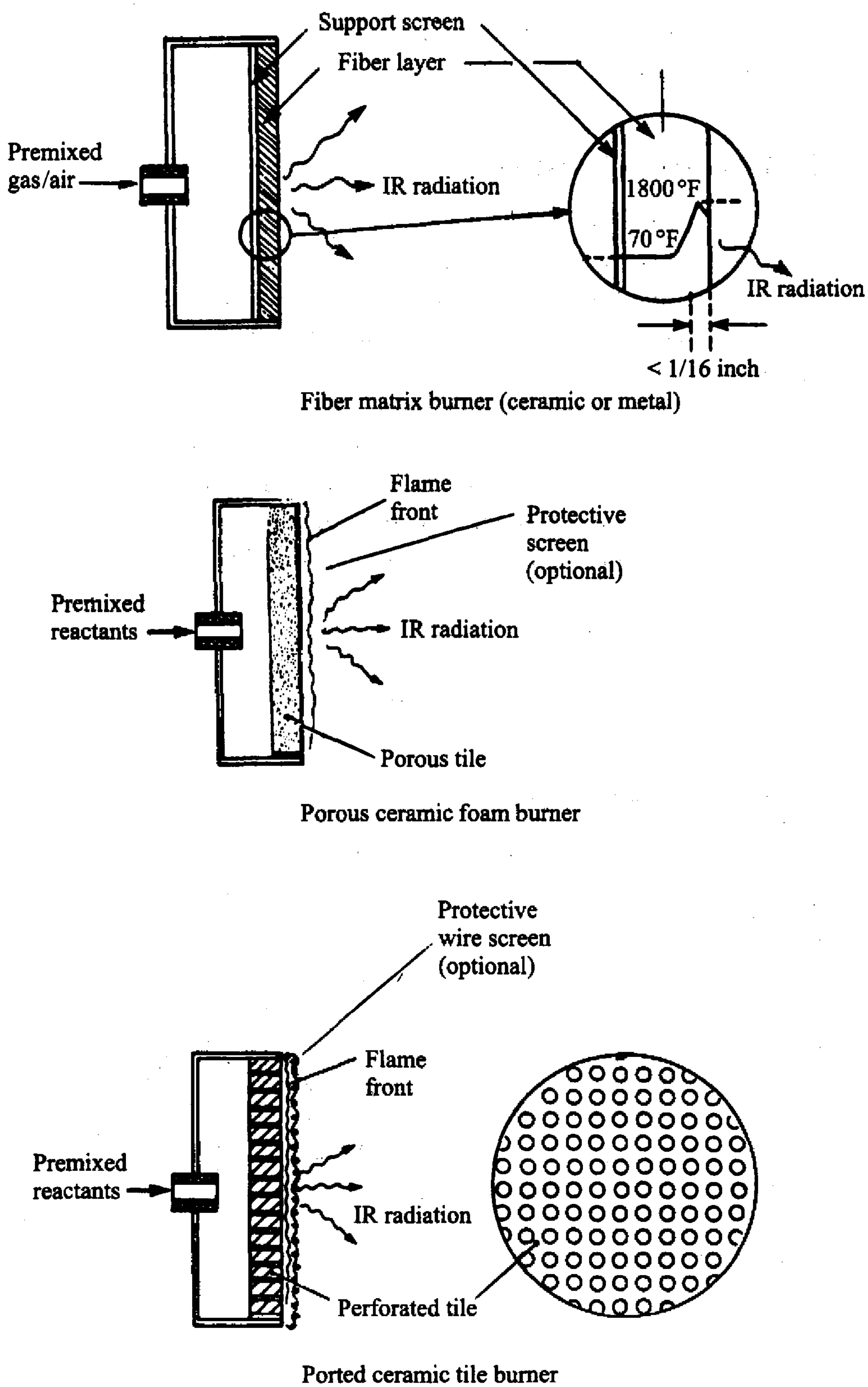


**Figure 8.4** Direct-fired radiant burners provide uniform heat flux and high efficiency.
SOURCE: Reprinted with permission from the Center for Advanced Materials, *Newsletter*, (1), 1990, Penn State University.

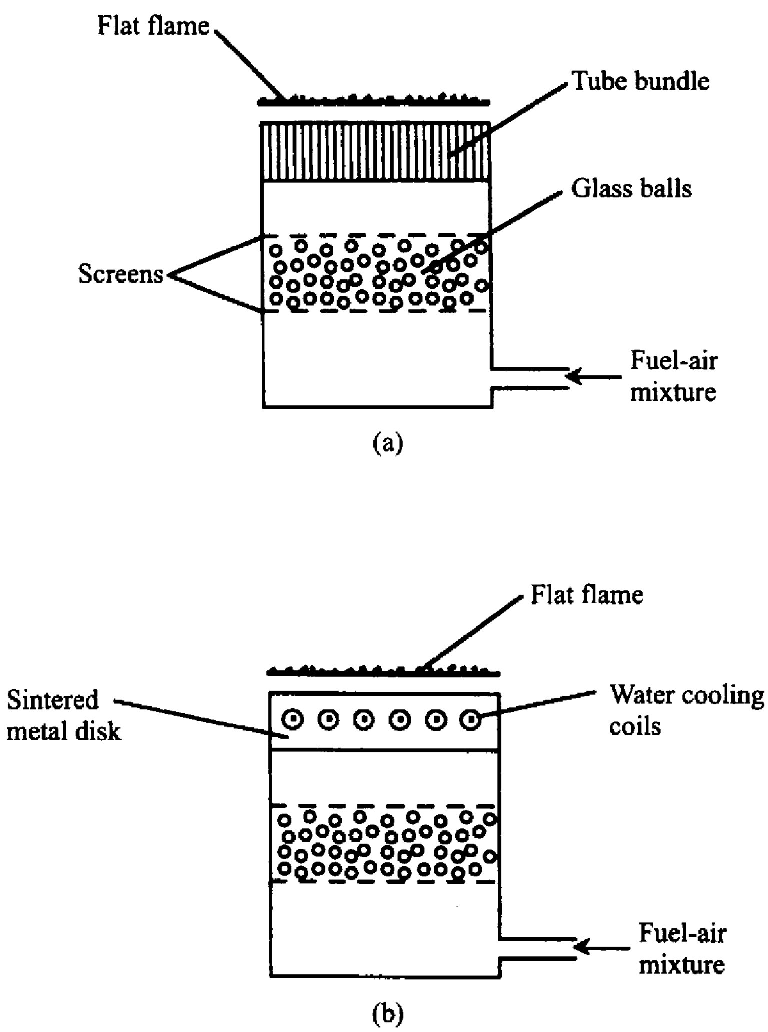


**Figure 8.5** (a) Adiabatic flat-flame burner. (b) Nonadiabatic flat-flame burner.

genre. In the adiabatic burner, a flame is stabilized over a bundle of small tubes through which the fuel–air mixture passes laminarly [6]. Over a narrow range of conditions, a stable flat flame is produced. The nonadiabatic burner utilizes a water-cooled face that allows heat to be extracted from the flame, which, in turn, decreases the flame speed, allowing flames to be stabilized over a relatively wide range of flow conditions [7].

---

**Example 8.1**

A premixed laminar flame is stabilized in a one-dimensional gas flow where the vertical velocity of the unburned mixture, $v_u$, varies linearly with the horizontal coordinate, $x$, as shown in the lower half of Fig. 8.6. Determine the flame shape and the distribution of the local angle of the flame surface from vertical. Assume the flame speed is independent of position and equal to 0.4 m/s, a nominal value for a stoichiometric methane–air flame.

**Solution**

From Fig. 8.7, we see that the local angle, $\alpha$, which the flame sheet makes with a vertical plane is (Eqn. 8.2),

$$\alpha = \sin^{-1}(S_L / v_u),$$

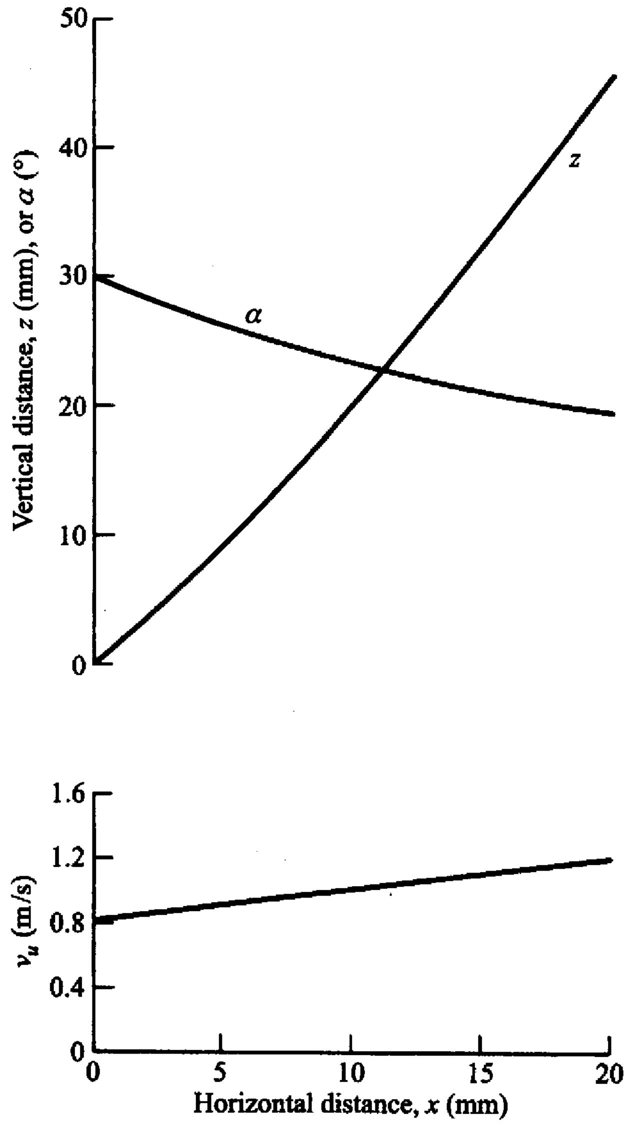


**Figure 8.6** Flow velocity, flame position, and angle from vertical of line tangent to flame, for Example 8.1.

where, from Fig. 8.6,

$$v_u(\text{mm/s}) = 800 + \frac{1200 - 800}{20} x\,(\text{mm}).$$

So,

$$\alpha = \sin^{-1}\left(\frac{400}{800 + 20x\,(\text{mm})}\right),$$

and has values ranging from 30° at $x = 0$ to 19.5° at $x = 20$ mm, as shown in the top part of Fig. 8.6.

To calculate the flame position, we first obtain an expression for the local slope of the flame sheet ($\mathrm{d}z/\mathrm{d}x$) in the $x$–$z$ plane, and then integrate this expression with respect to $x$ to find $z(x)$. From Fig. 8.7, we see that

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \tan\beta = \left(\frac{v_u^2(x) - S_L^2}{S_L^2}\right)^{1/2},$$

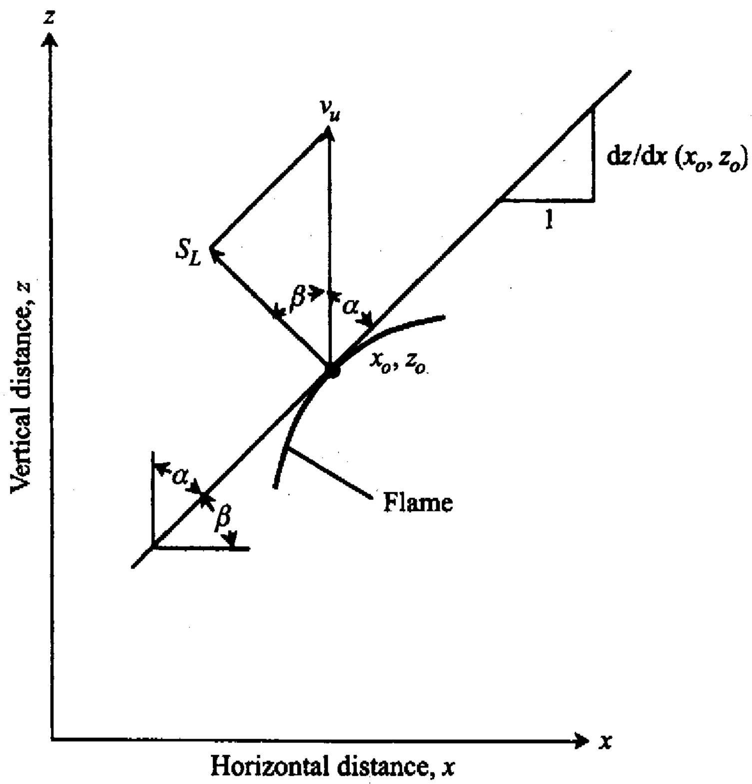


**Figure 8.7** Definition of flame geometry for Example 8.1.

which, for $v_u \equiv A + Bx$, becomes

$$\frac{dz}{dx} = \left[\left(\frac{A}{S_L} + \frac{Bx}{S_L}\right)^2 - 1\right]^{1/2}$$

Integrating the above with $A/S_L = 2$ and $B/S_L = 0.05$ yields

$$\begin{aligned} z(x) &= \int_0^x \left(\frac{dz}{dx}\right) dx \\ &= (x^2 + 80x + 1200)^{1/2}\left(\frac{x}{40} + 1\right) \\ &\quad - 10\ln[(x^2 + 80x + 1200)^{1/2} + (x + 40)] \\ &\quad - 20\sqrt{3} + 10\ln(20\sqrt{3} + 40). \end{aligned}$$

The flame position $z(x)$ is plotted in the upper half of Fig. 8.6. Here we see that the flame sheet is quite steeply inclined. (Note that the horizontal scale is twice that of the vertical.)

**Comment**

From this example, we see how the flame shape is intimately linked to the velocity distribution of the oncoming unburned gas.

---

In the next section, we turn our attention to establishing some theoretical basis for how various parameters, such as pressure, temperature, and fuel type, affect laminar flame speeds.

**Aviation Gasoline** Specifications for aviation gasoline [21] consider combustion characteristics and antiknock quality; fuel metering and aircraft range, as controlled by density and heat of combustion; carburetion and fuel vaporization, controlled by vapor pressure and distillation characteristics; corrosion; fluidity at low temperatures; and fuel cleanliness, handling, and storage stability. The basic composition of aviation gasoline differs from that of automotive gasoline; aviation gasoline consists of alkanes and *iso*-alkanes (50%–60%), cyclanes (20%–30%), small amounts of aromatics (<10%), and essentially no alkenes [9]. This composition contrasts with the somewhat smaller proportions of alkanes, *iso*-alkanes, and cycloalkanes; the presence of alkenes and cycloalkenes; and a greater proportion of aromatics (20%–50%) for automotive gasoline (see Table 17.3). The low aromatic content of aviation fuels results from the combined need to minimize the effects of the fuel on elastomers and to provide a high heating value and proper distillation characteristics [21]. The ASTM standard for aviation gasoline [21] indicates that an aromatics content of more than 25 percent is extremely unlikely. Tetraethyl lead is added to aviation gasoline to meet octane/performance number requirements. The decomposition products of tetraethyl lead scavenge radical species that lead to autoignition.

**Aviation Turbine Fuels** Specifications for Jet A and Jet A-1 turbine fuels [23] consider a large number of characteristics. Among them are the following: energy content, combustion, volatility, fluidity, corrosion, thermal stability, contaminants, and additives. The heat of combustion (see Chapter 2) is important as it controls the maximum range of an aircraft. The volumetric heating value (MJ/gallon) is the governing parameter for civil aviation [20], and a gravimetric specification (MJ/kg) is given in [23]. Minimizing the production of soot is important to meet emissions requirements and to minimize radiation to the combustor liner (see Chapters 10 and 15). To control soot formation, the aromatics content of the fuel is limited to 25 vol.%, and a minimum smoke point (see Tables 9.5 and 9.6 in Chapter 9) is specified. Aromatics are precursors to soot formation in the combustion of any fuel, and their presence as a fuel component promotes the production of soot. The freezing point is an important property as ambient temperatures at altitude can be quite low. Because the fuel is a mixture of many different hydrocarbons, the various components freeze (become wax) at various temperatures. The ASTM specification [23] of the freezing point is defined as the temperature at which the last wax crystals melt upon heating an initially completely solid fuel. Pumpability is the primary issue associated with fuel freezing, and most fuels will remain pumpable at temperatures slightly below the ASTM freezing point [20]. Jet A-1 fuel owes its existence to having a lower freezing point than Jet A. For more information on aviation fuels, we refer the reader to Refs. [20], [23], and [24].

## Natural Gas

Natural gas is typically found within or near oil fields. Natural gas is classified as *associated* or *nonassociated,* depending upon whether it is a product from an oil well (associated gas) or is the product of a gas well (nonassociated). Depending upon its composition, wellhead natural gas, particularly associated gas, must be processed before

**Table 17.11** Typical values or ranges of specifications for pipeline-quality natural gas[a]

| Property or Specification | Typical Value or Range | Comment |
|---|---|---|
| Presence of solids | Commercially free | — |
| Oxygen ($O_2$) vol.% | <0.2%–1% | Two companies specified a significantly stricter requirement of <50 ppm. |
| Carbon dioxide ($CO_2$) and nitrogen ($N_2$) vol.% | <2% $CO_2$ and/or <4% $CO_2$ & $N_2$ combined | These represent typical specifications from the variety presented in [27].[b] |
| Liquid hydrocarbons | No liquid HCs at temperature and pressure of delivery point | — |
| Hydrogen sulfide ($H_2S$) | 5.7–23 mg/m$^3$ | — |
| Total sulfur | 17–460 mg/m$^3$ | In addition to $H_2S$, includes carbonyl sulfide, mercaptans, and mono-, di-, and poly sulfides. |
| Water ($H_2O$) | 65–110 mg/m$^3$ | — |
| Lower heating value | >36,000 kJ/m$^3$ typical | 34,500 to > 40,900 kJ/m$^3$ range |

[a]Information in this table was compiled from data presented for 18 pipeline companies in Ref. [27]. Values in U.S. customary units have been converted to SI units.

[b]$CO_2$ is removed both to prevent corrosion and to maintain an appropriately high heating value.

**Table 17.12** Composition (mol%) and properties of natural gas from sources in the United States [28][a]

| Location | $CH_4$ | $C_2H_6$ | $C_3H_8$ | $C_4H_{10}$ | $CO_2$ | $N_2$ | Density[c] (kg/m$^3$) | HHV[d] (kJ/m$^3$) | HHV[d] (kJ/kg) |
|---|---|---|---|---|---|---|---|---|---|
| Alaska | 99.6 | — | — | — | — | 0.4 | 0.686 | 37,590 | 54,800 |
| Birmingham, AL | 90.0 | 5.0 | — | — | — | 5.0 | 0.735 | 37,260 | 50,690 |
| East Ohio[b] | 94.1 | 3.01 | 0.42 | 0.28 | 0.71 | 1.41 | 0.723 | 38,260 | 52,940 |
| Kansas City, MO | 84.1 | 6.7 | — | — | 0.8 | 8.4 | 0.772 | 36,140 | 46,830 |
| Pittsburgh, PA | 83.4 | 15.8 | — | — | — | 0.8 | 0.772 | 41,840 | 54,215 |

[a]Although not explicitly stated in Ref. [28], these gases appear to be pipeline gases.

[b]Also contains 0.01% $H_2$ and 0.01% $O_2$.

[c]At 1 atm and 15.6°C (60 F).

[d]Higher heating values for 1 atm and 15.6°C (60 F) [28].

**Table 17.13** Composition (mol%) and properties of natural gas from worldwide sources [28][a]

| Location | $CH_4$ | $C_2H_6$ | $C_3H_8$ | $C_4H_{10}$ | $CO_2$ | $N_2$ | Density[b] (kg/m$^3$) | HHV[c] (kJ/m$^3$) | HHV[c] (kJ/kg) |
|---|---|---|---|---|---|---|---|---|---|
| Algeria LNG | 87.2 | 8.61 | 2.74 | 1.07 | — | 0.36 | 0.784 | 42,440 | 54,130 |
| Groningen, Netherlands | 81.2 | 2.9 | 0.36 | 0.14 | 0.87 | 14.4 | 0.784 | 33,050 | 42,150 |
| Kuwait, Bergen | 86.7 | 8.5 | 1.7 | 0.7 | 1.8 | 0.6 | 0.784 | 40,760 | 51,990 |
| Libya LNG | 70.0 | 15.0 | 10.0 | 3.5 | — | 0.90 | 0.956 | 49,890 | 52,210 |
| North Sea, Bacton | 93.63 | 3.25 | 0.69 | 0.27 | 0.13 | 1.78 | 0.723 | 38,450 | 53,200 |

[a]Although not explicitly stated in Ref. [28], these gases appear to be pipeline gases.

[b]At 1 atm and 15.6°C (60 F).

[c]Higher heating values for 1 atm and 15.6°C (60 F) [28].

it can enter distribution pipeline systems. Unprocessed natural gas is primarily methane, with smaller quantities of other light ($C_2$–$C_8$) hydrocarbons. Noncombustible gases, $N_2$, $CO_2$, and He, are also frequently present. Hydrogen sulfide, mercaptans, water, oxygen, and other trace contaminants may be present. Separation of dissolved associated gas from crude oil is frequently not economical [9]; nevertheless, the amount of gas flared or vented annually worldwide is huge—110 billion cubic meters, the equivalent to the combined annual natural gas consumption of France and Germany [25]. However, initiatives are in place to significantly reduce flaring of associated gas [25].

Although there are no industry or governmental standards for pipeline natural gas, contracts between producers and pipeline companies define general ranges of composition and other properties [26, 27]. Processing removes solid matter (e.g., sand), liquid hydrocarbons, sulfur compounds, water, nitrogen, carbon dioxide, helium, and any other undesirable compounds to meet contract specifications. The removal of sulfur compounds results in making an acidic, i.e., *sour,* gas *sweet.* Table 17.11 shows typical values, or ranges, of important properties of pipeline gas based on the *General Terms and Conditions* of a set of geographically dispersed pipeline companies in the United States and Canada.

The composition of natural gas varies widely depending upon the source. Examples for U.S. sources of natural gas are shown in Table 17.12. Compositions for natural gases from a variety of non-U.S. sources are provided in Table 17.13.

---

**Example 17.2**

Using the 298.15 K reference state, calculate the higher heating value (HHV) for the natural gas from the Bergen field in Kuwait shown in Table 17.13. Compare the result with the value given in Table 17.13.

**Solution**

Our solution follows that of Example 2.4. From Fig. 2.9, we see that the HHV can be expressed as

$$\mathrm{HHV} = \Delta h_c = (H_{\mathrm{reac}} - H_{\mathrm{prod}})/MW_{\mathrm{fuel}}\ (\mathrm{kJ/kg_{fuel}})$$

where

$$H_{\mathrm{reac}} = \sum_{\mathrm{Reac}} N_i \bar{h}^o_{f,i} \quad \text{and} \quad H_{\mathrm{prod}} = \sum_{\mathrm{Prod}} N_i \bar{h}^o_{f,i}.$$

Using the given composition of the natural gas, we can calculate the apparent molecular weight of the fuel (natural gas) as

$$MW_{\mathrm{fuel}} = \sum \chi_i MW_i = \chi_{\mathrm{CH_4}} MW_{\mathrm{CH_4}} + \chi_{\mathrm{C_2H_6}} MW_{\mathrm{C_2H_6}} + \chi_{\mathrm{C_3H_8}} MW_{\mathrm{C_3H_8}} + \chi_{\mathrm{CO_2}} MW_{\mathrm{CO_2}} + \chi_{\mathrm{N_2}} MW_{\mathrm{N_2}}.$$

Substituting numerical values, we obtain

$$\begin{aligned} MW_{\mathrm{fuel}} &= 0.867(16.043) + 0.085(30.069) + 0.017(44.096) + 0.018(44.011) + 0.006(28.013) \\ &= 18.175\ \mathrm{kg/kmol_{fuel}}. \end{aligned}$$

The reactant enthalpy $H_{\mathrm{reac}}$ is evaluated using the given fuel composition and the enthalpies-of-formation:

# Burning Sulfur Compounds

Sulfur compounds such as hydrogen sulfide ($H_2S$), methyl mercaptan ($CH_4S$) and sulfur (S) burn in the presence of oxygen to produce sulfur oxides ($SO_2$ and $SO_3$) in the flue gas. Flue gas always (almost) contains substantial water vapor (hydrogen in the combustibles combines with oxygen in the combustion air to form $H_2O$).

Neither of the sulfur oxides presents much of a problem with normal materials of construction UNLESS the flue gas temperature falls below the gas dewpoint temperature.

The gas dewpoint temperature is where the first liquid droplets begin forming in the gas. Above the dewpoint there is no liquid. As the temperature falls below the dewpoint for the flue gas, more and more liquid forms. Room air can reach the dewpoint temperature on the outside of an ice water pitcher, and the water which condenses collects and forms a puddle under the pitcher. If the same pitcher was placed in a flue gas containing sulfur oxides, the condensed liquid would be sulfurous acid ($H_2SO_3$ from the $SO_2$) and/or sulfuric acid ($H_2SO_4$ from the $SO_3$). The puddle would be corrosive.

Either $SO_2$ or $SO_3$ in flue gas results in a much higher gas dewpoint temperature than what you would see with water vapor alone. For instance, flue gas with 5% water vapor and no sulfur oxides has a dewpoint of about 90°F. The same flue gas with just 0.01% $SO_3$ added has a dewpoint of about 245°F! If this gas reaches 245°F, sulfuric acid will begin to condense out of the gas. Adding the same amount of $SO_2$ presents much less of a problem, because the dewpoint change is not nearly as severe, plus sulfurous acid is much less corrosive than sulfuric acid.

The two graphs below can be used to calculate the dewpoint of flue gas containing varying amounts of $SO_3$. One graph shows very low SO3 concentrations and the other plots higher concentrations. In the high concentration graph, the line at the lower right with numbers running from 5 to 160 is the $H_2O$ Partial Pressure in the flue gas (air pressure at sea level is 760 MM Mercury). Thus 40 PP MM Mercury of water amounts to 40/760=0.0526 fraction (=5.26% by volume) of water in the flue gas. With no $SO_3$ in this flue gas, the first liquid will condense out when the temperature reaches about 95°F (the axis on the left). Starting with 40 PP MM Mercury of $H_2O$, add enough $SO_3$ to amount to 0.01% in the flue gas – on the graph, starting at 40 on the lower line, follow the diagonal line up and to the left to the line marked 0.01 along the top of the lines. Then look to the left axis of the graph to read about 250°F as the dewpoint temperature. The low concentration graph works in a similar way.

This is the easy part. The uncertainty begins when we try to predict the fraction of sulfur which will oxidize to form $SO_3$ instead of $SO_2$. This chemical reaction would reach a specific end point if enough time elapsed (maybe an hour). But no combustor holds flue gas for longer than a few seconds, so the "equilibrium" level of $SO_3$ is never reached. In practice, when burning sulfur-containing compounds, somewhere between 1% and 10% of the sulfur ends up as $SO_3$ in combustor flue gas. Most designers use 3% conversion to $SO_3$ but some use 7% conversion. Attempts at exact calculation of the conversion have not been successful. The most conservative estimate would be 10%. This is important because if any portion of the equipment in contact with the flue gas cools to the $SO_3$ dewpoint temperature, sulfuric acid will form. If this portion of the equipment will not tolerate sulfuric acid, corrosion problems will result.

In the real world, furnaces with excessive refractory (conserving heat but cooling the vessel shell) are often "holed" by condensing sulfuric acid. Flue gas / air preheat exchangers have been damaged when the metal temperature near the cold air entry point could not be kept above the $SO_3$ dewpoint temperature. Careful designs avoid problems like these. If condensation cannot be avoided, any metals should be able to resist concentrated sulfuric acid, which is the liquid that condenses!

For high concentrations of $SO_3$ in flue gas, use this graph:

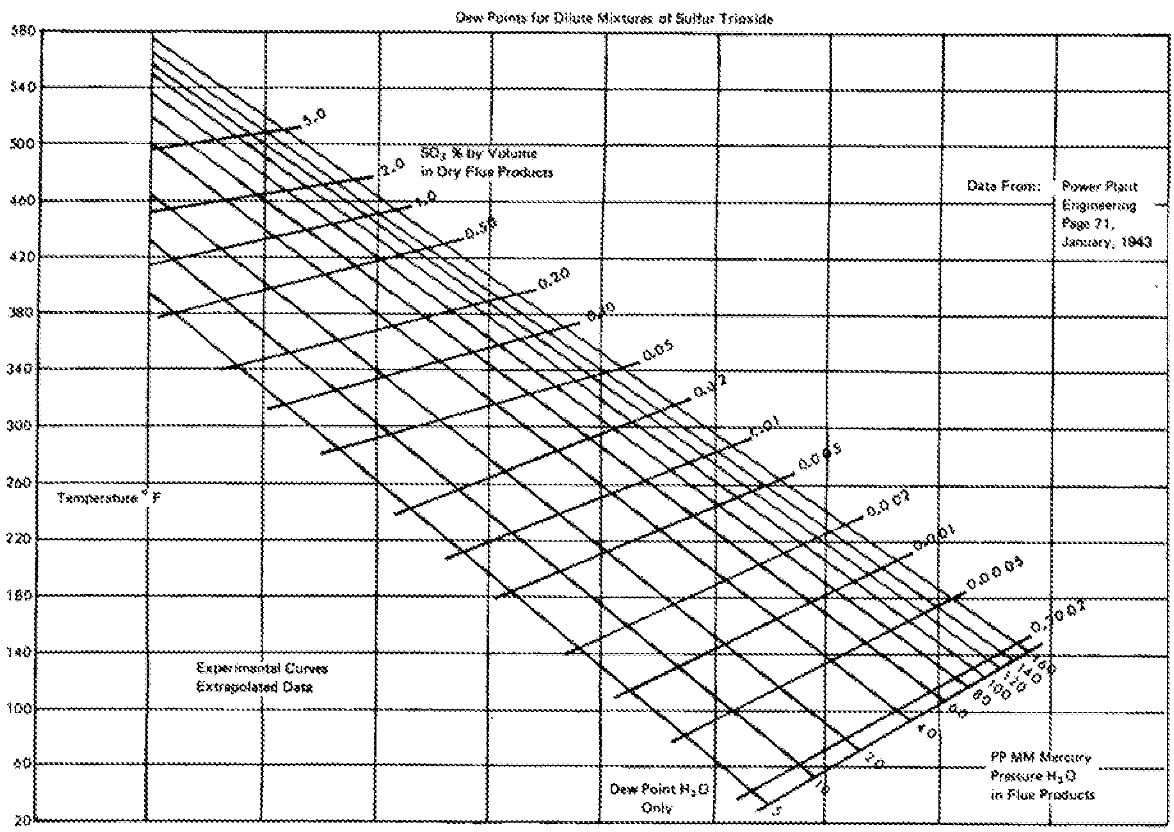


*Figure 3-7. Dew points for dilute mixtures of sulfur trioxide. (Data from Power Plant Engineering, Jan. 1943, p. 71.)*

For low concentrations of $SO_3$, use the graph below instead. Notice that the dewpoint temperature does not fall off as quickly when concentrations are low.

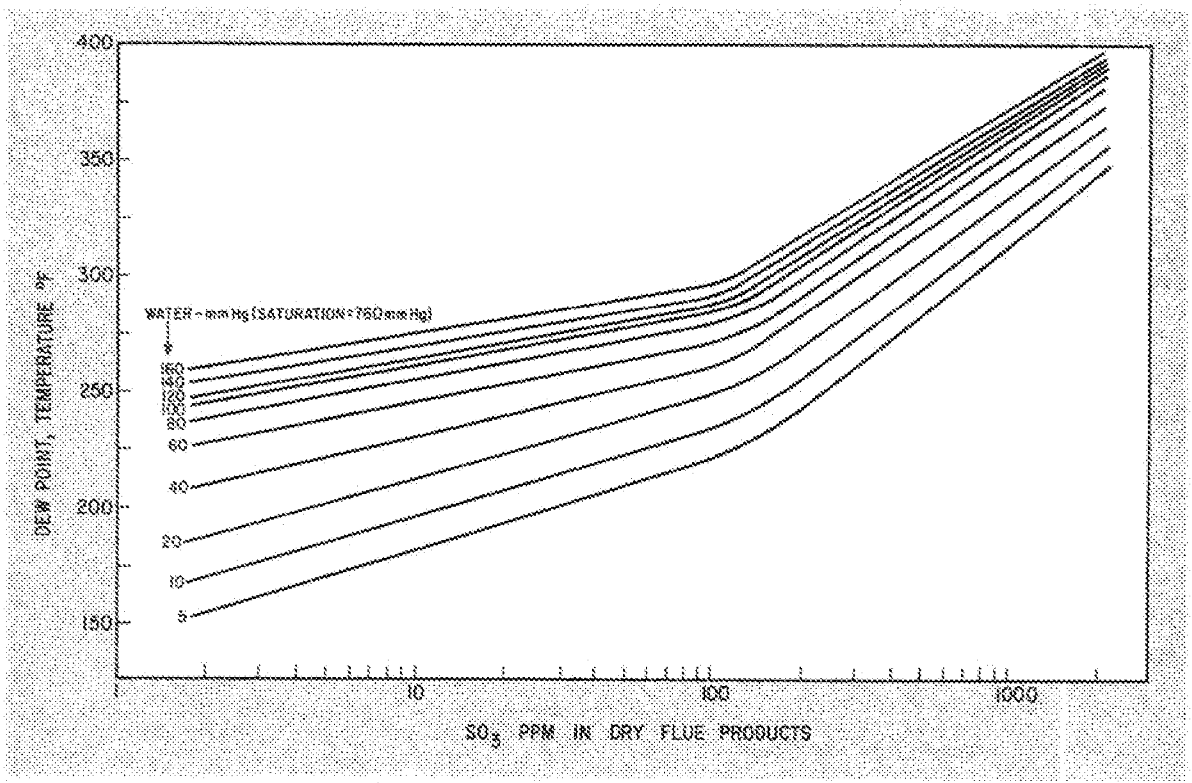


Fig. 1—Dew points for dilute mixtures of sulfur trioxide in stack gases with various water contents.


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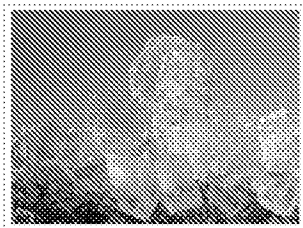
# Alkali metal halide

From Wikipedia, the free encyclopedia

**Alkali metal halides** (also known as **alkali halides**) are the family of inorganic compounds with the chemical formula MX, where M is an alkali metal and X is a halogen. These compounds are the often commercially significant sources of these metals and halides. The best known of these compounds is sodium chloride, table salt.[1]

## Contents

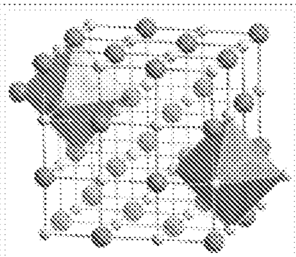




Halite is the mineral form of sodium chloride.

## Structure

Most alkali metal halides crystallize with the face centered cubic lattices. In this structure both the metals and halides feature octahedral coordination geometry, in which each ion has a coordination number of six. Caesium chloride, bromide, and iodide crystallize in a body-centered cubic lattice that accommodates coordination number of eight for the larger metal cation (and the anion also).[2]



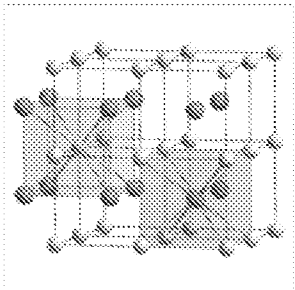
Ball-and-stick model of the coordination of Na and Cl in NaCl. Most alkali metal halides adopt this structure.

## Properties

The alkali metal halides exist as colourless crystalline solids, although as finely ground powders appear white. They melt at high temperature, usually several hundred degrees to colorless liquids. Their high melting point reflects their high lattice energies. At still higher temperatures, these liquids evaporate to give gases composed of diatomic molecules.

These compounds dissolve in polar solvents to give ionic solutions that contain highly solvated anions and cations.

The table below provides links to each of the individual articles for these compounds. The numbers beside the compounds show the electronegativity difference between the elements based on the Pauling scale. The higher the number is, the more ionic the solid is.



Ball-and-stick model of the coordination of Cs and Cl in CsCl

| | | *Alkali Metals* | | | | |
|---|---|---|---|---|---|---|
| | | **Lithium** | **Sodium** | **Potassium** | **Rubidium** | **Caesium** |
| ***Halogens*** | **Fluorine** | LiF (3.0) | NaF (3.1) | KF (3.2) | RbF (3.2) | CsF (3.3) |
| | **Chlorine** | LiCl (2.0) | NaCl (2.1) | KCl (2.2) | RbCl (2.2) | CsCl (2.3) |
| | **Bromine** | LiBr (1.8) | NaBr (1.9) | KBr (2.0) | RbBr (2.0) | CsBr (2.1) |
| | **Iodine** | LiI (1.5) | NaI (1.6) | KI (1.7) | RbI (1.7) | CsI (1.8) |

# References

1. ^ Greenwood, N. N.; & Earnshaw, A. (1997). Chemistry of the Elements (2nd Edn.), Oxford:Butterworth-Heinemann. ISBN 0-7506-3365-4.
2. ^ Wells, A.F. (1984) Structural Inorganic Chemistry, Oxford: Clarendon Press. ISBN 0-19-855370-6.

# Further reading

- Tastes of the alkali metal halides (except fluorides) (http://nsrdec.natick.army.mil/LIBRARY/80-89/R81-77.pdf)

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Categories: Alkali metals | Halides | Metal halides | Crystals | Salts | Inorganic compound stubs

# Alkali metal

From Wikipedia, the free encyclopedia

The **alkali metals** are a group in the periodic table consisting of the chemical elements lithium (Li), sodium (Na),[note 1] potassium (K),[note 2] rubidium (Rb), caesium (Cs),[note 3] and francium (Fr).[4] This group lies in the s-block of the periodic table[5] as all alkali metals have their outermost electron in an s-orbital.[6][7][8] The alkali metals provide the best example of group trends in properties in the periodic table,[6] with elements exhibiting well-characterized homologous behaviour.[6]

The alkali metals have very similar properties: they are all shiny, soft, highly reactive metals at standard temperature and pressure[6] and readily lose their outermost electron to form cations with charge +1.[9]:28 They can all be cut easily with a knife due to their softness, exposing a shiny surface that tarnishes rapidly in air due to oxidation.[6] Because of their high reactivity, they must be stored under oil to prevent reaction with air,[10] and are found naturally only in salts and never as the free element.[10] In the modern IUPAC nomenclature, the alkali metals comprise the **group 1 elements**,[note 4] excluding hydrogen (H), which is nominally a group 1 element[4][12] but not normally considered to be an alkali metal[13][14] as it rarely exhibits behaviour comparable to that of the alkali metals.[15] All the alkali metals react with water, with the heavier alkali metals reacting more vigorously than the lighter ones.[6][16]

All the discovered alkali metals occur in nature: in order of abundance, sodium is the most abundant, followed by potassium, lithium, rubidium, caesium, and finally francium, which is very rare due to its extremely high radioactivity and thus occurs only in traces due to its presence in natural decay chains.[17][18] Experiments have been conducted to attempt the synthesis of ununennium (Uue), which is likely to be the next member of the group, but they have all met with failure.[19] However, ununennium may not be an alkali metal due to relativistic effects, which are predicted to have a large influence on the chemical properties of superheavy elements;[20] even if it does turn out to be an alkali metal, it is predicted to have some differences in

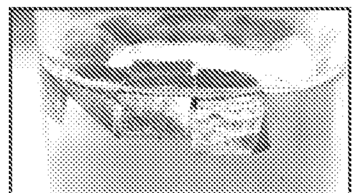
**Alkali metals**

noble gases ← → alkaline earth metals

| | |
|---|---|
| **IUPAC group number** | **1** |
| Name by element | lithium group |
| Trivial name | alkali metals |
| CAS group number (US) | IA |
| old IUPAC number (European) | IA |

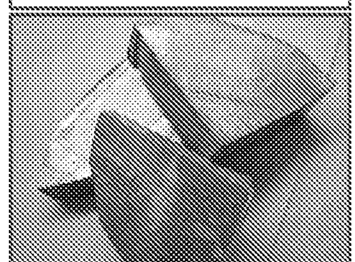
↓ **Period**

**2**



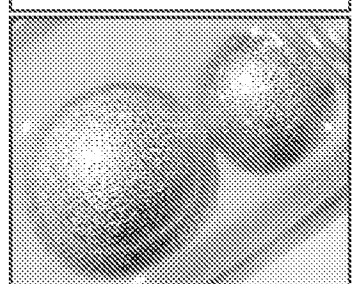
Lithium (Li)
3

**3**



Sodium (Na)
11

**4**

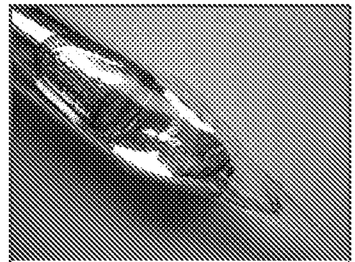


Potassium (K)
19

physical and chemical properties from its lighter homologues.[21]:1729–1733

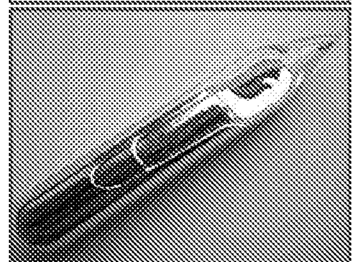
Most alkali metals have many different applications. Two of the most well-known applications of the pure elements are rubidium and caesium atomic clocks,[22] of which caesium atomic clocks are the most accurate and precise representation of time.[23][24] A common application of the compounds of sodium is the sodium-vapour lamp, which emits very efficient light.[25][26] Table salt, or sodium chloride, has been used since antiquity. Sodium and potassium are also essential elements, having major biological roles as electrolytes,[27][28] and although the other alkali metals are not essential, they also have various effects on the body, both beneficial and harmful.[29][30][31][32]

**5**



Rubidium (Rb)
37

**6**



Caesium (Cs)
55

**7**

Francium (Fr)
87

*Legend*

primordial

element by radioactive decay

Atomic number color:
black=solid

# Contents

PROPANE 101





# Grades of Propane - Gas Purity and Quality

Propane is considered propane regardless of the grade but the reality is that three grades of propane are processed or refined in the United States. Each of the three grades, HD5, HD10 and commercial propane differ in propane consistency and are used for different purposes. All grades of propane come from the same raw materials (crude oil or natural gas). The differing grades are created during the refining or processing of the gas at the refinery. In other words, the refinery specifies which grade is to be processed. Each grade of propane is stored separately following processing to ensure that the propane grade loaded at the refinery is what was specified by the buyer.



### HD-5 Propane

HD5 grade propane is "consumer grade" propane and is the most widely sold and distributed grade of propane in the U.S. market. HD5 is the highest grade propane available to consumers in the United States and is what propane companies ordinarily sell to their customers. What does HD5 propane mean in terms of specification to an ordinary consumer? It means that the propane is suitable and recommended for engine fuel use, which was the original purpose of the HD5 grade propane specification. HD5 spec propane consists of:

- Minimum of 90% propane
- Maximum of 5% propylene - propylene is used in the manufacture of plastics
- Other gases constitute the remainder (iso-butane, butane, methane, etc.)

The HD5 specification is based on "allowable" contents. For instance, 99% propane and 1% propylene is HD5 grade propane the same as 95% propane and 5% propylene is HD5 propane. Although the product consistency and purity is different, both mixtures are considered HD5 propane because they fall within the allowable limits for the product to be named and labeled as such. Consider this: **10,000 gallons of pure propane (100% propane) is classified as HD-5 grade propane.**

### HD5 Propane Quality - Fact vs. Fiction

Retail propane companies that advertise "highest quality propane" are actually selling propane that conform to the specifications as required to be labeled and sold as HD5 propane. An important fact to note is that there is no higher grade than HD5 propane available for resale through retail propane companies in the United States...HD5 is the highest grade propane available to U.S. consumers. A company stating that their propane is of a higher grade than HD5 is inaccurate in their claim. As presented above, a tank holding pure propane contains what is classified as HD5 propane.

### HD-10 Propane and Commercial Propane

HD10 propane is a grade below HD5 and is commonly found in California. HD10 grade propane allows up to 10% propylene in the propane/propylene mixture and is still labeled as "propane". Because propylene is used in creating plastics, HD10 can possibly create problems in some engines and vehicle applications. Propylene can cause engine components to "gum" or stick during operation. However, HD 10 spec propane works just fine in domestic and commercial propane powered appliances. The only problem that may be encountered in using HD-10 propane involves its use as an engine fuel (vehicles, forklifts, etc.).



Commercial grade propane and HD10 grade propane are sometimes used interchangeably due to the fact that both grades are sub-HD5 spec product and do not meet the standards of engine grade propane. Refineries use commercial propane in their processes and fractionation of chemicals for end use in numerous industries. Although commercial grade propane can be used in a manner similar to that of HD10 propane, it is not used in vehicle applications.

Thrifty Propane
1-800-879-3152
(Billing: x708)
info@thriftypropane.com



# The Truth About Propane

## THE TRUTH ABOUT PROPANE

### Introduction

HD5 propane is exported from the United States all over the world because HD5 propane is the only propane that other countries allow for home use. They do not permit importation of refinery "slop."

### The HD5 Difference as Told by Our Customers

Two recent unsolicited testimonials say everything about the HD5 propane difference. The first is from Betty in Bath County, KY, who began using Thrifty Propane's pure HD5 propane just this winter:

"I don't know if anyone else has noticed this since they have begun using HD5 Propane, but my daily winter headaches, that I've had every year, for over twenty years, disappeared this winter!! (2010-2011) It also is the FIRST winter I've had access to Thrifty Propane!! Coincidence? I don't think so. Nor do I think it's a coincidence that my windows aren't covered with a "film" this winter, again, for the first time. Of course, I, like many, have heard all the "canned" negative responses from Thrifty competitors, but, all I can say is, "Guys, you have DEFINITELY been misinformed!!" Thrifty, PLEASE don't stop delivering in my area!! You have saved me money, kept me warmer, and, for the first time ever, made my winter "pain free"!! I have absolutely no way of expressing how grateful I am, except to say, "Thank you so much for making winter nice for me again!!"

That her headaches vanished this winter and her windows are no longer covered in a murky film is the direct result of the fact that she is using HD5 propane for the first time, and she has a better life while she saves money. HD5 propane delivered Betty a better life, every day.

The value provided by HD5 propane is reflected in Ron Brinker's letter to Thrifty:

"I went from averaging 1000 gallons a year usage down to 600 gallons with Thrifty. If you consider that my previous supplier's prices were at least 1.5 times higher (after fighting with them to get the prices that low), the savings have been astronomical."

Burns Hotter Video
Burns Longer Video
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Follow us on Twitter
SAFETY Concerns
Order Online
Own Your Tank In 12 Months
Pre-Buy Special
Buy a Tank
Lease a Tank
Ask Questions

Ron tells you all you need to know about HD5 propane. We deliver service: we make sure you get the propane you need when you need it. We deliver value: our lowest price guarantee for gas that lasts longer means you will spend less to heat your home year in and year out. Ron saved 400 gallons a year: that translates into real money. When publicly-trade propane majors often charge more than $3.00 per gallon, saving 400 gallons per season translates into a $1200 savings every year. These savings, made greater by our guaranteed lowest price, require no sacrifice, because they are part of the HD5 advantage.

**THERE ARE TWO KINDS OF FUEL CALLED "PROPANE"**

There is only one chemical that is propane: $C_3H_8$, found in nature, bound up with natural gas. In 1932, the Gas Processors' Association published a standard for propane, GPA 2140, that has been the standard ever since. This standard requires that the propane that is drawn out of the "raw make," the natural gas that comes from the ground, be tested, and that the material tested be at least 90% chemical propane and no more than 5% propylene and no more than 5% other gases, including ethane and butane. Gas processors have strictly adhered to this standard, because the only way they have to transport the gas is over "common carrier" pipelines, that require that every customer of the pipeline have equal access to the pipeline. Because of the length of time it takes to pump propane from Texas to where it used in the Midwest and Eastern Seaboard, customers would have to wait days and even weeks for the gas they bought in Texas, where the propane is stored, to arrive at the terminals where they picked it up. In the middle of winter, such a system would never work. To solve the problem, the gas transporters made the propane "fungible:" all the propane would be identical, so that the gas a customer picked up in Pennsylvania was identical to the gas stored in Texas. To make all the gas identical, the transporters required that all the propane be HD5 propane, and they tested it to make sure that all the propane that went into their pipeline began as HD5 and remained HD5 so long as it was in their pipelines. Homeowners benefited from this business requirement with access to pure HD5 propane.

By contrast, since 1975, oil refineries were able to take advantage of the definition of propane in the ASTM (American Society for Testing and Materials) standard, ASTM Standard D1835, to market oil refining "odds and ends," known by chemical engineers as "slop," because they could claim that the slop fit the definition of "commercial grade" propane: any hydrocarbon mixture that held a flame. Such a hydrocarbon mixture need not contain a single molecule of chemical propane, and could contain any poison that came out the top of a refinery column. This slop used to be flared off, simply to pollute the air. But when the sulfur was taken out, beginning in 1971, the refineries saw how they could profit from this waste product by selling it to their allies, the publicly-traded major propane marketers, who would drastically mark it up and sell it to house holders as propane. This poisonous slop is marketed throughout the Midwest and East, wherever the marketers can reach, as propane. Slop may be marketed with particular impunity in the so-called "dump ground" states in which there is no regulation of fuel products. In these states,Ohio, Kentucky, Michigan and Indiana, fuel products that cannot be sold elsewhere are marketed to those who do not know they have a choice. In fact, waste product is piped into midwest from US and Canada refinery's for sale as propane to it's residents. Residents of these states must be particularly vigilant regarding their fuel products. For residents of these "dump ground" states the difference between HD5 and "commercial grade" propane is particularly important.

How "commercial grade" propane became slop is the hidden history of propane, which follows.

## The Story Behind HD5 Propane

This is the story behind HD5 propane: what it is and why it is different from the propane other marketers offer. In these modern times, there is a standard for every product, from baby formula to window screens. The standards are drawn up by people, people who are part of communities and owe all kinds of loyalties to their friends, their allies and their employers. It is no different at the American Society for Testing and Materials, that has published Standard ASTM D1835, the standard, equivalent to GPA 2140, defining what the propane you buy is. The ASTM Standard has been in use since 1961, and over the fifty years we have relied upon it, it has changed at least a dozen times. We went to MIT and the Cleveland Public Library Science and Technology Collections to find all the published versions of ASTM D1835 since 1961. When we dug out the old standards, we discovered HD5's hidden history.

## Propane: The Hidden History

When we went through the ASTM Standards from 1961 to the present, we found propane's hidden history. We found, just as we suspected, an elegant flim-flam on the American public: in 1975, whens HD5 propane was introduced into ASTM Stardard D1835, "commercial grade" propane became the code-word for slop. In 2010, the GAO reported that half of the propane was produced as a by-product of natural gas processing and half was produced as a by-product of oil refining. The GAO reported the facts as they stood, without the history. The history tells us that where once the dominant source of propane was natural gas processing, by 1975, when "Special Duty" propane, "equivalent to HD5 propane" described in GPA Standard 2140, was introduced, the sources of propane, and with the source of propane, the quality of propane, shifted. In 1961, almost all the propane in America was produced by natural gas processing, which meant that almost all of it was HD5, since the propane so produced had to conform to GPA 2140, the standard of the Gas Processors Association, which had been in effect since 1932.

In 1961, what was to become "commercial grade" propane, used by most homes in four "dump-ground" states and wherever else the US and Canadian refiners could market it, was simply flared off as waste. It smelt terrible and watered people's eyes because it was loaded with sulfur. By 1970, the detrimental effects of sulfur dioxide ($SO_2$) were obvious, particularly its ill-effects on trees in the Northeast, and the federal government began to impose regulations that required that smoke stacks be scrubbed of the $SO_2$, so-called "desulphurization." The unintended consequence of this regulation was that by 1975 oil refiners began to see profits two ways in capturing the 'odds and ends" and selling it as propane. First, since these odds and ends were hydrocarbons that could hold a flame, they could be sold as "commercial grade" propane, because all the ASTM standard required for "commercial grade" propane was that it be hydrocarbon gas and hold a flame. Second, the oil refiners saved millions a year because they did not have to dispose of the odds and ends, since they were beginning to sell it as propane to home owners. The oil refiners also began to make further millions by supplying the sulfur they captured as fertilizer. Sulfur haulers such as the Kochs also emerged as big winners in the fertilizer sweepstakes. As waste product suddenly emerged as a champion money-maker, production of counterfeit "commercial grade" propane climbed until, as the GAO said last year, half the propane was produced in natural gas processing, HD5, and half was counterfeit propane, consisted of "odds and ends" waste products of high-heat oil refining.

## Sulfur's Role in Hidden History

Sulfur profiteering and the mass-marketing of slop as a home-heat hydrocarbon emerged together. In 1971, the first U.S. E.P.A. rules for sulfur emissions was brought out. In response to the rules, refineries brought Flue Gas Desulfurization units on-line to capture the sulfur. Their compliance with the new rules had over time two unintended consequences: 1.) agricultural land, that had obtained "free sulfur" from smokestack emissions, now experienced sulfur depletion as a result of the constant working of the soil, and 2.) the flue gases that remained were possible to transport, since the corrosive sulfur was taken out. The refining industry, never one to miss opportunity, seized the opportunities that arose from both these circumstances – it began to aggressively to market sulfur as a fertilizer, and to offer the recaptured flue gases as hydrocarbon fuel. The second opportunity is of most importance to you as a home owner who uses propane for heating and cooking.

Since 1971, increasing volumes of recaptured flue gases, so-called "slop" has been marketed as propane, taking advantage of the ASTM definition of "commercial grade" propane that has stood since 1961. By 1975, when "special duty" equivalent to HD5 was introduced into the standard, it was apparent that "commercial grade" propane was on its way to becoming not a natural gas-processing product, but a bonus profit source for the refineries that did not have to show a speck of propane in what they sold, so long as it held a flame. By 2010, half of the fuel marketed as propane was desulfurized oil refinrery "odds and ends" captured at the top of the refining column and sold as fuel. But it has, which leaves you with one best and only choice: HD5 Propane.

## Conclusion

Slop is sold to benefit the refineries who are able to profit by price-gouging propane consumers. Real money is also made by the transporters who are able to sell the sulfur to America's farmers throughout the Midwest to shock their exhausted fields back to life for another season. The profiteering on slop and the profiteering on agricultural sulfur came together when the oil refineries seized the chance to make money on their refinery byproduct and the transporters seized the chance to profiteer on sulfur, which keeps America's farm land productive year in and year out despite the constant abuse of industrialized methods that kill the soil.

our hd5 propane burns hotter- burns cleaner-burns longer

Environmental Health and Safety
The Dangers of Olefin Laced Refinery Gas Byproducts

Propane Quality Testing Labs

# Electrolyte

From Wikipedia, the free encyclopedia

An **electrolyte** is a compound that ionizes when dissolved in suitable ionizing solvents such as water. This includes most soluble salts, acids, and bases. Some gases, such as hydrogen chloride, under conditions of high temperature or low pressure can also function as electrolytes. Electrolyte solutions can also result from the dissolution of some biological (e.g., DNA, polypeptides) and synthetic polymers (e.g., polystyrene sulfonate), termed polyelectrolytes, which contain charged functional groups.

Electrolyte solutions are normally formed when a salt is placed into a solvent such as water and the individual components dissociate due to the thermodynamic interactions between solvent and solute molecules, in a process called solvation. For example, when table salt (sodium chloride), NaCl, is placed in water, the salt (a solid) dissolves into its component ions, according to the dissociation reaction

$$NaCl_{(s)} \rightarrow Na^{+}{}_{(aq)} + Cl^{-}{}_{(aq)}$$

It is also possible for substances to react with water, producing ions. For example, carbon dioxide gas dissolves in water to produce a solution that contains hydronium, carbonate, and hydrogen carbonate ions.

Note that molten salts can be electrolytes, as well. For instance, when sodium chloride is molten, the liquid conducts electricity.

An electrolyte in a solution may be described as concentrated if it has a high concentration of ions, or dilute if it has a low concentration. If a high proportion of the solute dissociates to form free ions, the electrolyte is strong; if most of the solute does not dissociate, the electrolyte is weak. The properties of electrolytes may be exploited using electrolysis to extract constituent elements and compounds contained within the solution.

## Contents

# Physiological importance

In physiology, the primary ions of electrolytes are sodium ($Na^+$), potassium ($K^+$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), chloride ($Cl^−$), hydrogen phosphate ($HPO_4^{2−}$), and hydrogen carbonate ($HCO_3^−$). The electric charge symbols of plus (+) and minus (−) indicate that the substance is ionic in nature and has an imbalanced distribution of electrons, the result of chemical dissociation. Sodium is the main electrolyte found in extracellular fluid and is involved in fluid balance and blood pressure control.

All known higher lifeforms require a subtle and complex electrolyte balance between the intracellular and extracellular environment. In particular, the maintenance of precise osmotic gradients of electrolytes is important. Such gradients affect and regulate the hydration of the body as well as blood pH, and are critical for nerve and muscle function. Various mechanisms exist in living species that keep the concentrations of different electrolytes under tight control.

Both muscle tissue and neurons are considered electric tissues of the body. Muscles and neurons are activated by electrolyte activity between the extracellular fluid or interstitial fluid, and intracellular fluid. Electrolytes may enter or leave the cell membrane through specialized protein structures embedded in the plasma membrane called ion channels. For example, muscle contraction is dependent upon the presence of calcium ($Ca^{2+}$), sodium ($Na^+$), and potassium ($K^+$). Without sufficient levels of these key electrolytes, muscle weakness or severe muscle contractions may occur.

Electrolyte balance is maintained by oral, or in emergencies, intravenous (IV) intake of electrolyte-containing substances, and is regulated by hormones, in general with the kidneys flushing out excess levels. In humans, electrolyte homeostasis is regulated by hormones such as antidiuretic hormone, aldosterone and parathyroid hormone. Serious electrolyte disturbances, such as dehydration and overhydration, may lead to cardiac and neurological complications and, unless they are rapidly resolved, will result in a medical emergency.

## Measurement

Measurement of electrolytes is a commonly performed diagnostic procedure, performed via blood testing with ion-selective electrodes or urinalysis by medical technologists. The interpretation of these values is somewhat meaningless without analysis of the clinical history and is often impossible without parallel measurement of renal function. Electrolytes measured most often are sodium and potassium. Chloride levels are rarely measured except for arterial blood gas interpretation, since they are inherently linked to sodium levels. One important test conducted on urine is the specific gravity test to determine the occurrence of electrolyte imbalance.

## Rehydration

In oral rehydration therapy, electrolyte drinks containing sodium and potassium salts replenish the body's water and electrolyte levels after dehydration caused by exercise, excessive alcohol consumption, diaphoresis, diarrhea, vomiting, intoxication or starvation. Athletes exercising in extreme conditions (for three or more hours continuously, e.g. marathon or triathlon) that do not consume electrolytes risk dehydration (or hyponatremia).[1]

An electrolyte drink can be home-made by using the correct proportions of water, sugar, salt, salt substitute for potassium, and baking soda.[2]

Electrolytes are commonly found in fruit juices, coconut water, sports drinks, milk, and many fruits and vegetables (whole or in juice form) (e.g., potatoes, avocados).

# Electrochemistry

*Main article: electrolysis*

When electrodes are placed in an electrolyte and a voltage is applied, the electrolyte will conduct electricity. Lone electrons normally cannot pass through the electrolyte; instead, a chemical reaction occurs at the cathode, consuming electrons from the anode. Another reaction occurs at the anode, producing electrons that are eventually transferred to the cathode. As a result, a negative charge cloud develops in the electrolyte around the cathode, and a positive charge develops around the anode. The ions in the electrolyte neutralize these charges, enabling the electrons to keep flowing and the reactions to continue.

For example, in a solution of ordinary table salt (sodium chloride, NaCl) in water, the cathode reaction will be

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2$$

and hydrogen gas will bubble up; the anode reaction is

$$2NaCl \rightarrow 2\ Na^+ + Cl_2 + 2e^-$$

and chlorine gas will be liberated. The positively charged sodium ions $Na^+$ will react toward the cathode, neutralizing the negative charge of $OH^-$ there, and the negatively charged hydroxide ions $OH^-$ will react toward the anode, neutralizing the positive charge of $Na^+$ there. Without the ions from the electrolyte, the charges around the electrode would slow down continued electron flow; diffusion of $H^+$ and $OH^-$ through water to the other electrode takes longer than movement of the much more prevalent salt ions.

Also: Electrolytes dissociate in water because water molecules are dipoles and the dipoles orient in an energetically favorable manner to solvate the ions.

In other systems, the electrode reactions can involve the metals of the electrodes as well as the ions of the electrolyte.

Electrolytic conductors are used in electronic devices where the chemical reaction at a metal/electrolyte interface yields useful effects.

- In batteries, two materials with different electron affinities are used as electrodes; electrons flow from one electrode to the other outside of the battery, while inside the battery the circuit is closed by the electrolyte's ions. Here, the electrode reactions convert chemical energy to electrical energy.[3]
- In some fuel cells, a solid electrolyte or proton conductor connects the plates electrically while keeping the hydrogen and oxygen fuel gases separated.
- In electroplating tanks, the electrolyte simultaneously deposits metal onto the object to be plated, and electrically connects that object in the circuit.
- In operation-hours gauges, two thin columns of mercury are separated by a small electrolyte-filled gap, and, as charge is passed through the device, the metal dissolves on one side and plates out on the other, causing the visible gap to slowly move along.
- In electrolytic capacitors the chemical effect is used to produce an extremely thin 'dielectric' or insulating coating, while the electrolyte layer behaves as one capacitor plate.
- In some hygrometers the humidity of air is sensed by measuring the conductivity of a nearly dry electrolyte.
- Hot, softened glass is an electrolytic conductor, and some glass manufacturers keep

the glass molten by passing a large current through it.

# Solid electrolytes

Solid electrolytes can be mostly divided into three groups:

- Gel electrolytes - they closely resemble liquid electrolytes. In essence, they are liquids in a flexible lattice framework. Various additives are often applied to increase the conductivity of such systems.[3][4]
- Dry polymer electrolytes - they differ from liquid and gel electrolytes in the sense that salt is dissolved directly into the solid medium. Usually it is a relatively high dielectric constant polymer (PEO, PMMA, PAN, polyphosphazenes, siloxanes, etc.) and a salt with low lattice energy. In order to increase the mechanical strength and conductivity of such electrolytes, very often composites are used, and inert ceramic phase is introduced. There are two major classes of such electrolytes: polymer-in-ceramic, and ceramic-in-polymer.[5][6][7]
- Solid ceramic electrolytes - ions migrate through the ceramic phase by means of vacancies and/or interstitials within the lattice. There are also glassy-ceramic electrolytes.

# See also

- Strong electrolyte
- ITIES (Interface between Two Immiscible Electrolyte Solutions)

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Retrieved from "http://en.wikipedia.org/w/index.php?title=Electrolyte&oldid=592486682"
Categories: Electrolytes | Blood tests | Urine tests | Physical chemistry | Acid-base physiology

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# COUNTER ELECTROMOTIVE FORCE IN THE ALUMINUM RECTIFIER

BY

ALBERT LEWIS FITCH

A DISSERTATION

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN THE UNIVERSITY OF MICHIGAN

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# COUNTER ELECTROMOTIVE FORCE IN THE ALUMINUM RECTIFIER.

BY ALBERT LEWIS FITCH.

## I. INTRODUCTION.

THE anomalous action of aluminum in the electrolytic cell was first discovered by Wheatstone in 1855. Soon after this, Buff found that an electrolytic cell one electrode of which was aluminum would rectify the alternating current. Among the other men who have been interested in this cell may be mentioned Ducretet,[1] Hutin and Leblanc,[2] Montpellier,[3] Nodon,[4] Guthe,[5] Greene,[6] and Schulze.[7] The latter has perhaps done the largest amount of work of any. His articles have appeared from time to time in a number of magazines.

The earlier experimenters with this cell confined themselves to the study of aluminum but later investigation[7] has shown that many other metals possess this same property to a greater or less degree. Among these may be mentioned iron, nickle, cobalt, magnesium, cadmium, tin, bismuth, zirconium, tantalum, etc.

A great many electrolytes may be used in the rectifier. The most commonly used are the alums, phosphates, and carbonates; however Greatz and Pollak[8] have shown that any electrolyte which will liberate oxygen on electrolysis may be used more or less satisfactorily.

It has been found that the ability of the cell to rectify alternating current depends upon the current density at the aluminum anode,[9] the inductance and resistance of the circuit,[10] and its temperature.[11] The cell works best when the current density is high and the inductance, resistance, and temperature are low.

[1] Comptes Rendus, Vol. 80, p. 280.
[2] French Patents, No. 215945.
[3] Electrician, Vol. 22, p. 17.
[4] Comptes Rendus, Vol. 136, p. 445.
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[10] Ann. der Physik, Vol. 39, p. 976.
[11] Zeitschr. Elektrochem., Vol. 14, p. 333.

Two prominent theories have been advanced to explain the action of this cell. The earlier theory, known as *the solid film theory*, ascribes this action to the electrolytic deposition and decomposition of a solid film of some oxide or hydroxide of aluminum on the aluminum anode. The deposition takes place while the current flows in at the aluminum and, being a high resistance material, the film soon grows to a thickness which shuts off the current in that direction. The decomposition takes place when the current is in the opposite direction and permits the current to flow unimpeded from the electrolyte to the electrode.

In 1902 Guthe[1] first gave us the later theory, known as *the gas film theory*. This theory ascribes the action to a film of oxygen gas which is spread over the solid layer. The free electrons of the metal are forced through the gas film by the very high potential gradient with very little difficulty, when the aluminum is the cathode, but when the current reverses, and the aluminum is the anode, no such thing can take place because there are no free electrons in the electrolyte. Instead, the current must be carried through the film by the ions of the electrolyte and these being relatively large as compared to the electrons are with difficulty forced through.

It has been known for a great many years that the aluminum cell acts to a certain extent like a condenser. Schulze[2] states that a cell 40 $\times$ 40 $\times$ 40 cm. with both plates of aluminum had a capacity of 5,000 mfd. on 160 volts alternating current of a frequency of 50 cycles per second. It was possible, he states, to take an alternating current of 250 amperes through this cell. But one must not go too far in likening this cell to an ordinary leaking condenser as Greene[3] has shown.

This investigation was undertaken to determine if a more careful study of the counter electromotive force, which is produced when current enters at the aluminum, would throw some light on the action of the cell as a condenser and also on the theories advanced.

The cell used was composed of a lead plate with an area of approximately 90 sq. cm. and an aluminum wire .258 cm. in diameter and 10 cm. in length, immersed in a saturated solution of sodium phosphate. The aluminum wire was tested and found to contain .27 per cent. iron and some silicon in the form of silicates. It is about 99 per cent. pure. The lead is the same grade as that used in the chemistry department in qualitative experiments and is believed to be as pure as the aluminum. Both electrodes are heavily coated with a good grade of sealing wax where

[1] PHYS. REV., Vol. 15, p. 327.

[2] Zeitschr. Elektrochem., Vol. 14, p. 333.

[3] PHYS. REV., Vol. 3, series 2, p. 264.

they emerge from the solution to eliminate surface effects which were found to be present when the electrodes were not coated.

## II. Experimental Work.

As a preliminary study, a potentiometer method was devised for the measurement of the counter electromotive force. The cell was placed directly across the storage battery terminals for a time with the aluminum as anode and then the counter electromotive force, after a certain period of open circuit, was compared directly with the storage battery voltage. This period of open circuit was adjusted and measured by means of the disk described in the following method. Although this potentiometer method gives very accurate measurements of time of open circuit and of counter electromotive force, it is too slow to give the desired results.

Since the time for taking the readings by the former method could not be decreased, the oscillographic method was devised. This method enables one to take a complete set of readings in about one second. This eliminates to a large degree the objection to the former method and also enables one to get readings for much shorter periods of closed circuit.

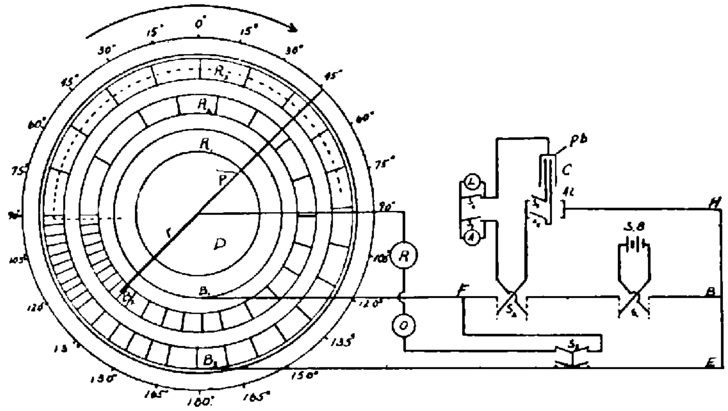


Fig. 1.

The diagram for the arrangement of apparatus is shown in Fig. 1. In this method the same disk was used as before with the same brush contacts and the same electrical connections on the disk. This disk is shown as *D*. It was designed for this work and made in the engineering shops of the University of Michigan. It is a solid, hard rubber disk of approximately 31 cm. radius. Firmly screwed to this disk are three concentric rings of brass. The inner ring $R_1$ has an inner radius of 12 cm. and an outer radius of 16 cm. It is made in one solid piece. The second ring $R_2$ has an inner radius of 19 cm. and an outer radius of 23 cm. It is divided into sectors ranging in magnitude from 5 degrees to

# 1. General Description of Aluminum Electrolytic Capacitors

## 1-1 Principles of Aluminum Electrolytic Capacitors

An aluminum electrolytic capacitor consists of cathode aluminum foil, capacitor paper (electrolytic paper), electrolyte, and an aluminum oxide film, which acts as the dielectric, formed on the anode foil surface.

A very thin oxide film formed by electrolytic oxidation (formation) offers superior dielectric constant and has rectifying properties. When in contact with an electrolyte, the oxide film possesses an excellent forward direction insulation property. Together with magnified effective surface area attained by etching the foil, a high capacitance yet small sized capacitor is available.

As previously mentioned, an aluminum electrolytic capacitor is constructed by using two strips of aluminum foil (anode and cathode) with paper interleaved. This foil and paper are then wound into an element and impregnated with electrolyte. The construction of an aluminum electrolytic capacitor is illustrated in Fig. 1-1.

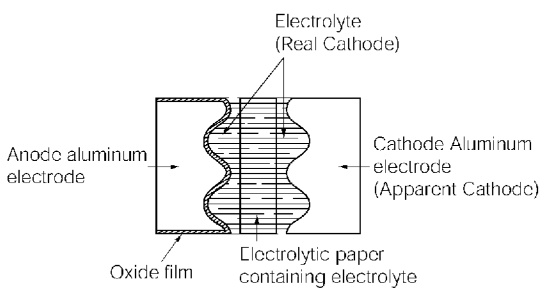



**Fig. 1 - 1**

Since the oxide film has rectifying properties, a capacitor has polarity. If both the anode and cathode foils have an oxide film, the capacitors would be bipolar (non-pola) type capacitor.

These technical notes refer to "non-solid" aluminum electrolytic construction in which the electrolytic paper is impregnated with liquid electrolyte. There is another type of aluminum electrolytic capacitor, which is the "solid" that uses solid electrolyte.

## 1-2 Capacitance of Aluminum Electrolytic Capacitors

The capacitance of an aluminum electrolytic capacitor may be calculated from the following formula same as for a parallel-plate capacitor.

$$C = 8.855 \times 10^{-8} \frac{\varepsilon S}{d} \ (\mu F) \cdots\cdots\cdots (1 - 1)$$

$\varepsilon$ : Dielectric constant of dielectric
S : Surface area ($cm^2$) of dielectric
d : Thickness (cm) of dielectric

To attain higher capacitance "C", the dielectric constant "$\varepsilon$" and the surface area "S" must increase while the thickness "d" must decrease. Table 1-1 shows the dielectric constants and minimum thickness of dielectrics used in various types of capacitors.

With aluminum electrolytic capacitors, since aluminum oxide has excellent withstand voltage, per thickness. And the thickness of dielectric can be freely controlled according to the rated voltage of the aluminum electrolytic capacitor.

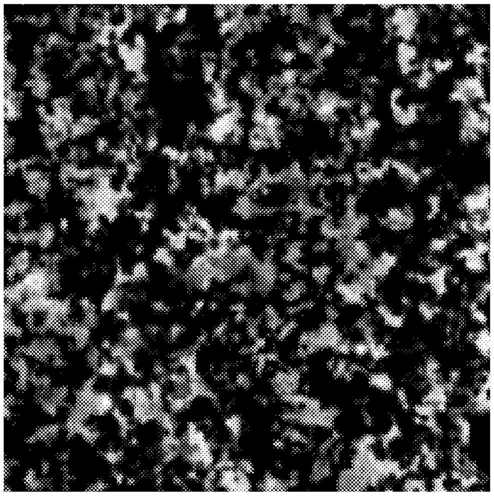
Therefore, in compare to other dielectric, similar voltage endurance is provided by dielectric even if thickness ("d" in the above formula) is thin.

Furthermore, by etching the surface of aluminum foil, the effective area of the foil as compared to the apparent area can be enlarged 80~100 times for low voltage capacitors and 30~40 times for middle / high voltage capacitors. Therefore, aluminum electrolytic capacitors have a higher capacitance for a specified apparent area than other types of capacitors.

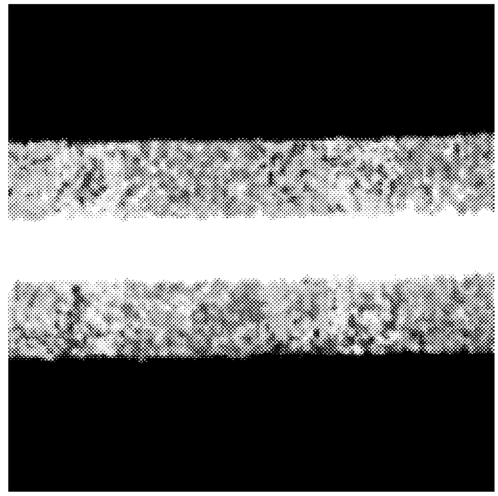
High purity aluminum foil for the anode is etched by electrochemical process in a chloride solution with DC, AC, or an alteration of DC and AC, or a concurring AC and DC current. Fine surface etching (photo 1-1) accomplished mainly by AC electrolysis is generally used for foil with a low voltage rating. Tunnel etching (photo 1-2) accomplished mainly by DC electrolysis is used for middle / high voltage foil. The etching of the cathode foil is mainly accomplished by AC electrolysis to increase the surface area.

**Table 1-1 Dielectric constants and minimum thickness of dielectrics used in various types of capacitors**

| Type of Capacitor | Dielectric | Dielectric Constant $\varepsilon$ | Dielectric Thickness d ($\mu$m) |
|---|---|---|---|
| Aluminum Electrolytic Capacitor | Aluminum Oxide | 7~10 | (0.0013~0.0015/V) |
| Tantalum Electrolytic Capacitor | Tantalum Oxide | 24 | (0.001~0.0015/V) |
| Film Capacitor (Metallized) | Polyester Film | 3.2 | 0.5~2 |
| Ceramic Capacitor (High Dielectric Constant Type) | Barium Titanate | 500~20,000 | 2~3 |
| Ceramic Capacitor (Temp. Compensation Type) | Titanium Oxide | 15~250 | 2~3 |

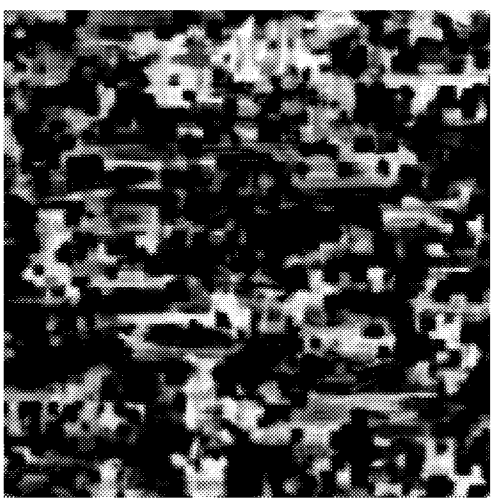


Surface

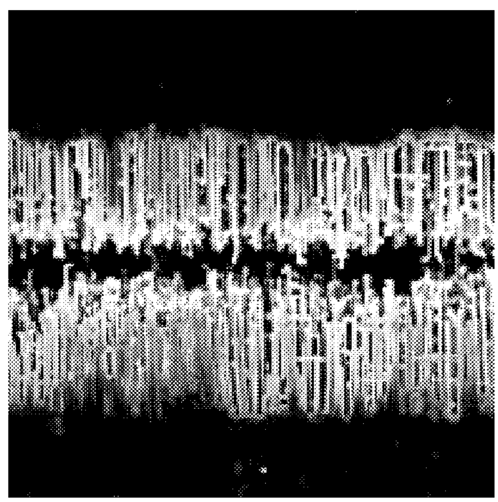


Section

**Photo 1-1 Surface and section photo of etched aluminum foil for low voltage capacitors.**



Surface



Section (Replica)

**Photo 1-2 Surface and section photo of etched aluminum foil for middle / high voltage capacitors.**

## 1-3 Dielectric (Aluminum Oxide Layer)

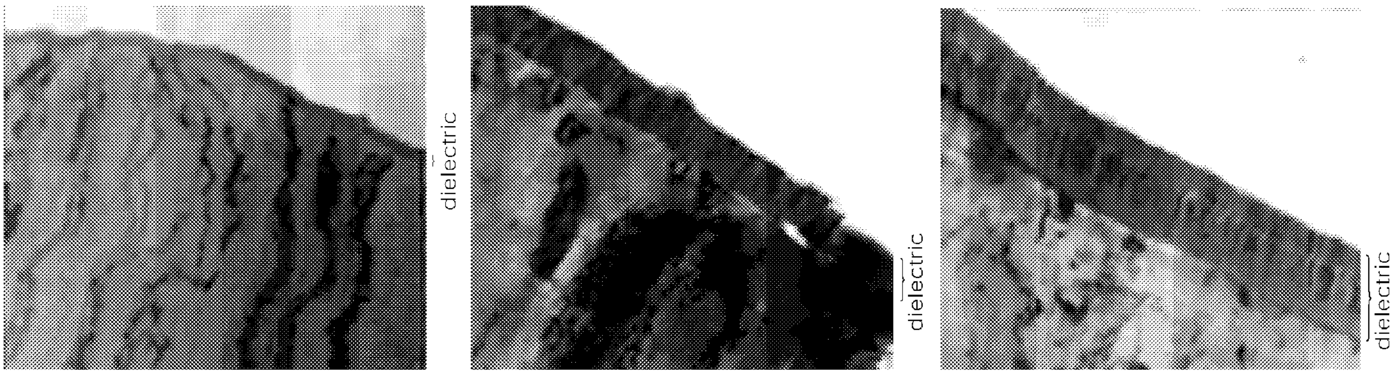
A high purity etched aluminum foil is anodized in a boric acid-ammonium water type solution, for exsample, to form an aluminum oxide film on its surface. This aluminum oxide film is what we call the dielectric of the aluminum electrolytic capacitor. The DC voltage that is applied to the foil to oxidize the anode foil is called "Forming Voltage".

The thickness of the dielectric is nearly proportional to the forming voltage and measures approximately 0.0013~0.0015 (μm)/ V.

Expanded photography of a dielectric (aluminum oxide layer) on the foil that has not been etched (plain foil) is shown in photo 1-3.

The fabrication reaction of the dielectric can be expressed as follows:

$2Al+3H_2O \Rightarrow Al_2O_3+3H_2$ (Gas) $\uparrow$ $+3e^-$ (Electron)




20V Formed 100V Formed 250V Formed

**Photo 1-3 Enlarged photo of oxide layer formed on a non-etched plain aluminum foil.**

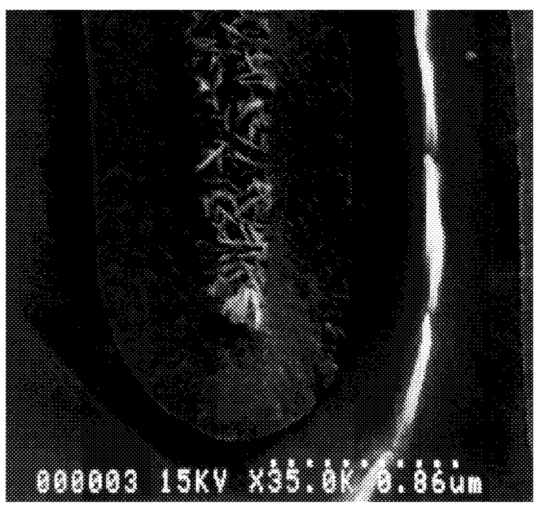



**Photo 1-4 Enlarged photo of middle, high voltage formed foil.**
**(Condition of oxide layer formation in a pit)**

## 1-4 Electrolyte

Anode foil and a cathode foil facing each other are interleaved with electrolytic paper and wound into a cylindrical shape. This is called a "capacitor element." At this stage, it has configuration of a capacitor when considers electrolytic paper and the aluminum oxide layer to be dielectric, however, the unit has few capacitance.

When this capacitor element is impregnated with liquid electrolyte, the anode foil and cathode foil are electrically connected. With the aluminum oxide layer formed on the anode foil acting as the sole dielectric, a capacitor with a high value of capacitance is now attainable. That is to say that the electrolyte is now functioning as a cathode. The basic characteristics required of an electrolyte are listed below:

(1) It must be electrically conductive.
(2) It must have a forming property to heal any flaws on the dielectric oxide of the anode foil.
(3) It must be chemically stable with the anode and cathode foils, sealing materials, etc.
(4) It must have superior impregnation characteristics.
(5) Its vapor pressure must be low.

The above characteristics of electrolyte greatly influence the various characteristics of aluminum electrolytic capacitors. For this reason, the proper electrolyte is determined by the electrical ratings, operating temperatures and the application of the capacitor.

## 1-5 Manufacturing Process of Aluminum Electrolytic Capacitors

| Process | Main Materials | Contents |
|---|---|---|
| Etching (Enlargement of the Surface Area) | High purity aluminum foil<br>Chloride<br>Pure water | A 0.05~0.11 mm thick anode foil and a 0.02~0.05 mm thick cathode foil are continuously etched electrochemically in a chloride solution with an AC or DC current. This enlarges the effective surface area of the aluminum foils to attain smaller capacitor sizes. |
| Forming (Formation of the Dielectric) | Etched foil<br>Borate, etc.<br>Pure water | The process develops aluminum oxide ($Al_2O_3$) to form a capacitor dielectric.<br>A high purity etched aluminum foil is anodized in a boric acid-ammonium water type solution, for example, to form an aluminum oxide layer on the surface of the anode foil. As for the cathode foil, an low DC voltage is sometimes used for formation, but there are also situations where formation is not conducted. |
| Slitting | Anode foil<br>Cathode foil | A foil is slited into specified widths according to capacitor case sizes. |
| Winding | Slited foils (anode/cathode)<br>Electrolytic paper<br>Leade<br>Winding aftixing material | Anode and cathode foils interleaved with an electrolytic paper are wound into a cylindrical capacitor element, with leads being connected to both foils. |

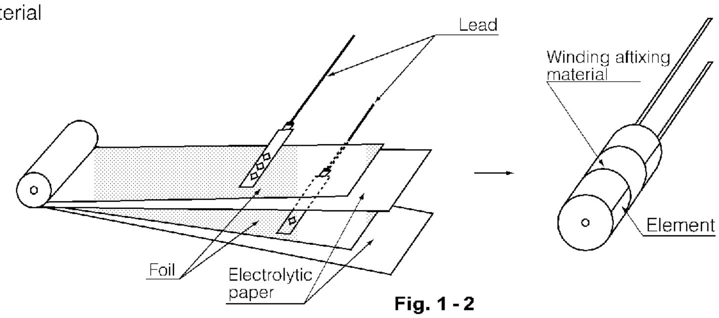



**Fig. 1 - 2**

| Prosess | Main Materials | Contents |
|---|---|---|
| Element Impregnation Electrolyte | Elements<br>Electrolyte | Elements are impregnated with liquid electrolyte.<br>The clearance between the two electrode foils is filled with liquid electrolyte. With this impregnation, an element can function as a capacitor. |
| Assembly & Finishing | Impregnated elements<br>Case (usually aluminum)<br>End seal<br>(Rubber packing, Rubber-bakelite with terminals, Mold plastic with terminals)<br>Exterior housing material (Sleeving, bottom plate, etc.) | The impregnated element, case and end seal are assembled. For the end seal , a rubber packing, a rubber lined bakelite (with terminals) or a molded plastic plate (with terminals) are used.<br>After assembly, the capacitors are covered with exterior housing material. Sleeving is not used for laminate case products, such as surface mount capacitors. |
| Aging | Assembled products | DC voltage is applied under high temperature conditions to reform the oxide film. |
| Processing | Plastic platform<br>Taping material<br>Accessories<br>(Capacitor mounting braket, terminal screws , etc.) | Leads are processed and the plastic platform is attached to surface mount capacitors.<br>Depending on customer specification, the lead cutting, forming, snap - in and taping are processed.<br>Accessories, such as mounting braket, are attached. |
| Inspection | | An inspection based on the standard specification and test requirements is performed to guarantee the quality of products. |
| Packaging | Packaging materials | |
| Shipping | | |

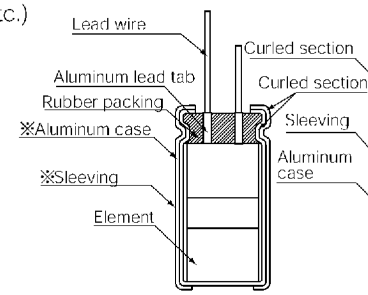



Fig. 1 - 3

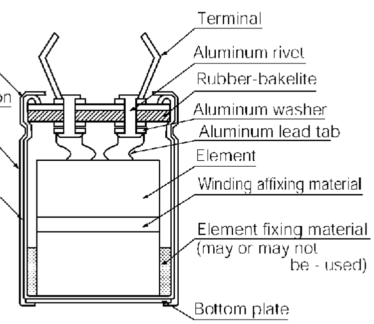



Fig. 1 - 4

※ laminate casing for laminate products (sleeveless)

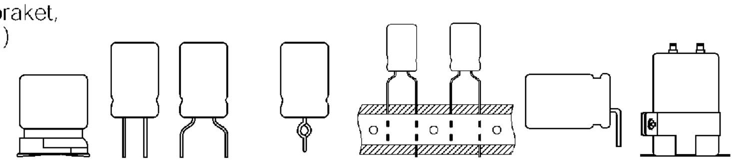


Fig. 1 - 5

# 1-6 Characteristics

### 1-6-1 Capacitance

The capacitance of the dielectric portion of the anode aluminum foil can be calculated with the following formula (discussed in 1-1) :

$$Ca = 8.855\times10^{-8}\ \frac{\varepsilon S}{d}\ (\mu F)$$

The cathode foil has a capacitance (Cc) that uses the oxide layer, which formed by the forming voltage or formed naturally during storage (generally 1V or less), as a dielectric. According to the construction of aluminum electrolytic capacitors, Ca and Cc are connected in a series. Therefore, the capacitance can be determined by the following formula:

$$C = \frac{Ca\times Cc}{Ca + Cc}$$

The standard capacitance tolerance is ±20%(M); however, capacitors with a capacitance tolerance of ±10%(K), etc. are also manufactured for special usage. The capacitance of aluminum electrolytic capacitors changes with temperature and frequency of measurement, so the standard has been set to a frequency of 120Hz and temperature of 20°C.

### 1-6-2 Equivalent Series Resistance (R), Dissipation Facter (tanδ), Impedance (Z)

The equivalent circuit of an aluminum electrolytic capacitor is shown below, The equivalent series resistance is also known as "ESR".

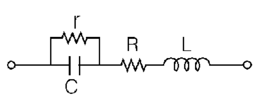
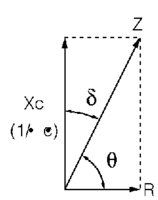



Fig. 1 - 6

C : Capacitance (F)
r : Equivalent parallel resistance of anode oxide film (Ω)
R : Equivalent series resistance (Ω)
L : Equivalent series inductance (H)

A reactance value due to the equivalent series inductance "L" is extremely small at low frequencies (50Hz~1kHz) and can be regarded as zero. Therefore, the following formula can be set up.




$$\tan\delta = \frac{R}{Xc} = \omega CR \quad \cdots(1-2)$$

$$DF = \tan\delta \times 100\ (\%) \quad \cdots(1-3)$$

$$PF = \cos\theta = \frac{R}{Z} = \frac{R}{\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}} \quad \cdots(1-4)$$

$$Q = \frac{1}{\tan\delta} = \frac{Xc}{R} \quad \cdots(1-5)$$

$$(\omega = 2\pi f)$$

Fig. 1 - 7

The impedance can be expressed by :

$$Z = \frac{1}{j\omega C} + j\omega L + R$$

Its absolute value can be expressed by :

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

Its relation with frequencies is shown by a model curve.

The inductance "L" is mainly from the wound electrode foils and the leads.

ESR "R" is from resistance of the electrode foils, the electrolyte, the leads and each connection.

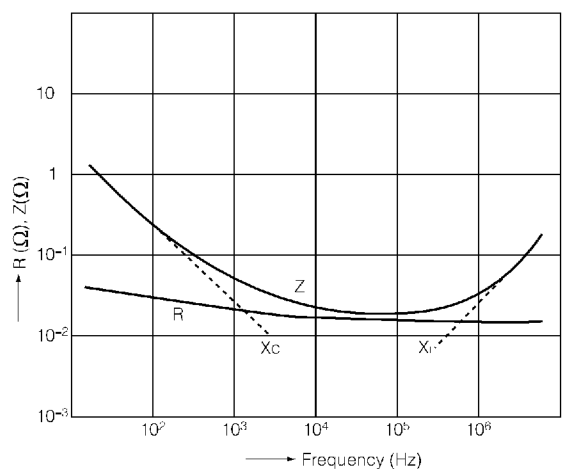



Fig. 1 - 8

### 1-6-3 Leakage Current

The causes of leakage current in aluminum electrolytic capacitors are listed below :

1)Distorted polarization of dielectric (aluminum oxide layer)
2)Resolution and formation of dielectric
3)Moisture absorption by dielectric
4)Breakdown of dielectric due to the existence of chlorine or iron particles.

The leakage current value can be decreased by proper selection of materials and production methods; however, cannot be totally eliminated.

Leakage current is also dependent upon time, applied voltage and temperature.

The specified leakage current value is measured after the rated voltage of the capacitor is applied at room temperature for a specified time period. When selecting a capacitor for a particular application, characteristics such as temperature dependency, aging stability and etc. must be taken into account.

### 1-6-4 Temperature Characteristics

Aluminum electrolytic capacitors have liquid electrolyte. This electrolyte has properties (conductivity, viscosity, etc.) that have rather conspicuous temperature characteristics.

Electrical conductivity increases as the temperature increases and reduces as the temperature decreases. Therefore, the electrical characteristics of aluminum electrolytics are affected by temperature more than other types of capacitors. The following section explains the relationship between temperature and capacitance, tangent delta, ESR, impedance and leakage current.

1) Capacitance

The capacitance of aluminum electrolytic capacitors increases as the temperature increases and decreases as the temperature decreases. The relationship between temperature and capacitance is shown in Fig. 1-9.

2) Tanδ, Equivalent Series Resistance (ESR), Impedance

The Tanδ, equivalent series resistance (ESR) and impedance changes with temperature and frequency. An example of the general characteristics is shown in Fig. 1-10 and 1-11.

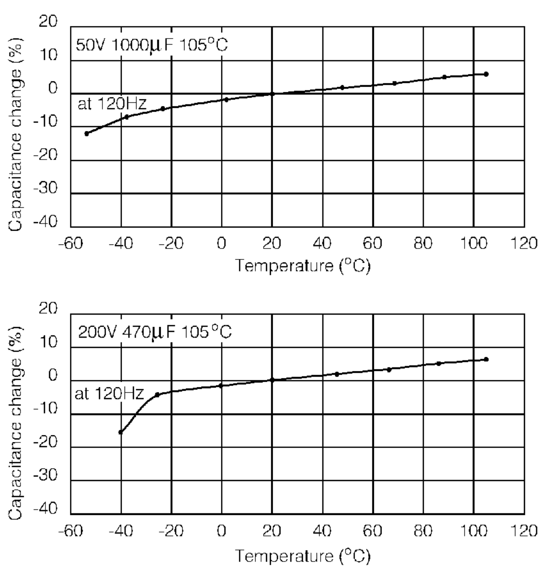



**Fig. 1 - 9 Capacitance vs. Temperature Characteristics**

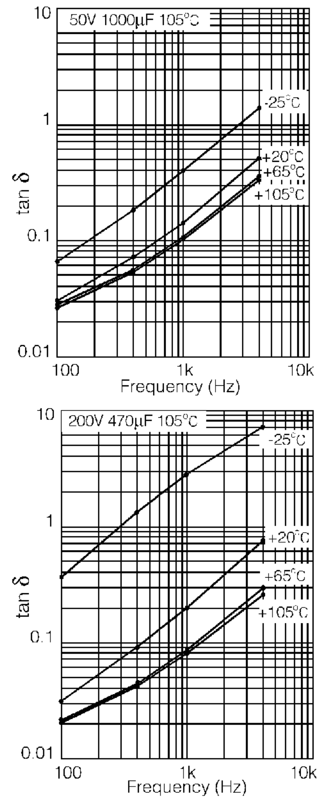



**Fig. 1 - 10 Tanδ vs. Frequency Characteristics**

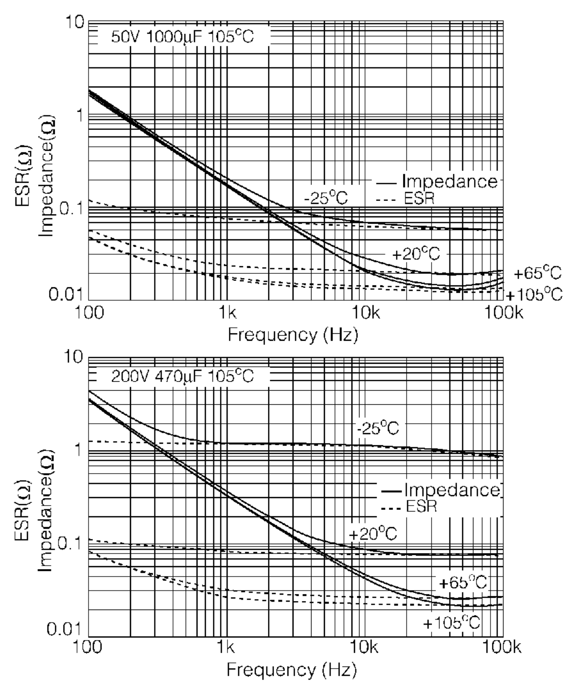



**Fig. 1 - 11 Impedance, ESR vs. Frequency Characteristics**

3) Impedance Ratio

The ratio between the impedance at 20°C and the impedance at various temperatures is called the impedance ratio. Impedance ratio becomes smaller as smaller change of ESR and capacitance with temperature. The quality of performance at low temperatures is particularly expressed with the impedance ratio at 120Hz.

4) Leakage Current

The leakage current increases as the temperature increases and decreases as the temperature decreases. Fig. 1-12 shows the relationship between temperature and leakage current.

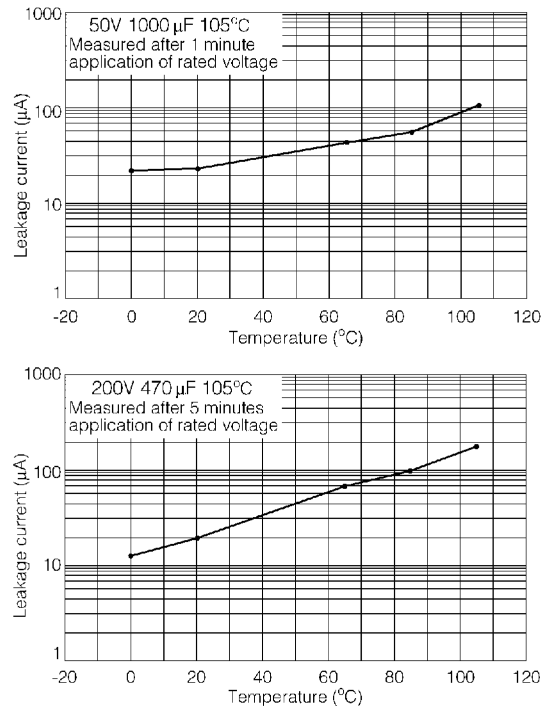



**Fig. 1 - 12 Leakage current vs. Temperature Characteristic**

# 2. Application Guidelines for Aluminum Electrolytic Capacitors

## 2-1 Application Guidelines

### 2-1-1. Circuit Design

( 1 ) Please make sure the application and mounting conditions to which the capacitor will be exposed are within the conditions specified in the catalog or alternate product specification (Referred as to specification here after).

( 2 ) Operating temperature and applied ripple current shall be within the specification.
①The capacitor shall not be used in an ambient temperature which exceeds the operating temperature specified in the specification.
②Do not apply excessive current which exceeds the allowable ripple current.

( 3 ) Appropriate capacitors which comply with the life requirement of the products should be selected when designing the circuit.

( 4 ) Aluminum electrolytic capacitors are polarized. Make sure that no reverse voltage or AC voltage is applied to the capacitors. Please use bi-polar capacitors for a circuit that can possibly see reversed polarity.
Note: Even bi-polar capacitors can not be used for AC voltage application.

( 5 ) For a circuit that repeats rapid charging/discharging of electricity, an appropriate capacitor that is capable of enduring such a condition must be used. Welding machines and photo flash are a few examples of products that contain such a circuit. In addition, rapid charging/discharging may be repeated in control circuits for servomotors, In which the circuit voltage fluctuates substantially.
For appropriate choice of capacitors for circuit that repeat rapid charging/discharging, please consult Nichicon.

( 6 ) Make sure that no excess voltage (that is, higher than the rated voltage) is applied to the capacitor.
①Please pay attention so that the peak voltage, which is DC voltage overlapped by ripple current, will not exceed the rated voltage.
②In the case where more than 2 aluminum electrolytic capacitors are used in series, please make sure that applied voltage will be lower than rated voltage and the voltage be will applied to each capacitor equally using a balancing resistor in parallel with the capacitors.

( 7 ) Aluminum electrolytic capacitors must be electrically isolated as follows:
The aluminum case and the cathode foil are connected by the unstable resistance of a naturally formed oxide layer inside the aluminum case and the electrolyte.
①(a) Case and negative terminal (except axial leaded part such as JIS configuration 02 type)
(b) Case and positive terminal
(c) Case and circuit pattern
②(a) Auxialiary terminal of can type such as JIS style symbol 693, 694 or 695 and negative and positive terminal, including the circuit pattern.
③Case and both terminals of a bi-polarized capacitor.

( 8 )①Outer sleeve of the capacitor is not guaranteed as an electrical insulator. Do not use a standard sleeve on a capacitor in applications that require the electrical insulation. When the application requires special insulation, please contact our sales office for details.
②Secondary shrinkage, bulging and/or crack could be seen on outer sleeve of capacitor when capacitors are kept in more than 2 minutes at 150°C ambient temperature during pre-heating at reflow process or resin curing process. Applying high temperature gas or heat ray to capacitor cause the same phenomenon. Further more, when temperature cycling test is performed beyond JIS standard (Temperature Cycles), aforementioned sleeve problem could be seen. Thus, please confirm their adaptation before the use.

( 9 ) Capacitors may fail if they are used under the following conditions:
①Environmental (climatic) conditions
(a) Being exposed to water, high temperature & high humidity atmosphere, or condensation of moisture.
(b) Being exposed to oil or an atmosphere that is filled with particles of oil.
(c) Being exposed to salty water or an atmosphere that is filled with particles of salt.
(d) In an atmosphere filled whith toxic gasses (such as hydrogen sulfide, sulfurous acid, nitrous acid, chlorine, bromine, methyl bromide, ammonia, etc.)
(e) Being exposed to direct sunlight, ozone, ultraviolet ray, or radication
(f) Being exposed to acidic or alkaline solutions
②Under severe conditions where vibration and/or mechanical shock exceed the applicable ranges of the specifications.

(10) When designing a P.C. board, please pay attention to the following:
①Have the hole spacing on the P.C. board match the lead spacing of the capacitor.
②There should not be any circuit pattern or circuit wire above the capacitor pressure relief vent.
③Unless otherwise specified, following clearance should be made above the pressure relief vent.

| Case Diameter | Clearance Required |
|---|---|
| ϕ6.3~16mm | 2mm or more |
| ϕ18~35mm | 3mm or more |
| ϕ40mm or more | 5mm or more |

④In case the vent side is placed toward P.C. board (such as end seal vented parts), make a

corresponding hole on the P.C. board to release the gas when vent is operated. The hole should be made to match the capacitor vent position.
⑤Screw terminal capacitors must be installed with their end seal side facing up. When you install a screw terminal capacitor in a horizontal position, the positive terminal must be in the upper position.

(11) The main chemical solution of the electrolyte and the separator paper used in the capacitors are combustible. The electrolyte is conductive. When it comes in contact with the P.C. board, there is a possibility of pattern corrosion or short circuit between the circuit pattern which could result in smoking or catching fire.
Do not locate any circuit pattern beneath the capacitor end seal.

(12) Do not design a circuit board so that heat generating components are placed near an aluminum electrolytic capacitor or reverse side of P.C. board (under the capacitor).

(13) Please refer to the pad size layout recommendations in our catalog when designing in surface mount capacitors.

(14) Electrical characteristics may vary depending on changes in temperature and frequency. Please consider this variation when you design circuits.

(15) When you mount capacitors on the double-sided P.C. boards, do not place capacitors on circuit patterns or over on unused holes.

(16) The torque for terminal screw or brackets screws shall be within the specified value on Nichicon's drawings.

(17) When you install more than 2 capacitors in parallel, consider the balance of current flowing through the capacitors. Especially, When a solid conductive polymer aluminum electrolytic capacitor and a standard aluminum electrolytic capacitor are conected in parallel, special consideration must be given.

(18) If more than 2 aluminum electrolytic capacitors are used in series, make sure the applied voltage will be lower than the rated voltage and that voltage will be applied to each capacitor equally using a balancing resistor in parallel with each capacitor.

### 2-1-2. Mounting

( 1 ) Once a capacitor has been assembled in the set and power applied. Even if a capacitor is discharged, an electric potential(restriking voltage) may exist between the terminals.

( 2 ) Electric potential between positive and negative terminal may exist as a result of returned electromotive force, so please discharge the capacitor using a 1kΩ resistor.

( 3 ) Leakage current of the parts that have been stored for more than 2 years may increase. If leakage current has increased, please perform a voltage treatment using 1kΩ resistor.

( 4 ) Please confirm ratings before installing capacitors on the P.C. board.

( 5 ) Please confirm polarity before in stalling capacitors on the P.C. board.

( 6 ) Do not drop capacitors on the floor, nor use a capacitor that was dropped.

( 7 ) Do not damage the capacitor while installing.

( 8 ) Please confirm that the lead spacing of the capacitor matches the hole spacing of the P.C. board prior to installation.

( 9 ) Snap-in can type capacitor such as JIS style symbol 692, 693, 694 and 695 type should be installed tightly to the P.C. board (allow no gap between the P.C. board an bottom of the capacitor).

(10) Please pay attention that the clinch force is not too strong when capacitors are placed and fixed by an automatic insertion machine.

(11) Please pay attention to that the mechanical shock to the capacitor by suction nozzle of the automatic insertion machine or automatic mounter. or by product checker,or by centering mechanism.

(12) Hand soldering.
①Soldering condition shall be confirmed to be within the specification.
② If it is necessary that the leads must be formed due to a mismatch of the lead space to hole space on the board, bend the lead prior to soldering without applying too much stress to the capacitor.
③ If you need to remove parts which were soldered, please melt the solder enough so that stress is not applied to lead.
④Please pay attention so that solder iron does not touch any portion of capacitor body.

(13) Flow soldering (Wave solder)
①Aluminum capacitor body must not be submerged into the solder bath. Aluminum capacitors must be mounted on the "top side" of the P.C. board and only allow the bottom side of the P.C. board to come in contact with the solder.
②Soldering condition must be confirmed to be within Nichicon specification.
Solder temperature: 260 ± 5°C Immersing lead time:10 ± 1 second, Thickness of P.C. board : 1.6mm.
③Please avoid having flux adhere to any portion except the terminal.
④Please avoid contact between other components and the aluminum capacitor.

(14) Reflow soldering (SMD only)
①Soldering condition must be confirmed to be within Nichicon specification.
②When an infrared heater is used, please pay attention to the extent of heating since the absorption rate of infrared, will vary due to difference in the color of the capacitor body, material of the sleeve and capacitor size.

(15) Soldeing flux
There are non-halogen types of flux that do not contain ionic halides, but contain many non-ionic halides. When these non-ionic halides infiltrate the capacitor, they cause a chemical reaction that is just as harmful as the use of cleaning agents. Use soldering flux that dose not contain non-ionic halides.

(16) Shrinkage,bulging and/or cracking could be seen on the outer sleeve of the capacitor when capacitors are kept in for more than 2 minutes at 150℃ ambient temperature during soldering at reflow process or resin curing process. Applying high temperature gas or heat ray to capacitor can cause the same phenomenon.

(17) Do not tilt lay down or twist the capacitor body after the capacitor are soldered to the P.C. board.

(18) Do not carry the P.C. board by grasping the soldered capacitor.

(19) Please do not allow anything to touch the capacitor after soldering. If P.C. board are stored in a stack, please make sure P.C. board or the other components do not touch the capacitor.
The capacitors shall not be effected by any radiated heat from the soldered P.C. board or other components after soldering.

(20) Cleaning Agent, Fixing material, Coating material
Please refer to the section 2-10-2, -3 for Cleaning agent, fixing material and coating material.

(21) Fumigation
Please refer to the section 2-10-4 for others.

### 3. In the equipment

( 1 ) Do not directly touch terminal by hand.

( 2 ) Do not short between terminals with conductor, nor spill conductible liquid such as alkaline or acidic solution on or near the capacitor.

( 3 ) Please make sure that the ambient conditions where the set is installed will be free from spilling water or oil, direct sunlight, ultraviolet rays, radiation, poisonous gases, vibration or mechanical shock.

### 4. Maintenance Inspection

( 1 ) Please periodically inspect the aluminum capacitors that are installed in industrial equipment. The following items should be checked:
①Appearance : Remarkable abnormality such as vent operation, leaking electrolyte etc.
②Electrical characteristic: Capacitance, dielectric loss tangent, leakage current, and items specified in the specification.

### 5. In an Emergency

( 1 ) If you see smoke due to operation of safety vent, turn off the main switch or pull out the plug from the outlet.

( 2 ) Do not bring your face near the capacitor when the pressure relief vent operates. The gasses emitted from that are over 100°C.
If the gas gets into your eyes, please flush your eyes immediately in pure water.
If you breathe the gas, immediately wash out your mouth and throat with water.
Do not ingest electrolyte. If your skin is exposed to electrolyte, please wash it away using soap and water.

### 6. Storage

( 1 ) It is recommended to keep capacitors between the ambient temperatures of 5°C to 35°C and a relative humidity of 75% or below.

( 2 ) Confirm that the environment does not have any of the following conditions:
①Where capacitors are exposed to water, high temperature & high humidity atmosphere, or condensation of moisture.
②Where capacitors are exposed to oil or an atmosphere that is filled with particles of oil.
③Where capacitors are exposed to salty water, high temperature & high humidity atmosphere, or condensation of moisture.
④The atmosphere is filled with toxic acid gasses (e.g. hydrogen sulfide, sulfurous acid, nitrous acid, chlorine, bromine, methy bromide, etc.)
⑤The atmosphere is filled with toxic alkaline gasses (e.g. ammonia)
⑥Where capacitors are exposed to acidic or alkaline solutions.

### 7. Disposal

( 1 ) Take either of the following methods in disposing of capacitors.
①Make a hole in the capacitor body or crush capacitors and incinerate them.
②If incineration is not applicable, hand them over to a waste disposal agent and have them buried in a landfill.

The above mentioned material according to EIAJ RCR - 2367B (issued in March, 2002), titled "Guideline of notabilia for aluminum electrolyic capacitors for use in electronic equipment".
Prease refer to the book for details.

## 2-2 Failure Modes of Aluminum Electrolytic Capacitors

### 2-2-1 Definition of Failure

The following two conditions must be considered in defining "failure."

**1) Catastrophic failure**

When a capacitor has completely lost its function due to a short or open circuit.

**2) Degradation failure**

The gradual deterioration of a capacitor. In the case of a degradation failure, the criteria for failure differs according to the use of a capacitor. Capacitor requirements vary depending on the type of finished products. Therefore, the specified value in the specification is used as the judging criteria.

**3) Capacitance Drop, High Loss (High ESR)**

If the capacitor is subjected to the following conditions, capacitance drop and high loss takes place: 1) if reverse voltage is continuously applied, 2) if a current exceeding the maximum rated ripple is applied, and 3) if the capacitor is subjected to extreme recharge and discharge.

**4) Destruction (Pressure Relief Vent Operation)**

The pressure relief vent may operate due to generation of gas caused by reverse voltage, over voltage, extreme ripple or AC voltage.

### 2-2-2 Failure Mode in the Field

**1) Short Circuit**

Short circuits in the field are very rare. A short circuit between the electrodes can be caused by vibration, shock and stress on leads. It can also be caused by application of voltage above the rated voltage, application of extreme ripple or by application of pulse current.

**2) Open Circuit**

- An open circuit can be caused if extreme force is applied to the capacitor at the time of mounting and if vibration / shock is then applied during usage. In such cases, the connection between the lead wire and tab could be distorted or twisted which eventually leads to an open circuit.
- If halogen is used as a cleaning agent for P.C. boards and a fixing agent (including conformal materials) for capacitors, infiltrates the capacitor, the operation of the circuit may be affected by an increased leakage current as a result of an open circuit due to corrosion of lead wires, foils and tabs.
- The electrolyte may vaporize and cause an open circuit if the tightness of the seal is broken as a result of sealing material deterioration due to use under high temperature exceeding the rated maximum operating temperature, or exposure to high heat transmitted through the P.C. board patterns, or prolonged use.
- If the sealing material ages due to long term usage. When subjected to such conditions, there is a possibility that the capacitor will open circuit due to drying of electrolyte.
- If an improper amount of ripple is applied, the internal temperature will rise. This will cause the electrolyte to increase its internal gas pressure and permeate through the end seal material. As a result of drying of electrolyte, open circuit will occur.

### 2-2-3 Analysis of Failure Mode

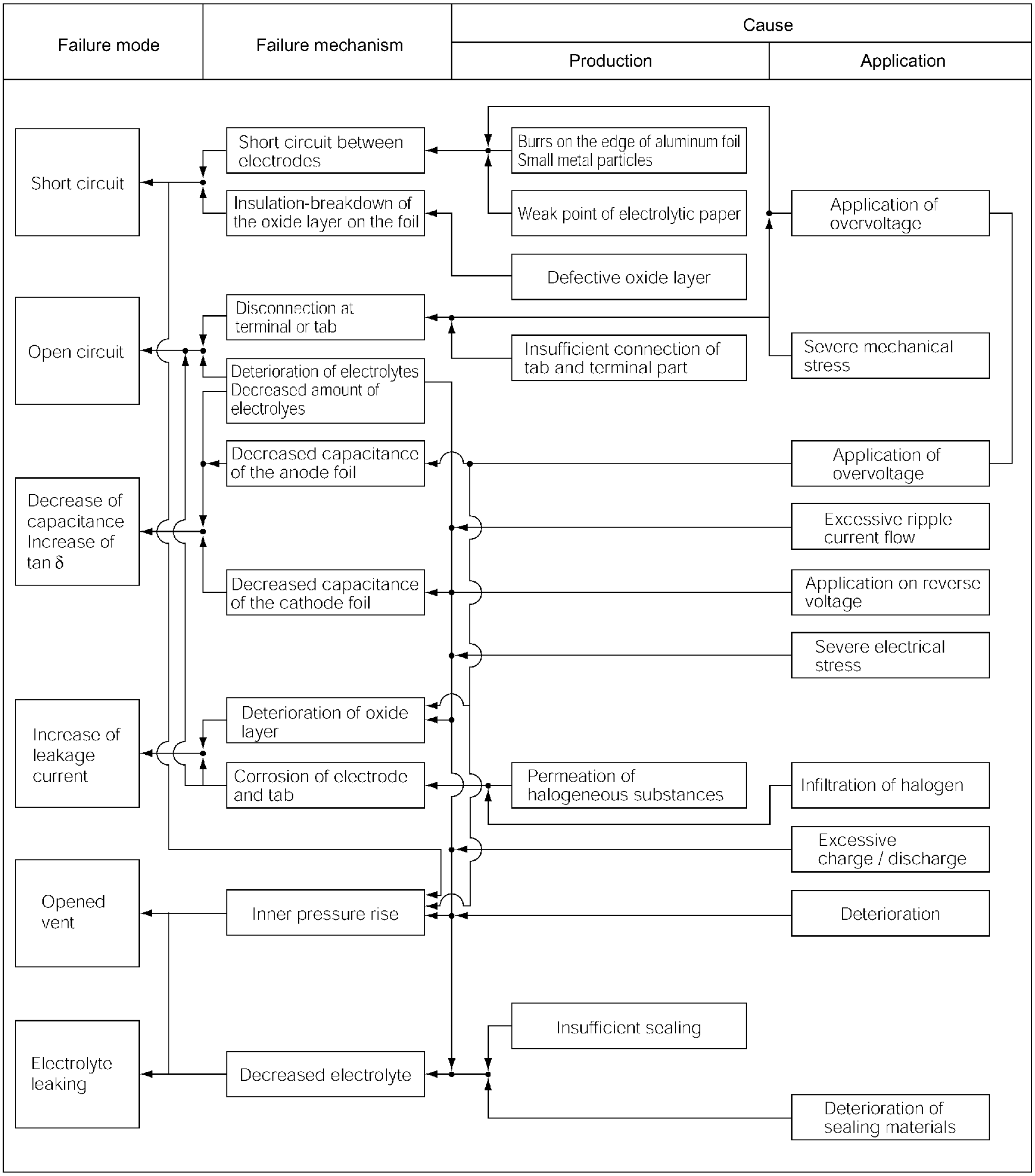



**Fig. 2 - 1 Analysis of Failure Mode**

## 2-3 Operating Voltage and Safety

### 2-3-1 Foreword

The relationship between the voltage and leakage current when voltage is applied to the aluminum electrolytic capacitor is shown in Fig. 2-2. From Fig. 2-2, the following can be said:

- If voltage is applied in directions of the polarity of the capacitor, the leakage current will start rapidly to rise if the applied voltage exceeds the rated voltage.
- If voltage is applied in reverse direction of the polarity of the capacitor, a large amount of current begins to run through with a low voltage.

The behavior and safety test method of the aluminum electrolytic capacitor, which withholds the above nature, under the below conditions is expressed in the following section.

1) Under reverse polarity
2) Under excess voltage application.
3) Under AC voltage application

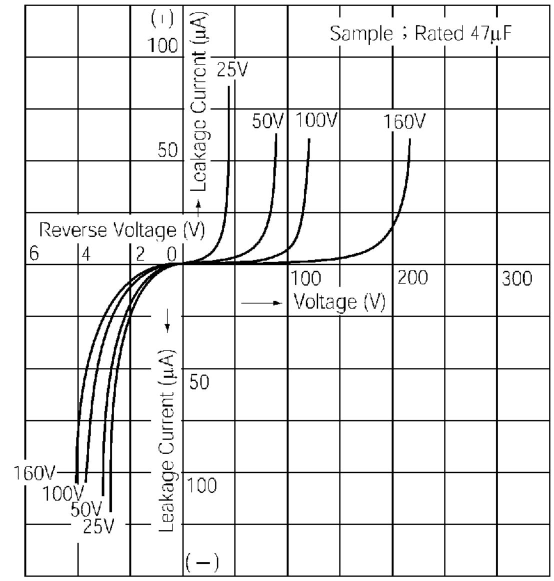



**Fig. 2-2 V - I Characteristics (Voltage - Current Characteristics)**

### 2-3-2 Reverse Voltage

The state of the capacitor changes according to the degree of reverse voltage applied.

1) If high reverse voltage is applied, the current will increase. Heat will generate due to power loss (W=Vc×Ic) caused by reverse voltage (Vc) and current (Ic). Heat caused by current and gas that generated due to the electrolytic dissociation of electrolyte will increase the inner pressure of the capacitor and activate the vent in a short period of time.
2) In case of a low reverse voltage and a low leakage current, a capacitor initially generated heat due the power loss. But the progressing formation of an oxide layer on the cathode electrode causes a decrease in current. Fig. 2-3 shows how the capacitance changes relative to the application of reverse voltage. The results shown in the figure is due to the decrease in cathode foil capacitance caused by oxide layer formation on the surface of the cathode aluminum foil. Again due to the consumption of electrolyte, the tan δ increases.

Normally a cathode foil has a withstand voltage of about 1V because of the natural oxide layer so it can withstand a reverse voltage as much as a diode's withstand reverse voltage. If the capacitor is being used a reverse voltage over the withstand voltage, the internal pressure will rise and activate the pressure relief vent. Please make sure to check the polarity of the capacitors before usage.

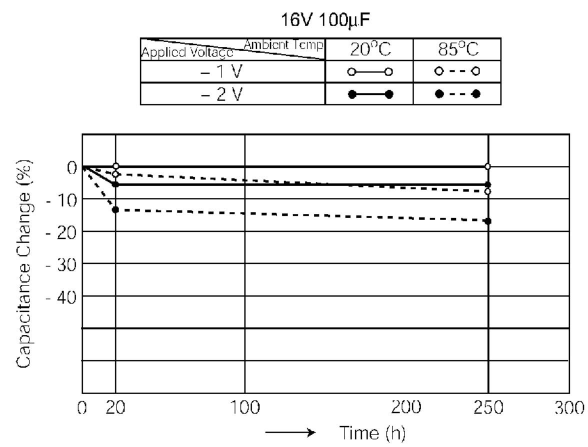



**Fig. 2-3 Capacitance vs. Reverse Voltage Characteristics**

### 2-3-3 Excess Voltage Application

As Fig. 2-4 shows, the leakage current rises sharply when voltage above the rated voltage is applied. When the withstand voltage of the anode foil decreases due to the generation of heat and the anode foil undergoes insulation breakdown, a large amount of current will flow through and cause the internal pressure to rise within a short period of time. If the pressure relief vent is activated, the electrolyte that has changed to gas is vigorously released from the opened vent. The energy of the capacitor is proportional to the second power of the voltage ( $J=\frac{1}{2}CV^2$ ). Therefore, the higher the applied voltage, the more severe the condition of the activated vent, and the more likely that a short between the foils will occur. Please use capacitors within their rated voltage.

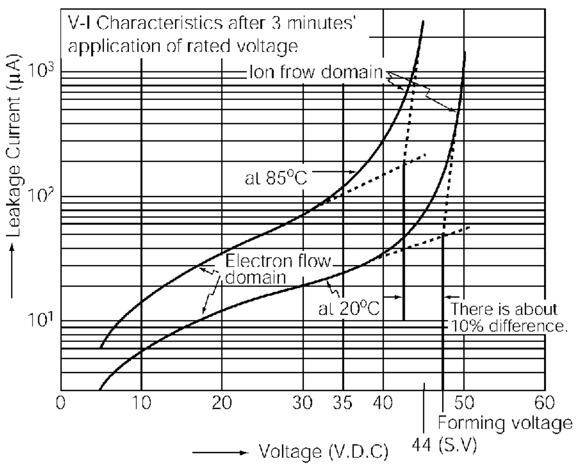



**Fig. 2 - 4 V - I Characteristics (ex. Rated at 35V)**

### 2-3-4 AC Voltage Application

If AC voltage is applied to an aluminum electrolytic capacitor, an electric current of $I = \omega CE$ (A) flows.

As (Fig. 2-2 V-I Characteristics) shows, the aluminum electrolytic capacitor does not have withstand voltage in the reverse direction. Therefore if the capacitor is used in an AC circuit, an electric current flow which is larger than that calculated from $I = \omega CE$. If the internal resistance of the aluminum electrolytic capacitor is labeled R (Ω), heat will generate due to the wattage loss $W = I^2R$ (W) according to the current. The degree of heat is large because the internal resistance of a capacitor is large; thus the pressure relief vent is activated when heat generates and causes the electrolyte to evaporate, causing the internal pressure to rise. Even bipolar capacitors (non-polar), cannot use it for continuous AC appication in addition to above.

### 2-3-5 Pressure Relief Vent Structure

The internal pressure of the capacitor will rise due to gas generation caused by heat generation, evaporation of electrolyte or electrolytic dissociation if the following is applied : extreme voltage, reverse voltage, AC current or extreme ripple. With this in mind, the pressure relief vent is provided to release internal pressure.

There are two types of pressure relief vents classified by their location on the capacitor : 1) end seal, 2) aluminum case.

**Testing Method**

**a. AC Voltage Method (JIS C5101-1, 4.28.1)**

(1)In the circuit shown in Fig.2-5 a series resisitance "R" is selected from Table 2-1 in accordance with the rated capacitance of the capacitor to be tested.

**Table 2-1**

| Rated Capacitance (μF) | Series Resistance (Ohm) | Rated Capacitance (μF) | Series Resistance (Ohm) |
|---|---|---|---|
| 1 or below | 1000±100 | Over 100~1000 | 1±0.1 |
| Over 1~10 | 100±10 | Over 1000~10000 | 0.1±0.01 |
| Over 10~100 | 10±1 | Over 10000 | Note 1 |

Note 1 : A resistance value equivalent to 1/2 of impedance at testing frequency.

(2)The capacitor is connected and AC voltage is applied as high as 70% of the rated voltage or 250Vrms, whichever is smaller. However, when 30Arms or more is applied, the voltage must be adjusted so that the maximum applied current is 30 Arms. The power source frequency is either 50Hz or 60Hz.

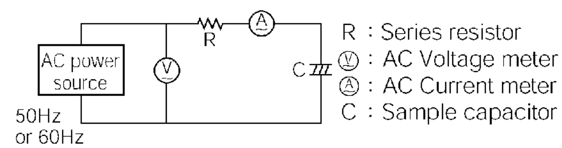



**Fig. 2 - 5**

**b. DC Reverse Voltage Method (JIS C5101-1, 4.28.2)**

(1)For the circuit shown in Fig.2-6, DC current is selected from Table 2-2 according to the nominal diameter of the capacitor to be tested.

**Table 2-2**

| Nominal Diameter (mm) | DC Current (A) |
|---|---|
| 22.4mm or less | 1A constant |
| Over 22.4mm | 10A constant |

(2)The capacitor is connected with its polarity reversed to a DC power source. Then a current selected from Table 2-2 is applied.

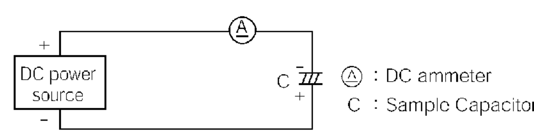



**Fig. 2 - 6**

**Judging Criteria**

If the reuslts of the prior tests show the following conditions, the safety vent has passed the test.

(1) The vent operates with no dangerous condetions such as flames or dispersion of pieces of the capacitor element and/or case.

(2)Nothing abnormal takes places even if the test voltage has been applied to the capacitor for 30 minutes.

# 2-4 Charging and Discharging

### 2-4-1 Effect of Charging and Discharging

Following are the phenomenon that occurs in the aluminum electrolytic capacitor, when used in a frequent charge/discharge circuit such as shown in Fig. 2-7.

In the circuit shown in Fig. 2-7, when the polarized aluminum electrolytic capacitor, which consists anode foil capacitance (Ca) and cathode foil capacitance (Cc), is charged with voltage (V), anode foil dielectric is charged with electrical charge of Q = Ca × V (C: coulomb). Next when discharges electrical charge through discharge resistance, electrical charge of anode foil moves and charges cathode foil. Since withstand voltage cathode foil dielectric is low, cathode foil reaches its withstand voltage by a part of electrical charge which moves from anode foil. When electrical charge moves continuously, electro-chemical reactions occur at interface between cathode foil surface and electrolyte. If charge and discharge are repeated, another dielectric layer is formed on the dielectric layer of the cathode foil. Cathode foil capacitance gradually decreases as additional dielectric layer is formed. Capacitance value of the capacitors decreases as the cathode foil capacitance decreases. The gas generated during oxide layer formation accumulates inside of the capacitor, and rises internal pressure. Depending upon the charge and discharge conditions, pressure relief vent may activate.

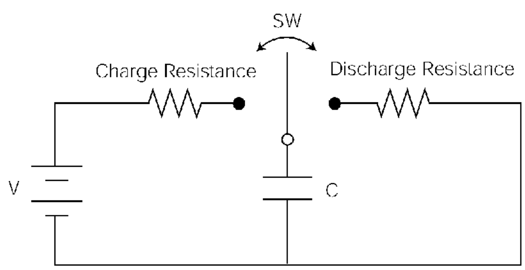



**Fig. 2 - 7**

### 2-4-2 Formation of the Oxide Layer

The voltage applied to the cathode foil during discharge is explained as follows.

Electrical charge of the anode foil moves until anode foil voltage and cathode foil voltage become equal (direction of voltage are opposite to each other and voltage between terminal is zero).

The following formula can be set, using anode foil capacitance (Ca), the initial cathode foil capacitance (Cc), discharge voltage (V), and the voltage applied to anode and cathode foil after discharging (Vc).

$$Ca \times V = Ca \times Vc + Cc \times Vc$$

$$\therefore Vc = \frac{Ca}{Ca + Cc} \times V \quad \cdots\cdots\cdots (2 - 1)$$

From the above, when considering usage of an aluminum electrolytic capacitor in a circuit that will repeat frequent charge and discharge, it is recommended to use capacitors designed to specifically meet conditions of frequent charge/discharge.

### 2-4-3 Measures Taken Against frequent Charge / Discharge

The following measures are taken to prevent an oxide layer formation on the cathode foil.

① Using a cathode foil with a formation of dielectric layer over the Vc voltage expected.

② The following Equation 2-2 led from Equation 2-1; Equation 2-2 shows that the greater the ratio between the capacitance of anode and capacitance of cathode foil, which is Cc / Ca, the smaller the Vc. From this, the Vc is made smaller than the forming voltage of the cathode foil by using a cathode foil with a sufficient (big enough) capacitance against the anode foil capacitance.

$$Vc = \frac{V}{1 + \frac{Cc}{Ca}} \quad \cdots\cdots\cdots (2 - 2)$$

Fig.2-8 shows examples of results, after the charge/discharge test, found in the charge / discharge type capacitor and standard capacitor.

Capacitance : 63V 10000uF
Charge resistance : 2Ω
Discharge resistance : 100Ω
Charge/discharge cycle : 1 second of charge, 1 second of discharge is 1 cycle.
Temperature : 70°C

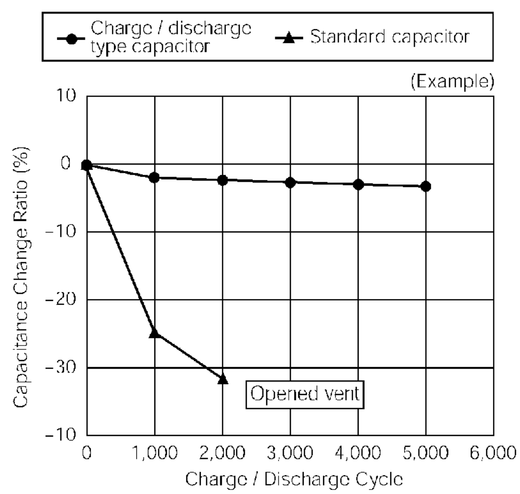


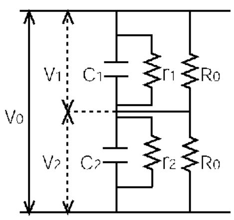

**Fig. 2 - 8**

If the application is a circuit that has large fluctuations in voltage, such as a power supply for an AC servo amplifier or an inverter, select a QS.QR series capacitor that allows rapid charging and discharging. QS,QR series capacitors employ a special structure to increase their durability against rapid charging and discharging. (Patent pending)

## 2-5 Method of Setting the Balance Resistance in a Series Connection

### 2-5-1 Equivalent Circuit and Leakage Current

The relationship between the balance resistance and leakage current resistance of aluminum electrolytic capacitors used in a series circuit, expressed in an equivalent circuit, is shown in Fig. 2-9.




C1 : Aluminum Electrolytic Capacitor No.1
C2 : Aluminum Electrolytic Capacitor No.2
r1 : Leakage Current resistance of Capacitor No.1
r2 : Leakage Current resistance of Capacitor No.2
V1 : Voltage between terminals in Capacitor No.1
V2 : Voltage between terminals in Capacitor No.2
R0 : Balance Resistance
V0 : Line Voltage

**Fig. 2 - 9**

If the leakage current of $C_1$ and $C_2$ are expressed as $i_1$ and $i_2$ :

$$i_1 = \frac{V_1}{r_1},\ i_2 = \frac{V_2}{r_2} \cdots\cdots\cdots (2\text{-}3 \cdot 2\text{-}4)$$

$$V_0 = V_1 + V_2,\quad V_1 - V_2 = R_0 \times (i_2 - i_1)$$

$$R_0 = \frac{V_1 - V_2}{i_2 - i_1} \cdots\cdots\cdots\cdots (2\text{-}5)$$

### 2-5-2 Leakage Current of the Aluminum Electrolytic Capacitor

If the rated voltage is expressed as V (V) and the capacitance as C (μF), variation of the leakage current in a PC board mounting type capacitor at room temperature can be generally expressed by the following equation:

$$i_{max} - i_{min} = \frac{\sqrt{C \times V}}{2} - \frac{\sqrt{C \times V}}{5}$$

$$= \sqrt{C \times V}\left(\frac{1}{2} - \frac{1}{5}\right)$$

$$= \frac{3}{10}\sqrt{C \times V} \cdots (\mu A) \cdots\cdots\cdots (2\text{-}6)$$

The leakage current of aluminum electrolytic capacitors increases as the temperature rises.

Generally if the leakage current at 20°C is referred to as 1, it becomes 2~3 times at 65°C and 3~5 times at 85°C. The leakage current also differentiates depending on the applied voltage and storage conditions, so it is necessary to multiply the leakage current variation coefficient to give a little leeway.

### 2-5-3 Example of Setting the Balance Resistance

The following shows the equation method for setting the balance resistance in using 2 (pcs) of 400V, 470μF aluminum electrolytic capacitors in a series circuit within an ambient temperature of 60°C.

Temperature coefficient for leakage current at 60°C: 2.0
Voltage balance rate: 10%
Coefficient for variation of leakage current: 1.4

Voltage balance
$V_1 - V_2 = 400 \times 0.1 = 40\ (V)$

Range of leakage current variation:

$$i_{max} - i_{min} = \frac{3}{10}\sqrt{C \times V} \times 2 \times 1.4$$

$$= \frac{3}{10}\sqrt{470 \times 400} \times 2 \times 1.4$$

$$= 364\ (\mu A)$$

$$\therefore R_0 = \frac{40}{364 \times 10^{-6}} \approx 109000 \cdots\cdots 100k\Omega$$

When setting the balance resistance, we recommend consideration of the method that is currently used as well.

## 2-6 Storage Performance

When an aluminum electrolytic capacitor is stored under no load conditions for a long period of time, its leakage current tends to increase slightly. This is due to a drop in the withstand voltage of the dielectric caused by the reaction of the anode oxide layer with the electrolyte. When the voltage is applied to the capacitor, the leakage current returns to its initial level because of the re-forming action of the electrolyte (called voltage treatment). If the storage temperature is high, the leakage current will increase substantially. Therefore, it is desirable to store capacitors at normal temperature level with no direct sunlight. A voltage treatment is recommended when using a capacitor stored for a long period of time. The treatment for an individual capacitor is accomplished by charging up to its rated voltage through a resistance of about 1 kΩ and applying the voltage for approximately 30 minutes. When a capacitor is already built into an appliance, the appliance must undergo aging. If the input voltage is adjustable or the power supply that supplies power to a module, first set the voltage to a low value (approximately half the rated voltage) and let it run for about ten minutes. Then, increase the voltage to the appropriate value little by little while monitoring the working of a device.

If the voltage is not adjustable, turn on the switch and let it run for about thirty minutes while confirming if the device complies with the specifications. Then turn off the switch before using the capacitor for practical applications.

Generally, if the capacitor has been stored within 2 years in the storage temperature range of 5~35°C, the capacitor can be used without voltage treatment.

Fig. 2-10 shows an example of the characteristic change in capacitors that were stored at normal temperatures.

| Mark | Ratings | Case Size | Temperature | Test Condition |
|---|---|---|---|---|
| —●— | 25V 4700μF | ϕ22×25L | Room Temperature | No load storage |
| --○-- | 400V 120μF | ϕ25×30L | Room Temperature | No load storage |

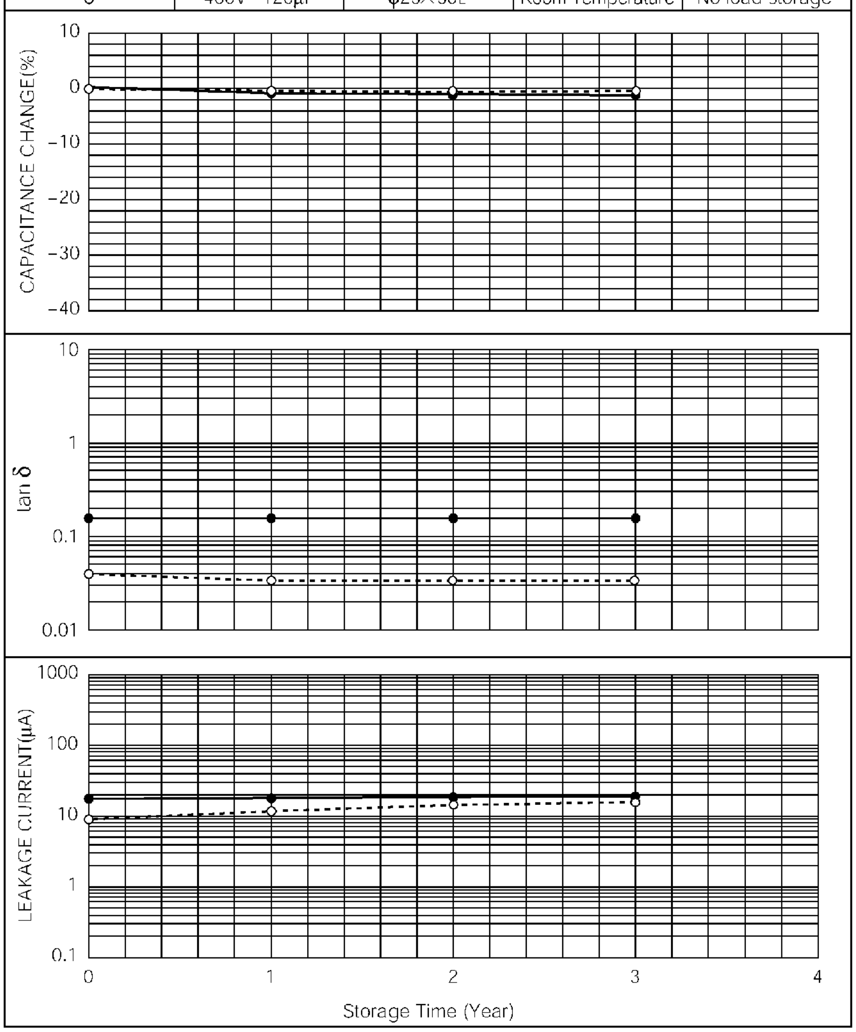



**Fig. 2 - 10**

## 2-7 Restriking-voltage

Aluminum electrolytic capacitors are discharged completely after inspection before shipping. Even if the capacitor has been discharged, voltage still appears between the terminals. This voltage is called restriking-voltage or remaining voltage.

By polarization phenomena, the surface of dielectric is charged positively and negatively respectively when voltage is applied to the capacitor. Then terminals are shorted, electrical charge at the surface discharges and loose electricity. However, terminals are opened, some voltage appears between terminals because dipole that had polarized and remained in the dielectric polarized again. This is what is referred to as the restriking-voltage. Restriking-voltage relates to the thickness of the dielectric. so it increases as the rated voltage becomes larger. When restriking-voltage occurs, electrical sparks may occur when a capacitor is installed to the circuit and surprise operator or destroy other low voltage disturbance elements. If there is fear that such situations may occur, it is recommended to discharge the accumulated electricity by connecting the terminals with a resistor that has a resistance of 100Ω~1 kΩ before usage. As for the capacitors of high voltage and large capacitance, packaging method that enable to short between terminals by aluminum foil or electrical conductive rubber, may be available. If such packaging is necessary, please contact our sales offices.

## 2-8 Usage at High Altitudes

Here are precautions in using aluminum electrolytic capacitors at high altitudes, such as in mountainous regions and in aircrafts.

As the altitude rises, the air pressure decreases. Therefore, if the capacitor is used at high altitudes, the atmospheric pressure becomes lower than the internal pressure of the capacitor. Due to the construction of the aluminum electrolytic capacitor, there is no concern in using them at altitudes lower than about 10,000 (m).

However, if the altitude rises, the temperature decreases. If the temperature of the capacitor decreases, the capacitance level drops, the tangent delta increases. Due to such factors, we recommend checking the performance of the electrical equipment at different temperatures.

**Table 2-3 Relationship Between Altitude, Temp. and Air Pressure**

| Altitude (m) | Temp.(°C) | Air Pressure (hPa) |
|---|---|---|
| 0 | 15.0 | 1013.3 |
| 2,000 | 2.0 | 795.0 |
| 4,000 | - 11.0 | 616.4 |
| 6,000 | - 24.0 | 471.8 |
| 8,000 | - 37.0 | 356.0 |
| 10,000 | - 50.0 | 264.4 |
| 20,000 | - 56.5 | 54.7 |

For more details, please contact our sales offices.

# 2-9 Life and Reliability

### 2-9-1 Foreword

The failure rate (λ) for electronic applications and components which require no particular maintenance follows their time transition (t) and shows a curve as shown in Fig.2-11. Because this curve resembles the shape of a western bathtub, it is called "Bathtub Curve."

The failure mode of aluminum electrolytic capacitors also forms a "Bathtub Curve." If the results of the life evaluation test of aluminum electrolytic capacitors is analyzed by "Weibull Probability Paper" as in Fig. 2-12, the shape parameter "m" is larger than 1, showing that the failure mode is a wear-out failure. Although the failure rate or the life estimation is generally used in designing a device, the reliability of an aluminum electrolytic capacitor is generally measured by its life (the expected life, in practical use) rather than failure rate since the failure mode of aluminum electrolytic capacitors is wear-out.

In other words it is expected that we have different failure rates in the same test time (number of speciments x test time) (e.g. 100 capacitors x 10 hours... zero failures is expected, 10 capacitors x 10 hours... 100% will be failed.

The factors that most effect the life of aluminum electrolytic capacitors are acceleration according to the ambient temperature ($F_T$), acceleration according to the ripple current ($F_I$) and acceleration according to the applied voltage ($F_U$). The expected life is calculated by multiplying the specified life time on Nichicon catalog, $F_T$, $F_1$, and Fu.

The life of aluminum electrolytic capacitors is discussed in the following.

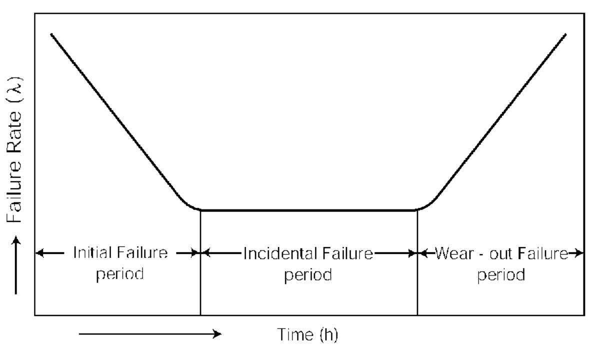



**Fig. 2 - 11 Failure Rate Curve (Bathtub Curve)**

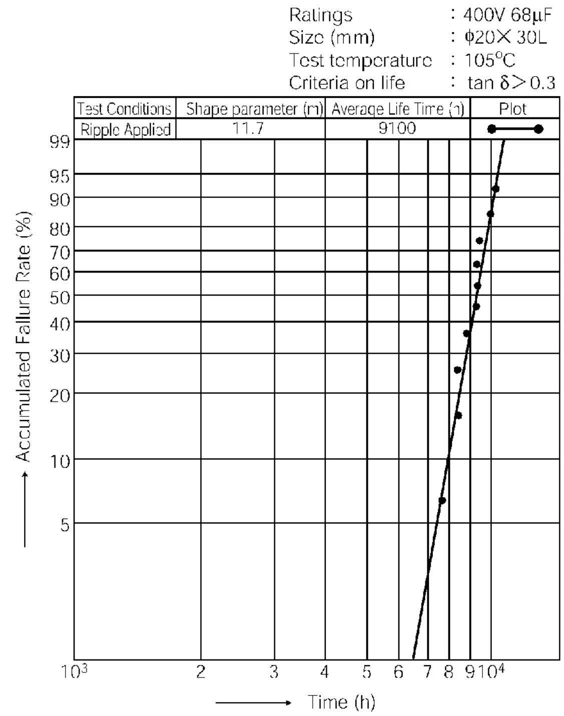



**Fig. 2 - 12 Failure Analysis by Weibull Probability Paper**

### 2-9-2 Life Evaluation Method

An aluminum electrolytic capacitor is determined to have reached its end of life when the capacitance change, tan δ and leakage current have exceeded the specified value or when a noticeable external abnormality occurs. Factors that effect the life of aluminum electrolytic capacitors are temperature, humidity and vibration, etc., but the factor that has the most effect is the temperature, which shortens the life as the temperature rises. From this, life tests are determined by applying the DC voltage or by applying ripple superimposed upon DC voltage at the specified maximum operating temperature of the capacitor. Examples of the test results are shown in Fig. 2-13 and 2-14.

| Mark | Ratings | Size | Temp. | Test Condition |
|---|---|---|---|---|
| —●— | 200V 220μF | φ20×25L | 105°C | 120Hz 1.00Arms+DC191V |
| -○- | 400V 68μF | φ20×30L | 105°C | 120Hz 0.56Arms+DC384V |

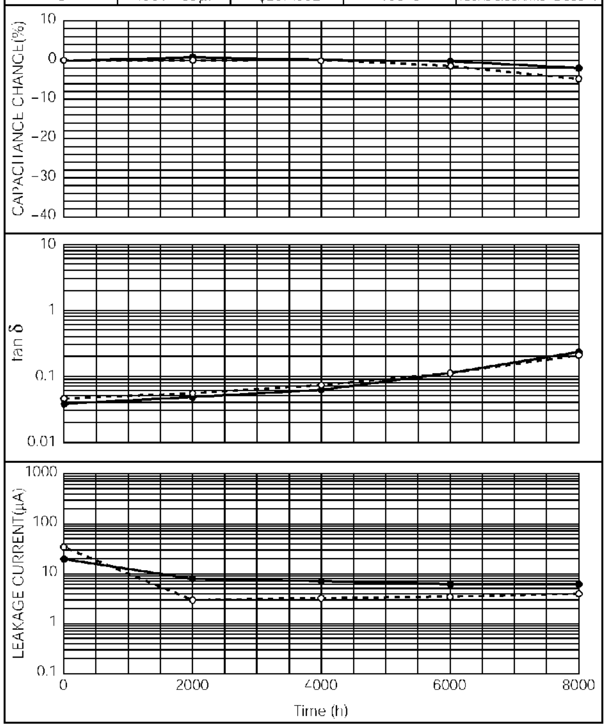



**Fig. 2 - 13 High Temperature Life Evaluation Test**

| Mark | Ratings | Size | Temp. | Test Condition |
|---|---|---|---|---|
| —●— | 50V 1000μF | φ16×25L | 105°C | 100kHz 2235mArms+DC48V |
| -○- | 16V 4700μF | φ16×31.5L | 105°C | 100kHz 3010mArms+DC15V |

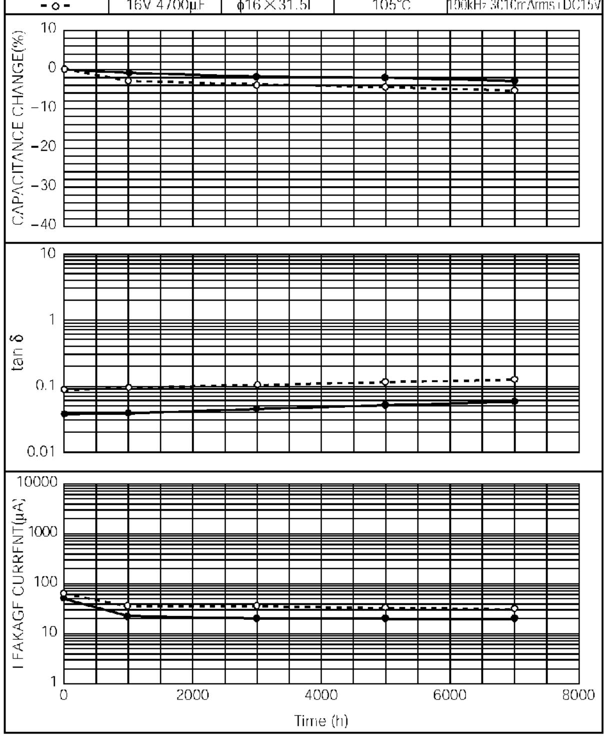



**Fig. 2 - 14 High Temperature Life Evaluation Test**

### 2-9-3 Ambient Temperature and Life

In general, but not necessarily in all cases, if a capacitor is used at the maximum operating temperature or below (generally to a minimum of plus 40°C operating temperature) life expectancy can be calculated according to Arrhenius theory in which the life doubles for each 10deg C drop in temperature. Refer to Fig 2-15 showing the expected life.

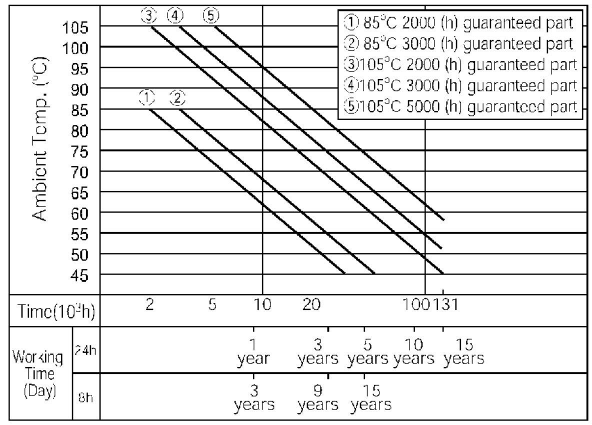



**Fig. 2 - 15 Life Estimation Table**

### 2-9-4 Applied Voltage and Life

The degree that applied voltage effects the life of the capacitor when used below the rated voltage is small, compared to the degree that ambient temperature and ripple current effects life. Therefore, when estimating the life of a capacitor, the voltage coefficient to the applied voltage (Fu) is calculated as 1. An example of the test results is shown in Fig.2-16.

| Mark | Ratings | Size | Temp. | Test Condition |
|---|---|---|---|---|
| —●— | 50V 12000μF | φ35×45L | 105°C | DC 50V |
| -○- | 50V 12000μF | φ35×45L | 105°C | DC 40V |
| —×— | 50V 12000μF | φ35×45L | 105°C | DC 30V |

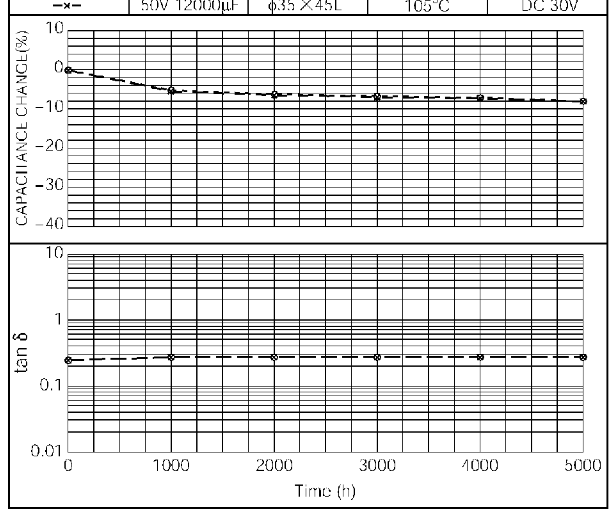



**Fig. 2 - 16 High Temp. Evaluation Test When Applied Voltage is Charge**

In regards to high voltage capacitors used in smoothing circuits for power electronic equipment, the leakage current decreases as the voltage drops and lessens the consumption of electrolyte. In such cases, the life of the capacitor may be extended. For more details, please contact our sales offices.

### 2-9-5 Ripple Current and Life

The tan δ of the aluminum electrolytic capacitor is larger than other types such as film capacitors, and heat generates inside electrolytic capacitors due to power loss when ripple current is applied. Heat generation effects the life of the capacitor because it causes a temperature rise.

#### 1) Ripple Current and Heat Generation

The power loss due to ripple current being applied along with a DC voltage can be calculated by the following formula :

$$W = W_{AC} + W_{DC}$$
$$W = I_{AC}^2 \times Re + V_{DC} \times I_{DC} \quad \cdots \; (2 \text{-} 7)$$

W : Consumption of electricity by the capacitor (W)
$W_{AC}$ : Power loss due to ripple current (W)
$W_{DC}$ : Power loss due to DC (W)
$I_{AC}$ : Ripple current (A)
Re : E.S.R. of the capacitor
$V_{DC}$ : DC Voltage (V)
$I_{DC}$ : Leakage Current (A)

If the DC voltage is below the rated voltage, the leakage current is extremely small and becomes $W_{AC} >> W_{DC}$. From this, power loss can be calculated by the following formula :

$$W = I_{AC}^2 \times Re \quad \cdots \; (2 \text{-} 8)$$

The external temperature of the capacitor rises to a point where the internal heat generation balances with the heat radiation. The temperature rise up to a balance point can be given by the following formula:

$$I_{AC}^2 \times Re = \beta \times A \times \Delta t \quad \cdots\cdots\cdots \; (2 \text{-} 9)$$

$$\Delta t = \frac{I_{AC}^2 \times Re}{\beta \times A} \quad \cdots\cdots\cdots \; (2 \text{-} 10)$$

β : Heat Radiation Constant ($10^{-3}$W / °C·cm$^2$)
A : Surface Area (cm$^2$)

When the size of the capacitor is φ D × L :

$$A = \frac{\pi}{4} D (D + 4L) \quad \cdots\cdots\cdots \; (2 \text{-} 11)$$

The surface area can be figured from the above equation.
Δt = Temperature rise of ripple (°C)

The relationship between internal resistance "Re," capacitance "C" and tanδ is as follows :

$$Re = \frac{\tan\delta}{\omega C} \quad \cdots\cdots\cdots \; (2 \text{-} 12)$$

However, according to $\omega = 2\pi f$, $\cdots\cdots\cdots$ (2 - 13 )

$$\Delta t = \frac{I_{AC}^2 \times Re}{\beta \times A} = \frac{I_{AC}^2 \times \tan\delta}{\beta \times A \times \omega C}$$

The heat radiation constant (β) and temperature rise multiplier, which is temperature rise ratio calculated by temperature rise at the surface Δts divided by at the core of element Δtc and is expressed as α, is as shown in Table 2-4.

**Table 2-4**

| Case dia (mm) | 5 or less | 6.3 | 8 | 10 | 12.5 | 16 | 18 | 20 | 22 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| β | 2.18 | 2.16 | 2.13 | 2.10 | 2.05 | 2.00 | 1.96 | 1.93 | 1.88 | 1.84 | 1.75 | 1.66 | 1.58 |
| α | 1.0 | | 0.94 | 0.90 | 0.85 | 0.80 | 0.77 | 0.75 | 0.74 | 0.71 | 0.67 | 0.64 | 0.62 |

α :Temperature rise ratio calculated α=Δts/Δtc
β : Heat radiation constant ($10^{-3}$ W / °C·cm$^2$)

#### 2) Frequency Coefficient of Allowable Ripple Current

Equivalent series resistance of aluminum electrolytic capacitor (Re) is frequency dependence. Higher the frequency, lower the ESR. Assuming that temperature rise due to ripple current at a frequency of (fx) and at a frequency of (fo) are same, when (Ro) is ESR at a frequency of (fo) and (Rx) is ESR at a frequency of (fx). The following equation would be set.

$$I_0^2 \times R_0 = I_x^2 \times R_x$$

$$\therefore I_x = \sqrt{\frac{R_0}{R_x}} \times I_0 \quad \cdots\cdots\cdots \; (2 \text{-} 14)$$

Thus, $\sqrt{R_0/R_x}$ becomes the frequency coefficient Kf. Table 2-5 shows examples of frequency coefficients.

**Table 2-5 Frequency coefficient of allowable ripple current <Example>**

· Snap - in terminal type capacitors (For input smoothing circuit)

| Frequency (Hz) | | 50 | 60 | 120 | 300 | 1k | 10k | 50k~ |
|---|---|---|---|---|---|---|---|---|
| Frequency coefficient (Kf) | 16~100V | 0.88 | 0.90 | 1.00 | 1.07 | 1.15 | 1.15 | 1.15 |
| | 160~250V | 0.81 | 0.85 | 1.00 | 1.17 | 1.32 | 1.45 | 1.50 |
| | 315~450V | 0.77 | 0.82 | 1.00 | 1.16 | 1.30 | 1.41 | 1.43 |

· Lead type capacitors (For output smoothing circuit)

| Rated voltage(V) | Frequency (Hz) / Cap.(μF) | 50 | 120 | 300 | 1k | 10k~ |
|---|---|---|---|---|---|---|
| 6.3~100V | ~56 | 0.20 | 0.30 | 0.50 | 0.80 | 1.00 |
| | 68~330 | 0.55 | 0.65 | 0.75 | 0.85 | 1.00 |
| | 390~1000 | 0.70 | 0.75 | 0.80 | 0.90 | 1.00 |
| | 1200~15000 | 0.80 | 0.85 | 0.90 | 0.95 | 1.00 |

#### 3) Temperature Coefficient of Allowable Ripple Current

The applicable ripple current value below the maximum operating temperature must be limited by specified ripple temperature rise at the center of element per ambient temperature.( Table 2-6.)

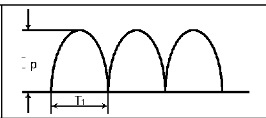
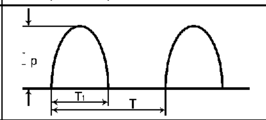
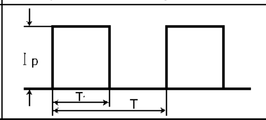
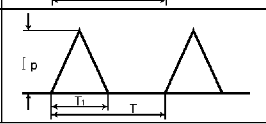
**Table 2-6 Limit of element core temperature rise (Over 315 Voltage with Snap-in terminal type capacitors)**

| Ambient Temperature (°C) | 40 | 55 | 65 | 85 | 105 |
|---|---|---|---|---|---|
| Δtc (°C) | 30 | 30 | 25 | 15 | 5 |

#### 4) The method which seeks for effective current value from Ripple current wave form

In case that a ripple, which ripple current of high frequency switching is superimposed upon commercial frequency ripple, is applied, such as in switching power supplies, inverter type supplies and active filter circuits, there is a method to obtain the effective value from the waveform pattern in Table 2-7 by finding the similar waveform observed in actuality.

**Table 2 - 7 Current Wave and Caluculation Expression for Effective Value**

| | Wave form | Formula of effective value |
|---|---|---|
| ① |  | $I_{rms} = \frac{I_P}{\sqrt{2}}$ |
| ② |  | $I_{rms} = I_P\sqrt{\frac{T_1}{2T}}$ |
| ③ |  | $I_{rms} = I_P\sqrt{\frac{T_1}{T}}$ |
| ④ |  | $I_{rms} = I_P\sqrt{\frac{T_1}{3T}}$ |

Effective ripple value is calculated from the wave form of ripple, which ripple current of high frequency switching ($I_l$) is superposed upon ripple current of commercial frequency ($I_L$)(as in Figure 2-17), by dividing it into each frequency component.

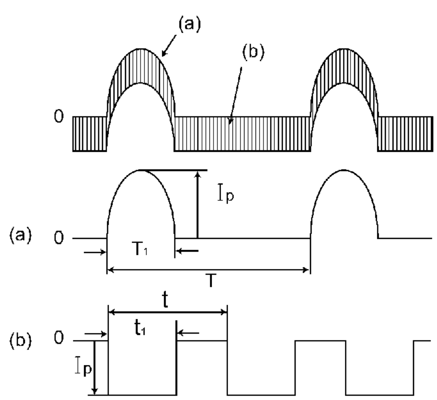



**Fig. 2 - 17**

Setting Model ② as the ripple current for a low frequency component ($I_L$):

$$I_L = I_P \times \sqrt{\frac{T_1}{2T}} \quad \cdots\cdots\cdots (2 - 15)$$

Setting Model ③ as the ripple current for a high frequency component ($I_H$) :

$$I_H = I_P \times \sqrt{\frac{t_1}{t}} \quad \cdots\cdots\cdots (2 - 16)$$

The equivalent series resistance of aluminum electrolytic capacitors has frequency characteristics; so if the frequency is different from the standard, it is converted to meet the standard frequency. If the frequency coefficient for low frequency components is labeled "$K_{fL}$" and the frequency coefficient for high frequency componentsis labeled "$K_{fH}$, " the synthetic ripple "$I_n$" converted to the standard frequency is :

$$I_n = \sqrt{\left(\frac{I_l}{K_{fL}}\right)^2 + \left(\frac{I_H}{K_{fH}}\right)^2} \quad \cdots\cdots\cdots (2 - 17)$$

**5) Estimating Temperature Rise due to Ripple Current**

Power loss is proportional to the second power of ripple current. If the temperature rises at the middle of the element, when the permissible ripple current "$I_o$" (A), is labeled "$\Delta t_o$," the temperature rise when ripple current "$I_n$" (A) is applied would be as follows :

$$\Delta t_n = \left(\frac{I_n}{I_o}\right)^2 \times \Delta t_o \quad \cdots\cdots\cdots (2 - 18)$$

The temperature rise "$\Delta t_o$" for a 105°C snap-in terminal type capacitor is approximately 5°C. However, since the equivalent series resistance "$R_c$" of aluminum electrolytic capacitors differs according to the temperature and because the ripple current wave - form has many complex frequency components in actuality, we recommend that the temperature rise is actually measured with thermocouples.

### 2-9-6 Estimated Life

The estimated life of an aluminum electrolytic capacitor is represented multiplying the specified life time on Nichicon catalog $F_T$, $F_1$, and Fu as explained in 2-9-1. Shown below are the formulase for obtaining the expected life for the large can type aluminum electrolytic capacitors and the miniature aluminum electrolytic capacitors. For further details, consult Nichicon.

(Large can type)
Formula 2-19 is for obtaining the estimated life of a large can type electrolytic capacitor.
For the formula for screw terminal capacitors, please consult Nichicon.

$$L_n = L_o \times 2^{\frac{T_c - T_n}{10}} \times 2^{1\ \frac{\Delta t_1}{K}\ \Delta t_n - t_o \times \left(\frac{I_n}{I_m}\right)^2} \quad \cdots\cdots\cdots (2 - 19)$$

$L_n$: Estimated life (h) at ambient temperature of Tn (°C) with a ripple current In (Arms) applied.

$L_o$: Specified life time (h) at maximum operating temperature To (°C) with the specified maximum allowable ripple current Im (Arms) at To (°C) applied

$T_o$: Maximum operating temperature of the capacitor (°C)

$T_n$: Ambient temperature of the capacitor (°C)

$\Delta t_o$ : The internal temperature rise (°C) of the capacitor at ambient temperature To (°C) with the maximum allowable ripple current Im (Arms) at To applied

$\Delta t_n$ : The internal temperature rise (°C) of the capacitor at ambient temperature Tn (°C) with the actually applied ripple current In (Arms)

K: Acceleration coefficient of temperature rise due to ripple [refer to the chart below ; applicable coefficient is for the range below the maximum operating temperature To (°C)]

- The formula is applicable for the range of ambient temperature Tn of 40°C and the maximum operating temperature To. Please note that fifteen years is generally considered to be the maximum for the estimated life obtained by the above formula.

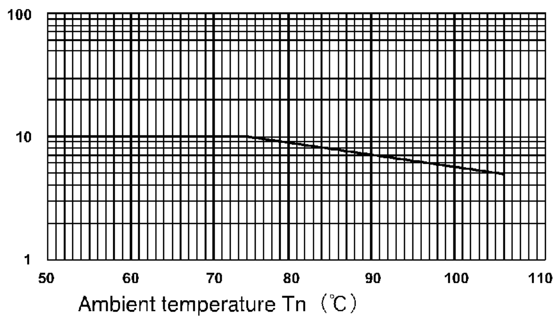



**Fig 2-18 Acceleration coefficient of temperature rise due to ripple; K**

(Miniature type)

There are two formulase for obtaining the estimated life of a miniature aluminum electrolytic capacitor, depending on the life specification of series on Nichicon catalog as shown in formulase 2-20 and 2-21.

(1) Capacitors life time is specified. with rated DC vortage applied only

$$L_n = L \times 2^{\frac{T_0 - T_n}{10}} \times \frac{1}{B_n} \quad \cdots\cdots\cdots \quad (2\text{-}20)$$

$$\text{Where } B_n = 2^{\alpha \times \left(\frac{I_n}{I_m}\right)^2 \times 2^{-\left(\frac{T_0 - T_n}{30}\right)}}$$

(2) Capacitors life time is specified with D.C. bias voltage plus rated ripple current.

[illegible]

Ln:Estimated life time (h) at ambient temperature of Tn (°C) with a ripple current In (Arms) applied.

L :Specified life time (h) at maximum operating temperature T (°C) with the rated DC voltage applied.

Lo:Specified life time (h) at maximum operating temperature T (°C) with the specified maximum allowable ripple current Im (Arms) at T (°C) applied.

To: Maximum operating temperature of the capacitor (°C)

Tn: Ambient temperature of the capacitor (°C)

Im:Rated ripple current (Arms) at maximum operating temperature T (°C)
Im need to be valued in the same frequency as that of the ripple current being used by multiplying specified ripple-frequency coefficient in Nichicon catalog.

In: Ripple current (Arms) actually applied at ambient temperature Tn (°C)

Bn:Acceleration coefficient when ripple In (Arms) is applied at ambient temperature Tn (°C)

α : Life constant
Contact us for details regarding the life constant.

The formula is applicable for the range of ambient temperature Tn of 40°C and the maximum operating temperature To. Please note that calculated life time is for reference only and not guaranteed. Typically, fifteen years is generally considered to be the maximum for the estimated life obtained by the above formula.

## 2-10 Effects of halogen

### 2-10-1 Foreword

When a halide substance seeps into the aluminum electrolytic capacitor:

The halide dissolves and frees halogen ions.

$RX+H_2O \Rightarrow ROH + H^+ + X^-$

Also, the following reaction (Electricity cauterization reaction ) can occur

$AL + 3X^- \Rightarrow ALX_3 + 3e^-$

$ALX_3 + 3H_20 \Rightarrow AL\ (OH)_3 + 3H^+ + 3X^-$

When this reaction is repeated, the leakage current increases and the safety vent will be activated and may lead to open vent. Because of this, halogen type cleaning agents or adhesive material and coating material is not recommended for usage. The following explains the recommended conditions for using cleaning agents, adhesive material and coating material. 2-10-3 explains the recommended condition for cleaning, when a halogen type cleaning agent will be used due to cleaning capabilities.

### 2-10-2 Recommended Cleaning Condition

Applicable : Any type, any ratings.

Cleaning Agents : Based Alcohole solvent cleaning agent
- Isopropyl Alcohol

Based water solvent cleaning agent
- Premium alcohole solvent type
  - Pine Alpha ST-100S
  - Techno Care FRW 14~17
  - Sanelek B-12
- Surfactant type
  - Clean Through 750H, 750L, 710M
- Alkaline saponification agent
  - Aqua Cleaner 210SEP

Cleaning Conditions :Total cleaning time shall be no greater than 5 minutes by immersion, ultrasonic or other method. (Temperature of the cleaning agent shall be 60°C maximun.)

After the board cleaning has been completed, the capacitors should be dried using hot air for a minimum of 10 minutes.

If the cleaning solution is infiltrated between the case and the sleeve, the sleeve might soften and swell when hot air temperature is too high. Therefore, hot air temperature should not exceed softening temperature(80°C) of the sleeve.

Hot air temperature should be below the maximum operating temperature of the capacitor.

Insufficient dries after water rinse may cause appearance problems, such as sleeve shrinking, bottom-plate bulging.

In addition, a monitoring of the contamination of cleaning agents (electric conductivity, pH, specific gravity, water content, etc.) must be implemented.

After the cleaning, do not keep the capacitors in an atmosphere containing the cleaning agent or in an air tight container.

Depending on the cleaning method, the marking on a capacitor may be erased or blurred.

Consult Nichicon before using a cleaning method or a cleaning agent other than those recommended.

The use of hydro-chlorofluorocarbon (HCFC) is expected to be banned in the future and Nichicon does not recommend the use of HCFC as a cleaning agent considering its impact on the environment. When it is absolutely necessary to use HCFC, cleaning is possible under the following conditions:

Applicable : Anti-solvent capacitors (listed in the catalogue)

Cleaning Agents : AK-225AES

Cleaning Conditions : Within 5 minutes, total cleaning time by immersion, vapor spray, or ultrasonic and such. For SMD and ultra-miniature type, 2 minutes maximum of total cleaning time. (Temperature of agent: 40°C or below)

Notes : Monitoring of the contamination of cleaning agents (electric conductivity, pH, specific gravity, water content, etc.) must be implemented.

After the cleaning, do not keep the capacitors in an atmosphere containing the cleaning agent or in an air tight container.

Consult Nichicon before using a cleaning method or cleaning agent other than those recommended.

### 2-10-3 Fixing Material and Coating Material

1)Do not use any affixing or coating materials, which contain halide substance.

2)Remove flux and any contamination, which remains in the gap between the end seal and PC board.

3)Please dry the cleaning agent on the PC board before using affixing or coating materials.

4)Please do not apply any material all around the end seal when using affixing or coating materials.

There are variations of cleaning agents, fixing and coating materials, so please contact those manufacture or our sales office to make sure that the material would not cause any problems.

**2-10-4 Others**

Wooden package material may be subjected to fumigation by a halogen(e.g. methyl bromide) before they are exported in order to protect them against pests. If devices with aluminum electrolytic capacitors or capacitors themselves are directly fumigated or packed with the pallet that is fumigated, the capacitors may internally corrode due to the halogen contents of fumigation agents.

## 2-11 CR Timing Circuit

### 2-11-1 Foreword

The following will explain precautions to be taken when considering usage of the aluminum electrolytic capacitor in a timing circuit and calculating out the timing for maintenance.

### 2-11-2 Recharge Circuit

The lead voltage of the capacitor, when applied voltage (V) is applied to capacitor (C) with series resistor (Ω) as in figure 2-19, must be taken into consideration.
Figure 2-20 shows the rise of terminal voltage during charging of the capacitor. The time "tn" needed to reach a specified voltage "Vn" may be expressed by formula 2-23.

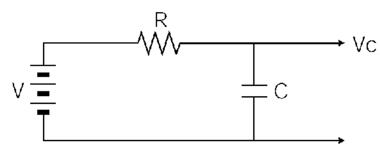



**Fig. 2 - 19**

$$V_c = V(1 - e^{-\frac{t}{CR}}) \quad \cdots\cdots\cdots (2-22)$$

$$t_n = CR\ln\left(\frac{V}{V - V_n}\right) \quad \cdots\cdots\cdots (2-23)$$

R : Series resistor (Ω)
C : Capacitance (μF)
V : Applied voltage (V)

### 2-11-3 Discharge Circuit

Figure 2-20 shows the situation where capacitor C is discharged with resistance Rd by laying down switch SW toward 2, after it has been charged with applied voltage V by laying down switch SW toward 1. The relationship between the terminal voltage Vc (V) and discharge time (t) may be expressed by formula 2-22. The time "tn" needed for the terminal voltage "Vc" (V) of a capacitor to reach voltage "Vn" may be expressed by formula 2-23.

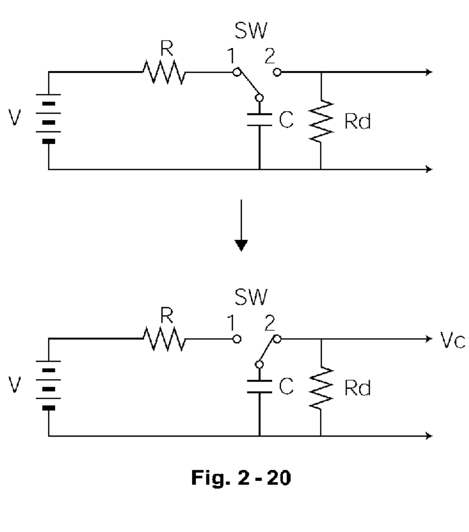



**Fig. 2 - 20**

$$V_c = V \times e^{-\frac{t}{CR_d}} \quad \cdots\cdots\cdots (2-24)$$

$$t_n = CR_d\ln\left(\frac{V}{V_n}\right) \quad \cdots\cdots\cdots (2-25)$$

Rd : Discharge resistor (Ω)
C : Capacitance (μF)
V : Applied voltage (V)

### 2-11-4 Leakage Current Resistance of Capacitors

When DC voltage is applied, leakage current flows through a capacitor. The leakage current of aluminum electrolytic capacitors is larger than other types of capacitors; furthermore, the leakage current changes according to the temperature, applied voltage and application time. If considering an equivalent circuit, the leakage current can be thought as the current flows through a resistance, which is connected in parallel to a capacitor. Leakage current becomes the power loss when capacitors are charged and self-discharge source when capacitors are discharged; therefore, it increases with error for the theoretical formulas shown in 2-11-2 and 2-11-3.
The time constant in charge becomes lager than theoretical value and time constant in discharge becomes smaller than theoretical value.

It is important to confirm that the capacitor meets the necessary requirements within the operating temperature range of the equipment, when using an aluminum electrolytic capacitor in a timing circuit.

# 2-12 Setting Up Capacitors

## 2-12-1 Foreword

The aluminum electrolytic capacitor is the most commonly used type of capacitor in a smoothing circuit. The reason for this is because the aluminum electrolytic capacitor has a higher capacitance/unit volume and also lower price/unit capacitance compared to other types of capacitors.

In the electrical component market, use of surface mount (SMD) types progresses due to demands for miniature, high efficiency, high frequency, high reliability and thin type electronic equipment. Furthermore, the PL Law (Product Liability) has been enforced, therefore, safety is regarded as important more than before. For such reasons, aluminum electrolytic capacitors that are used in power supplies are required to have the following features: miniature, light in weight, thin, extended life and high reliability, chip type, and safer. The following discusses factors that will help in proficiently using aluminum electrolytic capacitors.

## 2-12-2 Characteristics of the Aluminum Electrolytic Capacitor Series

### (1) Capacitor for input smoothing circuit of a power supply

Capacitors for input smoothing circuit of a power supply are located after diodes. They work to smooth the electrical current that rectified in the diode and are required to have characteristics, such as high ripple, high reliability and safety. Table 2-8 shows the series matrix for Can Type (snap-in terminal type) capacitors.

**Table. 2 - 8 Series Matrix for Can type (Snap-in Terminal type) Capacitors**

| Feature / Configuration | 85°C Type | | 105°C Type | | | | |
|---|---|---|---|---|---|---|---|
| | Standard type | Miniature type | Standard type | Miniature type | Long life (7000h) | Permissible abnormal voltage | Withstanding overvoltage |
| Standard type | LS | LN, LG | GU | GN, GG | GY | AK AQ,AS(Smaller-sized) | AD |
| Low profile | – | – | GJ·GJ(15) | – | – | – | – |
| Horizontal mounting type | DM | – | DQ | – | – | – | – |

The standard for 105°C capacitors is GU series; GN,GG is recommended if a miniature type is required; GJ is recommended if a low profile-type is required; finally, DQ is recommended if a horizontal mounting type is necessary to decrease the height in the application even further. If a higher reliable capacitor is required, GY series with guaranteed life of 7000 hours is recommended. As Figure 2-20 shows, for a power supply unit of commercial 100V /200V change type, a capacitor rated voltage of 250V is normally used. However, if mistakenly connect to 200V line when the switch is ON, a standard 250V part would become under over voltage conditions and will open vent in short time period. A capacitor that would not open vent under such conditions for a set amount of time is AD series. AK and AQ series is designed with specifications and construction that prevents the capacitor from short circuit conditions by allowing open-vent (which does not endanger the capacitor to catch fire). These series are recommended for usage in electrical equipment that are in constant operating 24 hours a day, such as facsimile machines and copy machines and other telecommunication equipments.

### (2)Capacitors for Usage in Output Smoothing Circuit of a Power Supply

Capacitors for usage in electrical output smoothing circuits are important to provide steady output voltage. With the switching frequency rising, capacitors within a high frequency range and with low impedance, equivalent series resistance are required. Furthermore, surface mount components (SMD) are being used in miniature switching power supplies and DC-DC converters. Table 2-9 shows the series matrix for radial lead type capacitors, and Table 2-10 is the series matrix for surface mount devices.

**Table. 2 - 9 Series Matrix for Lead type Capacitors**

| Feature / Configuration | Standard | 105°C Type | 125°C Type | Bi-polarized | Low impedance | Long life (105°C5000h) |
|---|---|---|---|---|---|---|
| 5mmL | MA | MT | — | MP | MF | MV |
| 7mmL | SA,SR | ST | | SP | SF | SV |
| 11mmL or more | VR,RS | VZ,RZ | BT | VP | PJ,PM | PV |

**Table. 2 - 1 0 Series Matrix for Chip type Capacitors**

| Feature / Configuration | Standard | 105°C Type | 125°C type | Bi-polarized |
|---|---|---|---|---|
| 3.0mmL | ZD | - | - | - |
| 3.95mmL | ZR | ZG | - | ZE |
| 4.5mmL | ZS | ZT | - | ZP |
| 5.5mmL | WX | WT WF (Low impedance) | - | WP |
| 6.2mmL or more | UR | UT UI (Long life) UX (High C / V) | UB | UP |
| Higher capacitance | UG | UJ | UH | UN |

The standard series for usage in output smoothing circuit of a power supply is PJ,
PS, SF (7mmL),and / or MF (5mmL) recommended if a miniature type is required,
PM is recommended for low impedance requirements,
PW is recommended if a low impedance, miniature type is required.

As for surface mount capacitors, WT is the standard series; for a capacitor with low height, ZT,ZG is recommended; WF is recommended if a low impedance series is needed; finally, UX and UJ is designed in a higher voltage and higher capacitance range.

**(3) Capacitors for Usage in Control Circuits**

In some cases, failure of capacitors for usage in control circuits may occur, due to the ambient temperature rising in electrical equipment that are led by miniature, multi-functioning, and high density assembly. This rise in the ambient temperature may occur if the capacitor is mounted near another component that generates heat. Nichicon has designed several capacitors for usage in control circuits: VZ (miniature type) has a maximum operating temperature of 105°C, and there are others, such as PV (long life), SV (7mmL) and MV (5mmL).

Please see our catalogue for more details on our series.

### 2-12-3 High density mounting and extension of product life

The ambient temperature of the capacitor is rising, due to electrical equipment becoming more miniaturized, multi-functioning, and its high density mounting conditions. In addition, there is much equipment that is continually operated, so the demands for higher reliability and longer life have become greater. The life of aluminum electrolytic capacitors is shortened as the ambient temperature rises. Please consider the following in order to prolong the life of the aluminum electrolytic capacitor.

①Please do not design a circuit board so that heat generating components are placed near an aluminum electrolytic capacitor on the or reverse side of the PC board.

②Please release as much heat as possible inside the electrical equipment, using a heat radiator fan or other device.

③Please have a hole somewhere in the equipment, so that the temperature within the electrical equipment will decrease, and open air coming through the hole will cool off the capacitor.

④Especially in electrical equipment that uses a double-sided circuit board requires care. If the capacitor is placed near a power module or heat generating component, there is a case that capacitor is exposed to the high temperature transmitted through circuit pattern. In particular, please pay attention when capacitor is used for a high power supply.

⑤The internal temperature of an electrical equipment is higher toward the top. Please set the capacitor a low position within the electrical device. Please consider this especially if the device is used standing upward.

### 2-12-4 In-rush current and Discharge Resistance

In the capacitor input type power supply, an in-rush current flows through the capacitor at the time of power-on. The in-rush current differs according to the timing of power-on, but it can be 10 times the constant current. If the in-rush current is repeated only several times a day, there should be no problem. However, if electrical input and turn-off is repeated frequently or if the electromagnetic noise that occurs at input causes any hindrance to the equipment, we recommend that an inductance or active filter is added to the circuit on the input side. If the circuit be designed so that the capacitor is automatically discharged when the electricity is turned off, we recommend that the capacitor is discharged with a discharge resistance of 1kΩ or more.

### 2-12-5 Surface Mount Type Capacitors

As a surface mount replacement for radial leaded parts, chip aluminum electrolytic capacitors are required to have good stability, solderability and resistance to heat, in order to be reflow soldered onto PC boards. In order to meet such requirements, we have processed the lead wiring into a flat lead and have attached a plastic platform that resists high heat; such capacitors are the mainstream in the vertical mount chip-type capacitors.

We are offering a wide range of vertical mount chip-type capacitors in case sizes ϕ 3, 4, 5, 6.3, 8 and 10mm, in rated voltages of 4V~50V with capacitance of 0.1~1500µF; we are also offering these capacitors with case sizes ϕ12.5, 16, 18, 20mm, in voltage of 6.3V~450V, with a capacitance range of 3.3µF~10000µF. Figure 2-23 shows the outward appearance of chip aluminum electrolytic capacitors. For more details, please see our catalog.

(Example)

ϕ3~ϕ10

ϕ12.5~ϕ20

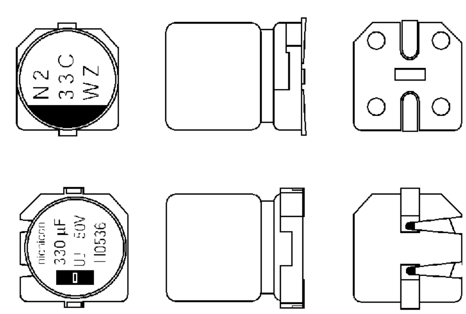



**Fig. 2 - 23 Outward appearance of chip aluminum electrolytic capacitors**

feature article

# Batteries and electrochemical capacitors

Héctor D. Abruña, Yasuyuki Kiya, and Jay C. Henderson

**Present and future applications of electrical energy storage devices are stimulating research into innovative new materials and novel architectures.**

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**Electricity generated** from renewable sources, such as solar and wind power, offers enormous potential for meeting future energy demands. But access to solar and wind energy is intermittent, whereas electricity must be reliably available for 24 hours a day: Even second-to-second fluctuations can cause major disruptions that cost tens of billions of dollars annually. Electrical energy storage devices will therefore be critical for effectively leveling the cyclic nature of renewable energy sources. (See the article by George Crabtree and Nathan Lewis, PHYSICS TODAY, March 2007, page 37.) They are also a key enabler in numerous areas of technological relevance ranging from transportation to consumer electronics.

Electrical energy storage systems can be divided into two main categories: batteries and electrochemical capacitors. Batteries store energy in the form of chemical reactants, whereas ECs store energy directly as charge. Due to that fundamental difference between the systems, they exhibit different energy and power outputs, charge–discharge cyclability, and reaction time scales.

Batteries can generally store significantly more energy per unit mass than ECs, as shown in figure 1a, because they use electrochemical reactions called faradaic processes. Faradaic processes, which involve the transfer of charge across the interfaces between a battery's electrodes and electrolyte solution, lead to reduction and oxidation, or redox reactions, of species at the interfaces. When a battery is charged or discharged, the redox reactions change the molecular or crystalline structure of the electrode materials, which often affects their stability, so batteries generally must be replaced after several thousand charge–discharge cycles.

On the other hand, ECs show no major changes in the properties of the electrode materials during operation, so they can be charged and discharged up to millions of times. The charge-storing processes employed in ECs are much faster than the faradaic processes in batteries, so although ECs have lower energy densities than batteries, they have higher power densities. Furthermore, their operation time scales are quite different: ECs can be charged and discharged in seconds, whereas high-performance rechargeable batteries require at least tens of minutes to charge and hours or days to discharge. Those differences have made for different market applications and opportunities, depending on the performance needs. In fact, some important applications require the use of batteries and ECs in combination. For example, the next generation of hybrid vehicles will likely incorporate batteries and ECs.

However, the performance of current energy storage devices falls well short of the requirements for using electrical energy efficiently. Devices with substantially higher energy and power densities, faster recharge rates, and longer charge–discharge cycle lifetimes are needed if plug-in hybrid and pure electric vehicles are to be developed and broadly deployed as replacements for gasoline-powered vehicles. Moreover, the reliability and safety of the devices must be improved to prevent premature and sometimes catastrophic failures.

To meet the future needs of electrical energy storage, it is critical to understand atomic- and molecular-level processes that govern their operation, performance limitations, and failure. Engineering efforts have incrementally advanced the performance of the devices, but breakthroughs are needed that only fundamental research can provide. The goal is to develop novel energy storage systems that incorporate revolutionary new materials and chemical processes.[1]

## Batteries

A battery is composed of an anode (negative electrode), a cathode (positive electrode), and an electrolyte that allows for ionic conductivity. Rigid separators (made of polymeric materials, for example) separate the anode and cathode to prevent a short circuit. Today commercially available rechargeable batteries include lithium-ion, nickel-metal-hydride, and nickel–cadmium devices. As shown in figure 1b, lithium-ion and other lithium-based batteries have the highest energy densities (per unit volume or per unit mass) of all rechargeable batteries. First commercialized by Sony Corp in 1990, lithium-ion batteries (LIBs) are now used in portable electronic devices, power tools, stationary power supplies, and medical instruments and in military, automotive, and aerospace applications. They are likely to be among the most important energy storage devices of the future.[2]

Figure 2 depicts the charge and discharge processes for a conventional LIB.[3] In the discharge process, the anode is electrochemically oxidized, which results in the release, or

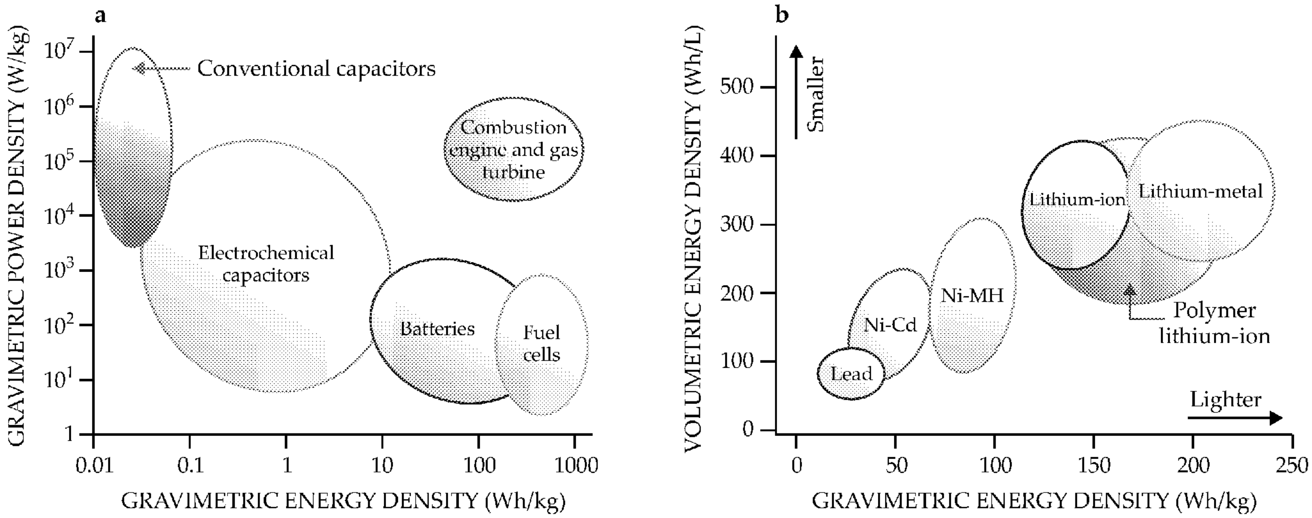



**Figure 1. (a) Batteries store more energy** per unit weight than electrochemical capacitors, but ECs provide more power. Thus batteries tend to be preferred for long-time operation of a device, whereas ECs are used to provide high power in a short time period. Other systems for generating and storing energy are shown for comparison. **(b)** Rechargeable batteries include those based on lead, nickel–cadmium, and nickel–metal hydride. But lithium-based batteries store the most energy per unit mass or per unit volume.

deintercalation, of Li ions into the electrolyte. At the same time, electrons move through the external circuit and travel toward the cathode. The Li ions travel through the electrolyte to compensate for the negative charge flowing through the external circuit, which results in the uptake, or intercalation, of Li ions into the cathode. When the battery is recharged, the reverse processes occur. In this mode of operation, LIBs are generally called rocking-chair batteries to describe the toggling of Li ions back and forth between anode and cathode.

The energy output of a battery depends on the operating voltage (determined by the redox reactions that take place at the two electrodes) and the charge storage capacities of the electrode materials. However, a battery does not always deliver as much energy as it theoretically can. For example, when a battery is discharged rapidly to provide high power, an overpotential is needed to drive the electrode reactions at sufficiently fast rates, which decreases the operating voltage and therefore the energy. To minimize that energy loss, researchers are interested in identifying reactions that proceed sufficiently fast on their own or that can be suitably catalyzed. Ohmic losses, which result from the electrical resistance of the electrolyte and contact resistances at the electrodes, also lower a battery's energy output.

The high energy outputs of Li-based batteries are mainly a result of the electrochemical and physicochemical properties of Li. As the lightest metal, Li has a theoretical gravimetric capacity—storable charge per unit weight—of 3860 mAh/g. Moreover, Li is the strongest metal reducing agent. A Li anode thus generates a large potential difference between the anode and cathode, which leads to a larger energy output.

However, significant safety issues are associated with the use of Li metal as an anode material. When the current distribution during the charging process is not uniform, Li metal dendrites can form at the anode surface, which can cause short circuits. Anodes of commercially available LIBs are instead typically made of carbonaceous materials such as graphite, which are capable of intercalating one Li atom per six carbon atoms—$LiC_6$—when the battery is fully charged.[4] With the aim of enhancing the anode capacity, researchers have focused on materials such as silicon, tin, metal oxides, and Li alloys.[4] Research is also under way to design safer Li metal anodes by improving the reversibility of Li electrodeposition (thus mitigating dendrite formation) or preventing the deposition altogether.

The cathodes of LIBs are typically made of metal oxides and phosphates.[5] $LiCoO_2$ has been used most extensively in practical applications, but cobalt is relatively expensive. The cost and availability of materials is becoming a more important consideration as the market for LIBs grows and targets larger applications, such as hybrid and pure electric vehicles, for which vast amounts of material will be required. Mixed layered oxides (such as $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$) and $LiFePO_4$ have therefore captured the attention of numerous research groups.[6] Their electrochemical performance is comparable to that of $LiCoO_2$, they are less expensive, and they are thermally more stable and therefore safer. In fact, LIBs based on the mixed layered oxide and $LiFePO_4$ cathodes have been commercialized, respectively, by Sony and A123 Systems Inc.

Capacities obtainable from conventional inorganic cathode materials are limited by the number of lithium ions that they can intercalate while remaining structurally stable. When Li ions are deintercalated from an oxide such as $LiCoO_2$, the material's lattice contracts. Extraction of all, or even 80–90%, of the Li ions would change the structure so much that the electrode would fail after a small number of charge–discharge cycles. In practice, therefore, batteries are generally designed so that only about half of the Li ions are ever deintercalated from the cathode. The gravimetric capacities of cathode materials are thus limited to 120–160 mAh/g.

Anode materials, in contrast, have gravimetric capacities of 372 mAh/g or more. The capacity difference between anode and cathode materials means that the cathode in an LIB must be several times more massive than the anode. That imbalance affects not only the energy density of the battery as a whole but also its charge–discharge performance. The need for more cathode material means that the cathode will be thicker, so the Li ions must travel a greater distance to undergo intercalation

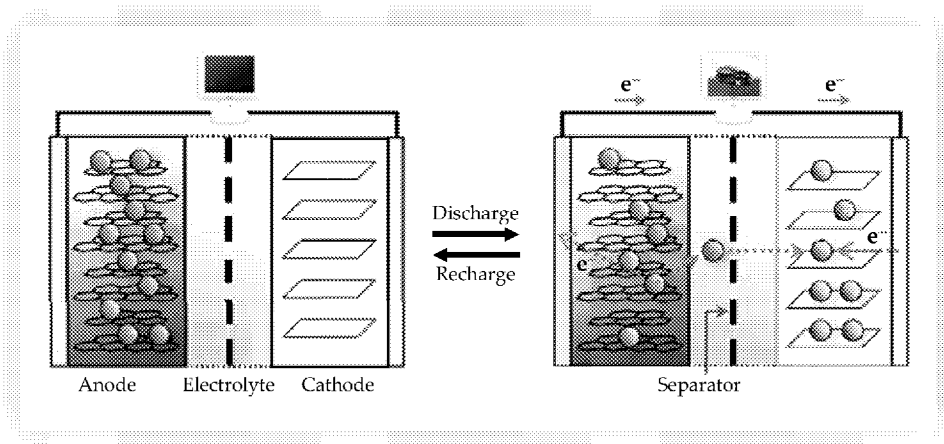



**Figure 2. Charging and discharging** a lithium-ion battery. In the discharge process, the anode is electrochemically oxidized, and intercalated Li ions (purple) are released. At the same time, electrons travel through the external circuit to the cathode. The Li ions travel through the electrolyte and are intercalated in the cathode. When the battery is recharged, the reverse processes occur.

and deintercalation. It is thus particularly important to develop cathode materials with higher capacities.

Recently, researchers have paid a great deal of attention to organic materials as a feasible solution to increasing cathode capacities. The building blocks of organic compounds—carbon, nitrogen, oxygen, and sulfur—are all abundant and inexpensive. Since organic materials are generally amorphous, the problem of structural changes during charge and discharge is precluded. Moreover, chemical tunability of the compounds makes them even more attractive. Organic materials can be designed to optimize the capacity, energy, or charge–discharge cycle performance, as desired.

Organic molecules containing S, O, or N atoms appear to be especially promising. As cathode materials, they may provide reversible and fast charge-transfer reactions in addition to high gravimetric capacities. In particular, organosulfur compounds with multiple thiolate ($S^-$) groups have been extensively considered due primarily to their high theoretical gravimetric capacities, as shown in figure 3a.[7] The charge and discharge reactions are based on formation and cleavage of disulfide bonds, so the number of electrons transferred per unit weight is determined by the number of thiolate groups, which can be made quite large. (However, they offer no significant advantage in terms of volumetric capacity because organic materials are generally less dense than inorganic materials.) In addition, organosulfur compounds can release and capture Li ions during charge and discharge reactions, so they can easily be incorporated into the rocking-chair system.

But the redox reactions of thiolate compounds are generally very slow at room temperature, so efficient electrocatalysts, such as conducting polymers, are required to accelerate the reactions.[8] Moreover, thiolate compounds often exhibit poor charge–discharge cyclability due to dissolution of the reduction products (the thiolate monomers in figure 3b), particularly when the electrolyte is an organic liquid. In order for organosulfur compounds to be of practical use as high-energy cathode materials, procedures or novel materials must be developed to prevent such dissolution. Elemental sulfur, $S_8$, whose charge–discharge reactions likewise involve formation and cleavage of disulfide bonds, has also been widely studied as a cathode material due to its exceptionally high gravimetric capacity. However, similar to organosulfur compounds, issues related to slow kinetics and dissolution of the reduction products of $S_8$ have precluded its practical use.

## Electrochemical capacitors

Like a conventional capacitor, an electrochemical capacitor stores energy as charge on a pair of electrodes. Unlike a conventional capacitor, however, an EC stores charge in an electric double layer that forms at the interface between an electrode and an electrolyte solution, as shown in figure 4.[9] The electrolyte can be an aqueous solution such as sulfuric acid or potassium hydroxide, an organic electrolyte such as acetonitrile or propylene carbonate, or an ionic liquid. As in LIBs, gel- and solid-type polymer electrolytes have also been used to improve safety and thus system reliability.

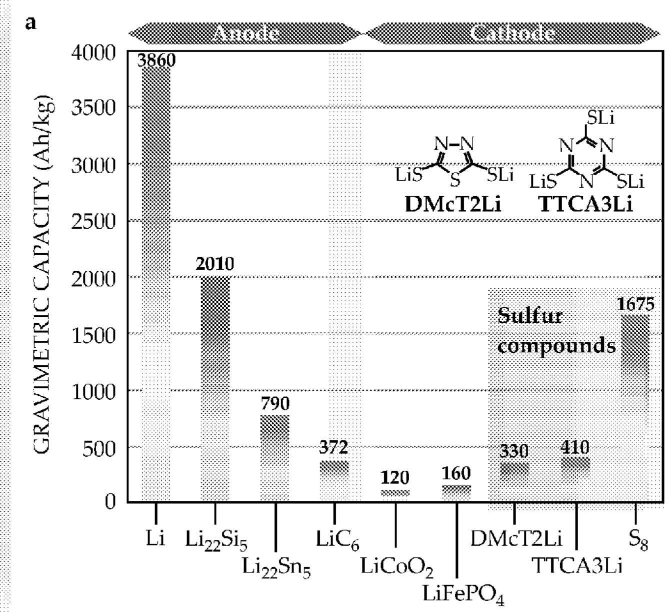
Because of their intrinsically fast mechanism for storing and releasing charge, ECs are well suited for applications that require high power. In particular, they can store energy that is normally wasted as heat during repetitive motions such as the deceleration of automobiles during braking. Light hybrid vehicles have successfully used batteries for that purpose, but heavy vehicles, such as buses and trucks, need more power, so ECs are more suitable. Other applications of ECs include energy management in cranes, forklifts, and elevators.

The charge that can be stored in an EC is proportional to the surface area of the electrodes, so both the anode and the cathode are typically made of activated carbon, a porous material whose internal surface area can exceed 1000 $m^2/g$. ECs typically have capacitances of 100–140 F/g and energy densities of 2–5 Wh/kg—several orders of magnitude greater than those of conventional capacitors—so they are often called supercapacitors or ultracapacitors.[10]

New types of carbon materials, such as carbon nanotubes and nanofibers, have been studied as possible EC electrode materials. They have larger surface areas than conventional activated carbon and thus offer higher capacitance. Recent studies have suggested that carbon materials with nanopore structures can exhibit even higher capacitance, ostensibly because ions in confined geometries are stripped of their solvating molecules, which decreases their effective size.[11]

The ECs described so far derive their capacitance from the electric double layer alone and are specifically referred to as electric double-layer capacitors (EDLCs). Another class of ECs, pseudocapacitors, employ faradaic processes but still behave like capacitors.[12] The fast and reversible faradaic processes at the electrode surfaces, in combination with the nonfaradaic formation of the electric double layer, allow pseudocapacitors to store much more energy than EDLCs. For instance, pseudocapacitor electrodes made of $RuO_2$ adsorb and desorb hydrogen, theoretically providing a gravimetric capacitance of 1358 F/g.

Although $RuO_2$ is an attractive material for high-performance pseudocapacitors, its cost has precluded any practical use. Alternatives include conducting polymers such as polythiophene, which can store energy through doping and dedoping of ions from the electrolyte.[13] An advantage of conducting polymers is that one can, via appropriate choice of materials, tune the operational voltage of the



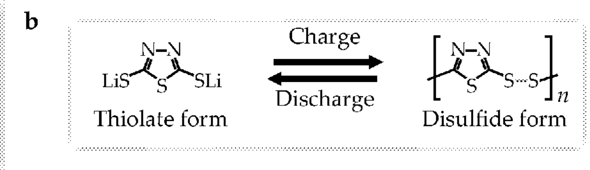




**Figure 3. (a) Theoretical gravimetric capacities** for lithium-ion battery electrode materials. Li metal is the highest-capacity anode material, but its use poses safety issues. Graphite, which intercalates Li ions to form $LiC_6$, is more often used in practice. Among cathode materials, organosulfur compounds such as DMcT2Li and TTCA3Li have significantly higher gravimetric capacities than the commonly used metal oxides and phosphates. Elemental sulfur is shown for comparison to the organosulfur compounds. **(b)** Charge and discharge reactions of the thiolate compound DMcT2Li, where *n* represents a large number of units that connect to form a polymer. The thiolate ($S^-$) groups attract Li ions when the battery is discharged and bind to one another when the battery is recharged.

pseudocapacitor. However, polymer-based pseudocapacitors have poor charge–discharge cyclability compared to EDLCs because the redox processes degrade the molecular structure of the electrode materials.

Pseudocapacitors have energy densities of about 30 Wh/kg, more than EDLCs but still much less than LIBs, which today can average about 150 Wh/kg. Researchers have therefore focused on designing new materials to enhance a pseudocapacitor's charge capacity while maintaining the device's high power and exceptional charge–discharge cyclability. Organic materials capable of reversible multi-electron transfer have been recently studied and appear most promising.[14]

A third class of ECs are the asymmetric hybrid capacitors, which combine a nonfaradaic, or capacitor-type, electrode with one that is faradaic, or battery-type. The battery-type electrode provides high energy output, and the capacitor-type electrode provides high power. The high energy output is mainly due to the fact that the energy stored in a capacitor is proportional to the square of the cell voltage, as shown in figure 5. For instance, the combination of a carbon anode predoped with Li ions and an activated carbon cathode exhibits one of the highest energy outputs among ECs, because the Li redox chemistry allows an operating voltage of about 4 V, higher than any other EC.

## Outlook

Major challenges for electrical energy storage devices include enhancing energy and power densities and charge–discharge cyclability while maintaining stable electrode–electrolyte interfaces. The need to mitigate the volumetric and structural changes in the active electrode sites that accompany ion intercalation and deintercalation–particularly in the case of metal oxides–has prompted researchers to look at nanoscale systems. Synthetic control of materials' architectures at the nanoscale could lead to transformational breakthroughs in key energy storage parameters.[15] For example, tailored nanostructured materials with very high surface areas could offer high and reproducible charge-storage capabilities and rapid charge–discharge rates. The development of revolutionary three-dimensional architectures is a particularly exciting possibility.[16]

The electrolyte is often the weak link in an energy storage device, due at least in part to the fact that many batteries and ECs operate at potentials beyond the thermodynamic stability limits of electrolyte systems. As a result, irreversible chemical reactions create films of solid material on the electrode surfaces, which affect the operation of the devices but

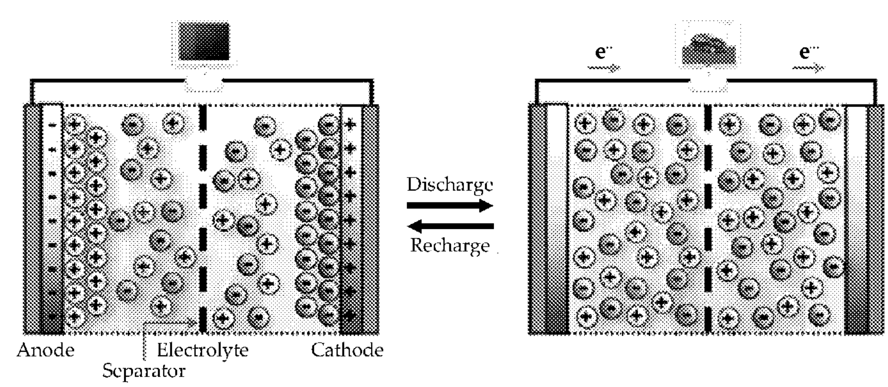



**Figure 4. Charging** and discharging an electric double-layer capacitor. When the capacitor is charged, ions from the electrolyte are attracted to the charged electrodes. The rigid separator acts to prevent a short circuit.

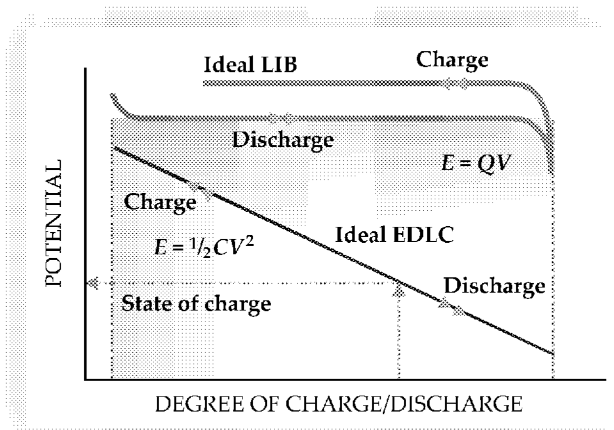



**Figure 5. During discharge,** the cell voltage on an ideal lithium-ion battery remains constant. But the voltage on an ideal electric double-layer capacitor decreases linearly. As a result, the energy $E$ stored in the LIB is proportional to the voltage $V$, whereas the energy stored in the EDLC is proportional to the voltage squared. Moreover, the voltage provides a convenient measure of the amount of charge left, or state of charge, in EDLCs, but not in LIBs.

are difficult to control in a rational fashion. At present, interactions among the ions, solvent, and electrodes in electrolyte systems are poorly understood. Fundamental research will provide the knowledge base that will permit the formulation of novel electrolytes of deliberate design, such as ionic liquids and nanocomposite polymer electrolytes, which will enhance the performance and lifetimes of energy storage devices.

It is also important to understand the interdependence of the electrolyte and electrode materials, especially with regard to charge transfer and ion transport that take place at the interfaces. Electrode–electrolyte interfaces are complex and dynamic and need to be thoroughly characterized so that the paths of electrons and attendant ion traffic may be directed with exquisite fidelity. New analytical tools are needed to observe the dynamics at the interfaces, in situ and in real time. The information such tools will provide should allow for rational materials design, which will in turn lead to novel materials that have longer charge–discharge lifetimes and can store more energy.

Advances in computational methods will provide the understanding needed to make groundbreaking discoveries. Theory, modeling, and simulation can offer insight into mechanisms, predict trends, identify novel materials, and guide experiments. Large multiscale computations that integrate methods over broad spatiotemporal regimes have the potential to provide a fundamental understanding of processes such as phase transitions in electrode materials, charge transfer at interfaces, electronic transport in electrodes, and ion transport in electrolytes, and thereby pave the way for future electrical energy storage technologies.

*This article is based on the conclusions contained in the report of the US Department of Energy Basic Energy Sciences Workshop on Electrical Energy Storage,[1] 2–4 April, 2007. One of us (Abruña) was a cochair of the workshop and a principal editor of the report. We acknowledge DOE for support of both the workshop and the preparation of this manuscript.*

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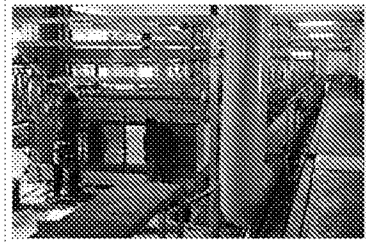
# Electroplating

From Wikipedia, the free encyclopedia



Copper electroplating machine for layering PCBs

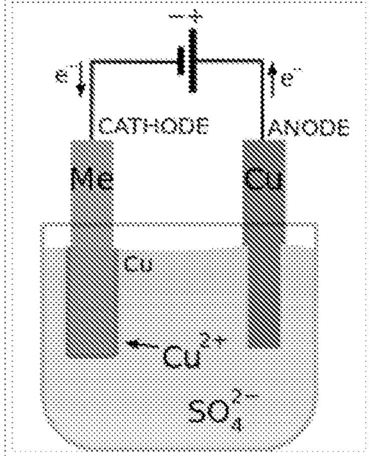
**Electroplating** is a process that uses electrical current to reduce dissolved metal cations so that they form a coherent metal coating on an electrode. The term is also used for electrical oxidation of anions onto a solid subtrate, as in the formation silver chloride on silver wire to make silver/silver-chloride electrodes. Electroplating is primarily used to change the surface properties of an object (e.g. abrasion and wear resistance, corrosion protection, lubricity, aesthetic qualities, etc.), but may also be used to build up thickness on undersized parts or to form objects by electroforming.

The process used in electroplating is called **electrodeposition**. It is analogous to a galvanic cell acting in reverse. The part to be plated is the cathode of the circuit. In one technique, the anode is made of the metal to be plated on the part. Both components are immersed in a solution called an electrolyte containing one or more dissolved metal salts as well as other ions that permit the flow of electricity. A power supply supplies a direct current to the anode, oxidizing the metal atoms that comprise it and allowing them to dissolve in the solution. At the cathode, the dissolved metal ions in the electrolyte solution are reduced at the interface between the solution and the cathode, such that they "plate out" onto the cathode. The rate at which the anode is dissolved is equal to the rate at which the cathode is plated, vis-a-vis the current flowing through the circuit. In this manner, the ions in the electrolyte bath are continuously replenished by the anode.[1]

Other electroplating processes may use a non-consumable anode such as lead or carbon. In these techniques, ions of the metal to be plated must be periodically replenished in the bath as they are drawn out of the solution.[2] The most common form of electroplating is used for creating coins such as pennies, which are small zinc plates covered in a layer of copper. [3]

## Contents

# Process



Electroplating of a metal (Me) with copper in a copper sulfate bath

The cations associate with the anions in the solution. These cations are reduced at the cathode to deposit in the metallic, zero valence state. For example, in an acid solution, copper is oxidized at the anode to $Cu^{2+}$ by losing two electrons. The $Cu^{2+}$ associates with the anion $SO_4^{2-}$ in the solution to form copper sulfate. At the cathode, the $Cu^{2+}$ is reduced to metallic copper by gaining two electrons. The result is the effective transfer of copper from the anode source to a plate covering the cathode.

The plating is most commonly a single metallic element, not an alloy. However, some alloys can be electrodeposited, notably brass and solder.

Many plating baths include cyanides of other metals (e.g., potassium cyanide) in addition to cyanides of the metal to be deposited. These free cyanides facilitate anode corrosion, help to maintain a constant metal ion level and contribute to conductivity. Additionally, non-metal chemicals such as carbonates and phosphates may be added to increase conductivity.

When plating is not desired on certain areas of the substrate, stop-offs are applied to prevent the bath from coming in contact with the substrate. Typical stop-offs include tape, foil, lacquers, and waxes.[4]

## Strike

Initially, a special plating deposit called a "strike" or "flash" may be used to form a very thin (typically less than 0.1 micrometer thick) plating with high quality and good adherence to the substrate. This serves as a foundation for subsequent plating processes. A strike uses a high current density and a bath with a low ion concentration. The process is slow, so more efficient plating processes are used once the desired strike thickness is obtained.

The striking method is also used in combination with the plating of different metals. If it is desirable to plate one type of deposit onto a metal to improve corrosion resistance but this metal has inherently poor adhesion to the substrate, a strike can be first deposited that is compatible with both. One example of this situation is the poor adhesion of electrolytic nickel on zinc alloys, in which case a copper strike is used, which has good adherence to both.[2]

## Brush electroplating

A closely related process is brush electroplating, in which localized areas or entire items are plated using a brush saturated with plating solution. The brush, typically a stainless steel body wrapped with a cloth material that both holds the plating solution and prevents direct contact with the item being plated, is connected to the positive side of a low voltage direct-current power source, and the item to be plated connected to the negative. The operator dips the brush in plating solution then applies it to the item, moving the brush continually to get an even distribution of the plating material. Brush electroplating has several advantages over tank plating, including portability, ability to plate items that for some reason cannot be tank plated (one application was the plating of portions of very large decorative support columns in a building restoration), low or no masking requirements, and comparatively low plating solution volume requirements. Disadvantages compared to tank plating can include greater operator involvement (tank plating can frequently be done with minimal attention), and inability to achieve as great a plate thickness.

## Electroless deposition

Usually an electrolytic cell (consisting of two electrodes, electrolyte, and external source of current) is used for electrodeposition. In contrast, an electroless deposition process uses only one electrode and no external source of electric current. However, the solution for the electroless process needs to contain a reducing agent so that the electrode reaction has the form:

$$M^{z+} + Red_{solution} \xrightarrow{\text{catalytic surface}} M_{solid} + Oxy_{solution}$$

In principle any water-based reducer can be used although the redox potential of the reducer half-cell must be high enough to overcome the energy barriers inherent in liquid chemistry. Electroless nickel plating uses hypophosphite as the reducer while plating of other metals like silver, gold and copper typically use low molecular weight aldehydes.

A major benefit of this approach over electroplating is that power sources and plating baths are not needed, reducing the cost of production. The technique can also plate diverse shapes and types of surface. The downside is that the plating process is usually slower and cannot create such thick plates of metal. As a consequence of these characteristics, electroless deposition is quite common in the decorative arts.

## Cleanliness

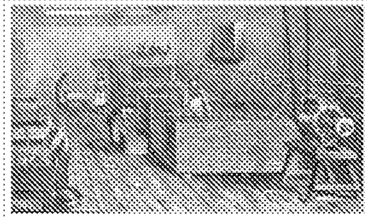
Cleanliness is essential to successful electroplating, since molecular layers of oil can prevent adhesion of the coating. ASTM B322 is a standard guide for cleaning metals prior to electroplating. Cleaning processes include solvent cleaning, hot alkaline detergent cleaning, electro-cleaning, and acid treatment etc. The most common industrial test for cleanliness is the waterbreak test, in which the surface is thoroughly rinsed and held vertical. Hydrophobic contaminants such as oils cause the water to bead and break up, allowing the water to drain rapidly. Perfectly clean metal surfaces are hydrophilic and will retain an unbroken sheet of water that does not bead up or drain off. ASTM F22 describes a version of this test. This test does not detect hydrophilic contaminants, but the electroplating process can displace these easily since the solutions are water-based. Surfactants such as soap reduce the sensitivity of the test and must be thoroughly rinsed off.

# Effects

Electroplating changes the chemical, physical, and mechanical properties of the workpiece. An example of a chemical change is when nickel plating improves corrosion resistance. An example of a physical change is a change in the outward appearance. An example of a mechanical change is a change in tensile strength or surface hardness which is a required attribute in tooling industry.[5]

# History

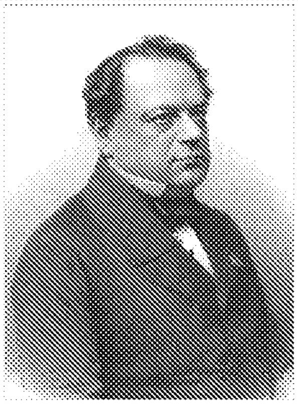
*See also: Johann Wilhelm Ritter*


Nickel plating

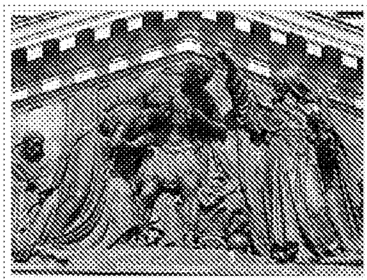
Although it is not confirmed, the Parthian Battery may have been the first system used for electroplating.

Modern electrochemistry was invented by Italian chemist Luigi V. Brugnatelli in 1805. Brugnatelli used his colleague Alessandro Volta's invention of five years earlier, the voltaic pile, to facilitate the first electrodeposition. Brugnatelli's inventions were suppressed by the French Academy of Sciences and did not become used in general industry for the following thirty years.

By 1839, scientists in Britain and Russia had independently devised metal deposition processes similar to Brugnatelli's for the copper electroplating of printing press plates.


Boris Jacobi developed electroplating, electrotyping and galvanoplastic sculpture in Russia

Boris Jacobi in Russia not only rediscovered galvanoplastics, but developed electrotyping and galvanoplastic sculpture. Galvanoplastics quickly came into fashion in Russia, with such people as inventor Peter Bagration, scientist Heinrich Lenz and science fiction author Vladimir Odoyevsky all contributing to further development of the technology. Among the most notorious cases of electroplating usage in mid-19th century Russia were gigantic galvanoplastic sculptures of St. Isaac's Cathedral in Saint Petersburg and gold-electroplated dome of the Cathedral of Christ the Saviour in Moscow, the tallest Orthodox church in the world.[6]


Galvanoplastic sculpture on St. Isaac's Cathedral in Saint Petersburg.

Soon after, John Wright of Birmingham, England discovered that potassium cyanide was a suitable electrolyte for gold and silver electroplating. Wright's associates, George Elkington and Henry Elkington were awarded the first patents for electroplating in 1840. These two then founded the electroplating industry in Birmingham from where it spread around the world.

The Norddeutsche Affinerie in Hamburg was the first modern electroplating plant starting its production in 1876.[7]

As the science of electrochemistry grew, its relationship to the electroplating process became understood and other types of non-decorative metal electroplating processes were developed. Commercial electroplating of nickel, brass, tin, and zinc were developed by the 1850s. Electroplating baths and equipment based on the patents of the Elkingtons were scaled up to accommodate the plating of numerous large scale objects and for specific manufacturing and engineering applications.

The plating industry received a big boost with the advent of the development of electric generators in the late 19th century. With the higher currents available, metal machine components, hardware, and automotive parts requiring corrosion protection and enhanced wear properties, along with better appearance, could be processed in bulk.

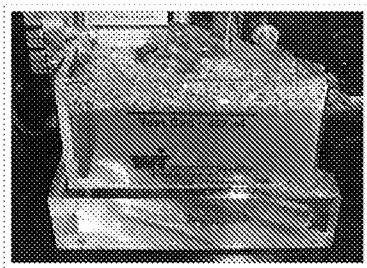
The two World Wars and the growing aviation industry gave impetus to further developments and refinements including such processes as hard chromium plating, bronze alloy plating, sulfamate nickel plating, along with numerous other plating processes. Plating equipment evolved from manually operated tar-lined wooden tanks to automated equipment, capable of processing thousands of kilograms per hour of parts.

One of the American physicist Richard Feynman's first projects was to develop technology for electroplating metal onto plastic. Feynman developed the original idea of his friend into a successful invention, allowing his employer (and friend) to keep commercial promises he had made but could not have fulfilled otherwise.[8]

# Use

Electroplating is a useful process. It is widely used in industry for coating metal objects with a thin layer of a different metal. The layer of metal deposited has some desired property, which metal of the object lacks. For example chromium plating is done on many objects such as car parts, bath taps, kitchen gas burners, wheel rims and many others.

# Hull cell



A zinc solution tested in a hull cell

The *Hull cell* is a type of test cell used to qualitatively check the condition of an electroplating bath. It allows for optimization for current density range, optimization of additive concentration, recognition of impurity effects and indication of macro-throwing power capability.[9] The Hull cell replicates the plating bath on a lab scale. It is filled with a sample of the plating solution, an appropriate anode which is connected to a rectifier. The "work" is replaced with a hull cell test panel that will be plated to show the "health" of the bath.

The Hull cell is a trapezoidal container that holds 267 ml of solution. This shape allows one to place the test panel on an angle to the anode. As a result, the deposit is plated at different current densities which can be measured with a hull cell ruler. The solution volume allows for a quantitative optimization of additive concentration: 1 gram addition to 267 mL is equivalent to 0.5 oz/gal in the plating tank.[10]

# References

1. ^ Dufour, IX-1.
2. ^ *a b* Dufour, IX-2.
3. ^ "US Mint Virtual Tour" (http://www.usmint.gov/mint_tours/?action=VTShell). US Mint.
4. ^ Dufour, IX-3.
5. ^ Todd, Robert H.; Dell K. Allen and Leo Alting (1994). "Surface Coating" (http://books.google.com/?id=6x1smAf_PAcC). *Manufacturing Processes Reference Guide*. Industrial Press Inc. pp. 454–458. ISBN 0-8311-3049-0.
6. ^ The history of galvanotechnology in Russia (http://www.galteh.ru/article_galvanotehnika.html) **(Russian)**
7. ^ Stelter, M.; Bombach, H. (2004). "Process Optimization in Copper Electrorefining". *Advanced Engineering Materials* **6**: 558. doi:10.1002/adem.200400403 (http://dx.doi.org/10.1002%2Fadem.200400403).
8. ^ Richard Feynman, *Surely You're Joking, Mr. Feynman!* (1985), in chap. 6: "The Chief Research Chemist of the Metaplast Corporation" (http://www.tenniselbow.org/scott/feyn_surely.pdf)
9. ^ *Metal Finishing: Guidebook and Directory. Issue 98* **95**. 1998. p. 588.
10. ^ Hull Cell 101 (http://www.allbusiness.com/manufacturing/chemical-manufacturing-paint/3993213-1.html)


## Bibliography


- Dufour, Jim (2006). *An Introduction to Metallurgy, 5th*. Cameron.

Electronic TUBES

# 5U4-GB

## TWIN DIODE

### FOR FULL-WAVE POWER RECTIFIER APPLICATIONS

## DESCRIPTION AND RATING

The 5U4-GB is a filamentary twin diode designed for use as a full-wave rectifier in the power supply of television receivers or other equipment which have high direct-current requirements. The 5U4-GB employs a straight-sided T-12 envelope and may be used as a replacement for either the 5U4-G or 5U4-GA.

### GENERAL

**ELECTRICAL**

Cathode—Coated Filament
Filament Voltage, AC or DC . . . . . 5.0 Volts
Filament Current . . . . . 3.0 Amperes

**MECHANICAL**

Mounting Position—Vertical*
Envelope—T-12, Glass
Base—B5-121 or B5-113, Short Medium Shell Octal 5-Pin
or B5-127, Flared Medium Shell Octal 5-Pin
or B8-118, Short Medium Shell Octal 8-Pin

### MAXIMUM RATINGS

**RECTIFIER SERVICE—DESIGN-CENTER VALUES†**

Peak Inverse Plate Voltage . . . . . 1550 Volts
AC Plate-Supply Voltage per Plate—See Rating Chart I‡
Steady-State Peak Plate Current per Plate . . . . . 1000 Milliamperes
Transient Peak Plate Current per Plate,
Maximum Duration 0.2 Second . . . . . 4.6 Amperes
DC Output Current—See Rating Chart I‡

### CHARACTERISTICS AND TYPICAL OPERATION

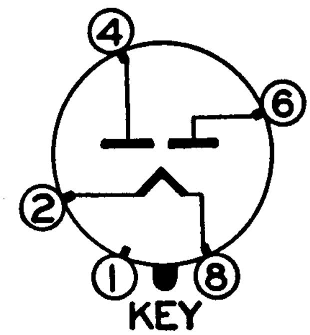
**FULL-WAVE RECTIFIER WITH CAPACITOR-INPUT FILTER**

| | | | |
|---|---|---|---|
| AC Plate-Supply Voltage per Plate, RMS | 300 | 450 | Volts |
| Filter Input Capacitor | 40 | 40 | Microfarads |
| Total Plate-Supply Resistance per Plate | 21 | 67 | Ohms |
| DC Output Current | 300 | 275 | Milliamperes |
| DC Output Voltage at Filter Input | 290 | 460 | Volts |

**FULL-WAVE RECTIFIER WITH CHOKE-INPUT FILTER**

AC Plate-Supply Voltage per Plate, RMS . . . . . 550 Volts
Filter Input Choke . . . . . 10 Henrys
DC Output Current . . . . . 275 Milliamperes
DC Output Voltage at Filter Input . . . . . 440 Volts
Tube Voltage Drop
Ib = 275 Milliamperes DC per Plate . . . . . 50 Volts

**BASING DIAGRAM**

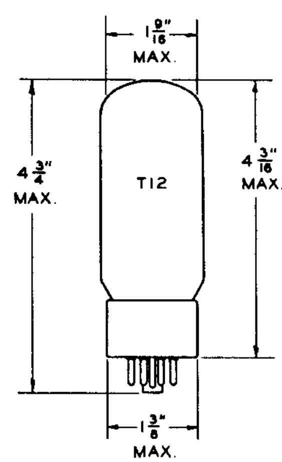



RETMA 5T

**TERMINAL CONNECTIONS**

Pin 1—No Connection
Pin 2—Filament
Pin 4—Plate Number 2
Pin 6—Plate Number 1
Pin 8—Filament

**PHYSICAL DIMENSIONS**



Electronic TUBES

# 5Y3-GT

## TWIN DIODE

### FOR FULL-WAVE POWER RECTIFIER APPLICATIONS

## DESCRIPTION AND RATING

The 5Y3-GT is a filamentary twin-diode designed for full-wave rectifier operation in power supplies that have d-c output current requirements up to approximately 125 milliamperes.

### GENERAL

**ELECTRICAL**

Cathode—Coated Filament

| | |
|---|---|
| Filament Voltage, AC or DC | 5.0 Volts |
| Filament Current | 2.0 Amperes |

**MECHANICAL**

Mounting Position—Vertical*

Envelope—T-9, Glass

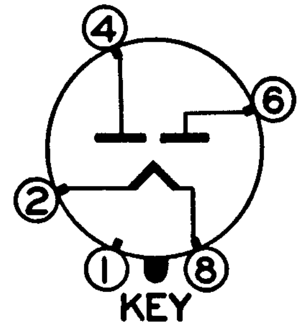
Base—B5-10, Intermediate Shell Octal 5-Pin
or B5-62, Short Intermediate Shell Octal 5-Pin

### MAXIMUM RATINGS

**RECTIFIER SERVICE—DESIGN-CENTER VALUES†**

| | | |
|---|---|---|
| Peak Inverse Plate Voltage | 1400 | Volts |
| AC Plate-Supply Voltage per Plate—See Rating Chart I‡ | | |
| Steady-State Peak Plate Current per Plate | 440 | Milliamperes |
| Transient Peak Plate Current per Plate, Maximum Duration 0.2 Second | 2.5 | Amperes |
| DC Output Current—See Rating Chart I‡ | | |

### BASING DIAGRAM

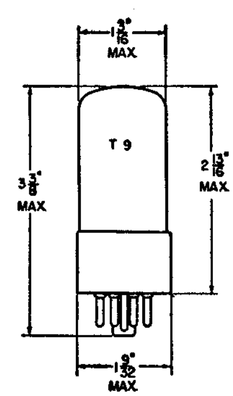



RETMA 5T

### TERMINAL CONNECTIONS

Pin 1—No Connection
Pin 2—Filament
Pin 4—Plate Number 2
Pin 6—Plate Number 1
Pin 8—Filament

### PHYSICAL DIMENSIONS




RETMA 9–13 OR 9–42

GENERAL ELECTRIC

*Supersedes ET-T250B, dated 6-50*

SYLVANIA

# engineering data service

**SYLVANIA 6X4 12X4**

## MECHANICAL DATA

| | |
|---|---|
| Bulb | T-5½ |
| Base | E7-1, Miniature Button 7-Pin |
| Outline | 5-3 |
| Basing | 5BS |
| Cathode | Coated Unipotential |
| Mounting Position | Any |

## ELECTRICAL DATA

### HEATER CHARACTERISTICS

| | 6X4 | 12X4 | |
|---|---|---|---|
| Heater Voltage[1] | 6.3 | 12.6 | Volts |
| Heater Current | 600 | 300 | Ma |
| Heater-Cathode Voltage (Design Center Values) | | | |
| Heater Negative with Respect to Cathode | | | |
| Total DC and Peak | 450 | 450 | Volts Max. |
| Heater Positive with Respect to Cathode | | | |
| Total DC and Peak | 100 | 100 | Volts Max. |

### RATINGS (Design Center Values)

| | |
|---|---|
| Peak Inverse Plate Voltage | 1250 Volts Max. |
| A C Plate Supply Voltage, R M S (Each Plate) | See Rating Chart I |
| Steady State Peak Plate Current, Rating Chart II (Each Plate) | 210 Ma Max. |
| Transient Peak Plate Current, Rating Chart III (Each Plate)[2] | 1.0 Ampere Max. |
| D C Output Current (Each Plate) | See Rating Chart I |

### CHARACTERISTICS

| | |
|---|---|
| Tube Voltage Drop, $I_b$ = 70 Ma Each Plate | 22 Volts |

### TYPICAL OPERATION

**Full-Wave Rectifier-Capacitor Input**

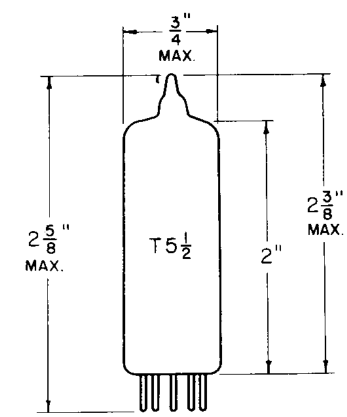
| | |
|---|---|
| A C Plate Supply Voltage Per Plate | 325 Volts |
| Filter Input Capacitor[3] | 10 µf |
| Total Effective Plate Supply Impedance (Per Plate) | 525 Ohms |
| D C Output Current | 70 Ma |
| D C Output Voltage at Filter Input (approx.) | |
| For D C Cathode Current of 35 Ma | 365 Volts |
| 70 Ma | 310 Volts |
| Difference (Voltage Regulation) | 55 Volts |
| Percentage Regulation | 15 Percent |

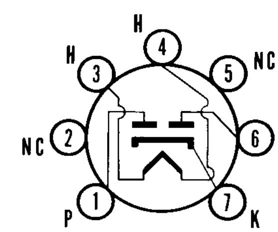
**Full-Wave Rectifier Service — Choke Input**

| | |
|---|---|
| A C Plate Supply Voltage Per Plate (R M S) | 450 Volts |
| Filter Input Choke | 10 Henrys |
| D C Output Current | 70 Ma |
| D C Output Voltage at Filter Input (approx.) | |
| For D C Cathode Current of 35 Ma | 395 Volts |
| 70 Ma | 385 Volts |
| Difference (Voltage Regulation) | 10 Volts |
| Percentage Regulation | 2.5 Percent |

## QUICK REFERENCE DATA

The Sylvania Types 6X4 and 12X4 are miniature, full-wave, cathode type rectifiers. They are intended for service in compact a c or auto receivers where the average current is not in excess of 70 Ma. Except for heater current and voltage the 6X4 is identical to the 12X4.




5-BS

SYLVANIA ELECTRIC PRODUCTS INC.

RADIO TUBE DIVISION
EMPORIUM, PA.

*Prepared and Released By The*
*TECHNICAL PUBLICATIONS SECTION*
*EMPORIUM, PENNSYLVANIA*

MARCH 1956

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# Tor Vergata Visual Analyser Project (Coming soon 2012 version **BETA available** )

## Visual Analyser

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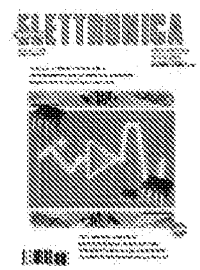
Detailed Features about:

1. Oscilloscope (dual channel, xy, time division, trigger);
2. Spectrum Analyzer with amplitude and phase display (linear, log, lines, bar, octaves band analysis 1/3, 1/6, 1/9, 1/12, 1/24);
3. Wave-form generator with "custom functions", triangular, square, sinus, white noise and pulse generation (NO ALIASING);
4. Frequency meter (in time and frequency domain) and counter; in time domain by means of a real time zero crossing algorithm;
5. Volt meter with DC, true RMS, peak to peak and mean display;
6. Filtering (low pass, hi pass, band pass, band reject, notch, "diode", DC removal);
7. Memo windows (data log) for analysis and storage of time series, spectrum and phase with "triggering" events; possibility to save in various formats and display them with a viewer;
8. A TRUE software digital analog conversion (for complete signal reconstruction using Nyquist theorem) ;
9. Frequency compensation: one can create/edit a custom frequency response and add it to the spectrum analyzer spectrum ; added standard weighting curves A,B,C in parallel with custom frequency response;
10. Support for 8/16/24 bit soundcard by means of API calls;
11. Unlimited frequency sampling (depend from the capabilities of your soundcard);
12. Cepstrum analysis;
13. Cross Correlation;
14. Extended THD measurements, with automatic sweep and compensation.
15. ZRLC-meter with Vector scope, automatic sweep in time and frequency for automatic measurement.

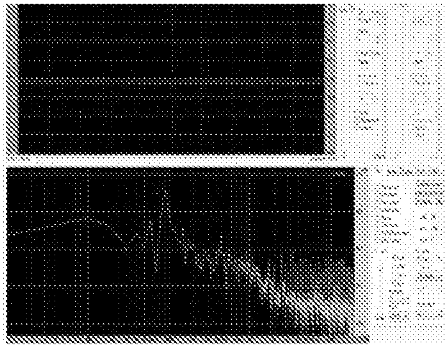
VA main form (version 8.x.x)

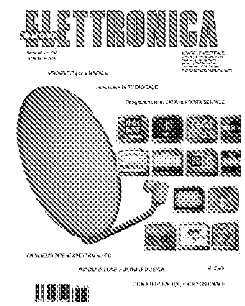
Latest VA reviews, articles:



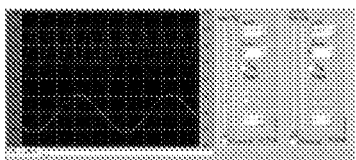


IMEKO



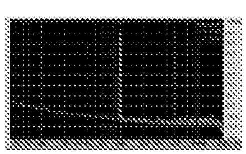




(1) - Oscilloscope



a. Dual channel
b. Bandwith : depends from your soundcard (typical 20 Khz) up to 96 Khz (192 Khz sampling frequency)
c. Resolution from 8 bit (S/N 46 dB) up to 24 bit (S/N >120 dB)
d. Time division adjust according the sampling frequency and sample resolution
e. Trigger (positive/negative slope) independent for both channels
f. Complete software D/A of digital samples : the Nyquist theorem allows reconstructing exactly the input signal
g. Utilities for quick frequency determination (hold left mouse button down and move mouse to get frequency/amplitude)
h. Y-axis in Volt and percent full scale
i. Auto calibration of scope (and spectrum) in volts (need an input signal of known amplitude)

(2) - Spectrum Analyzer



a. Dual channel

b. Bandwidth : same as point (1) (oscilloscope function): is the half of the sampling frequency. Typical for 44100 Hz is 22050 Hz (up to 96 Khz or ore depending of the acquisition board)

c. Resolution from 8 bit (S/N 46 dB) up to 24 bit (S/N >120 dB)

d. X-axis in Hz, logarithmic and linear; zoom x1..x16

e. Y-axis in dB or Volt (calibration needed); linear/logarithmic; zoom

f. Average on spectrum up to 200 buffer

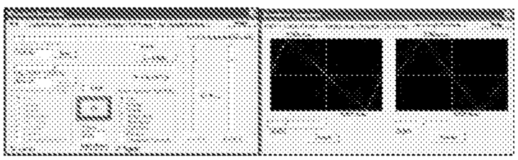
g. Direct window for amplitude with mouse

h. Auto-scale

i. Capacity to modify the zero dB level (manually/automatically)

j. Octave band analysis (1/1, 1/3, 1/6, 1/9, 1/12, 1/24)

(3) - Wave-form generator



- Dual channel
- Independent sampling frequency/resolution from scope/spectrum (up to 192 Khz/24 bit)
- Phase between channels (degree)
- Direct real time generation/ loop with predefined buffer
- Waveform CUSTOM, built with harmonics (with save/load in file ".fun" of defined waveform)
- Modulation of custom waveform with sinus/square/triangular
- Predefined waveform : sinus, square, triangular (parametric), white noise, pink noise, pulse, sinusoidal sweep
- Local volume levels
- Real time parameters variation (amplitude, frequency, phase between channels, type of waveform)

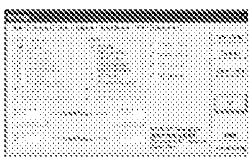
(4) - Frequency meter

- Dual channel
- Frequency meter in Hz/Time/Counter of the input signal being visualized in spectrum/scope
- Read the frequency of the harmonic of maximum amplitude
- Counter with threshold level

(5) - Volt meter (calibration needed)

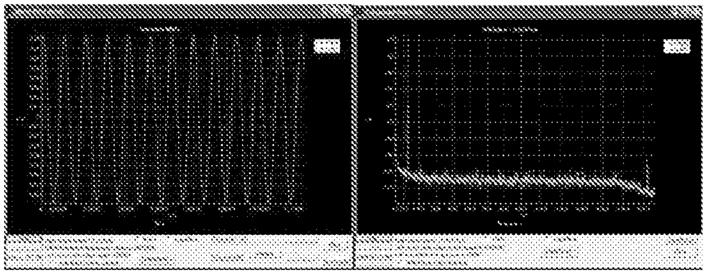

- Dual channel
- Vpp, True Rms
- Hold function

(6) - Filtering



- FIR low pass cut-off frequency user defined
- FIR high pass cut-off frequency user defined
- FIR band pass cut-off frequencies user defined
- FIR band reject cut-off frequencies user defined
- IIR notch cut-off frequency user defined
- IIR notch-inverted cut-off frequency user defined
- "Diode" function
- DC removal
- Dual filter (one for each channel)

(7) - Memo windows



- Aquiring of spectrum with average
- Edit offline (while VA running) of aquired spectrum: zoom, navigate
- Saving of spectrum in TXT format
- Clipboard for aquired spectrum
- Print of aquired spectrum
- Mark points for each valid point (harmonic) of spectrum
- Aquiring of scope points (points aquired in time domain)
- Edit offline (while VA running) of aquired time series: zoom, navigate
- Saving of samples in TXT format
- Clipboard for aquired samples
- Print of aquired samples
- D/A conversion: the points aquired may be converted using Nyquist theorem for full reconstruction of signal in time domain (see point 8 for D/A in real time)

(8) - real time DIGITAL/ANALOG conversion

- D/A in real time
- Dual channel
- Allows visualizing each aquired harmonic

Points (8) need a clairification:

<u>VA has the unbeatable feature to perform a full real time Digital-Analog conversion for the oscilloscope function.</u>

Consider using a frequency sampling of (standard) 44100 Hz, with a 16 bit resolution (resolution is not relevant for the purpose of the discussion below...)

Other programs similar to VA simply plot the raw points on the screen, which means you can’t easily analyze signals with a frequency higher than 3000/5000 Hz (there are limited points to plot). Even worse, think a sinusoidal signal of 20 KHz. You would have only 2 points (more or less) per cycle! ... The Nyquist theorem says that it is sufficient to RECONSTRUCT the original signal...try to see what happens if you draw a sine with only two points ...it will appear like a triangular waveform...

Try the power of VA enabling the function "full D/A", apply a sinusoidal signal of 15-20 KHz (for example using the Waveform generator included in VA) finally use the "Time division" control for the selected channel (mS/d) to display the signal at the desired detail level. You will see a perfect waveform with all the points of the original signal (not only two).

(9) Frequency compensation

Visual Analyser allows you to apply a predefined frequency response to compensate (for instance) the frequency response of a microphone. You should know the frequency response of your microphone; normally professional microphone should be shipped with the typical frequency response. You can add a limited number of points in VA, and apply. VA will interpolate a continues curve by means of cubic spline interpolation algorithm. You can do it through the windows below.

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Send an e-mail to va@sillanumsoft.org for questions and/or suggestions about the web site. The webmaster is Alfredo Accattatis.
Last modified: 01-apr-2012

# THE ART OF ELECTRONICS

## Second Edition

Paul Horowitz HARVARD UNIVERSITY

Winfield Hill ROWLAND INSTITUTE FOR SCIENCE, CAMBRIDGE, MASSACHUSETTS

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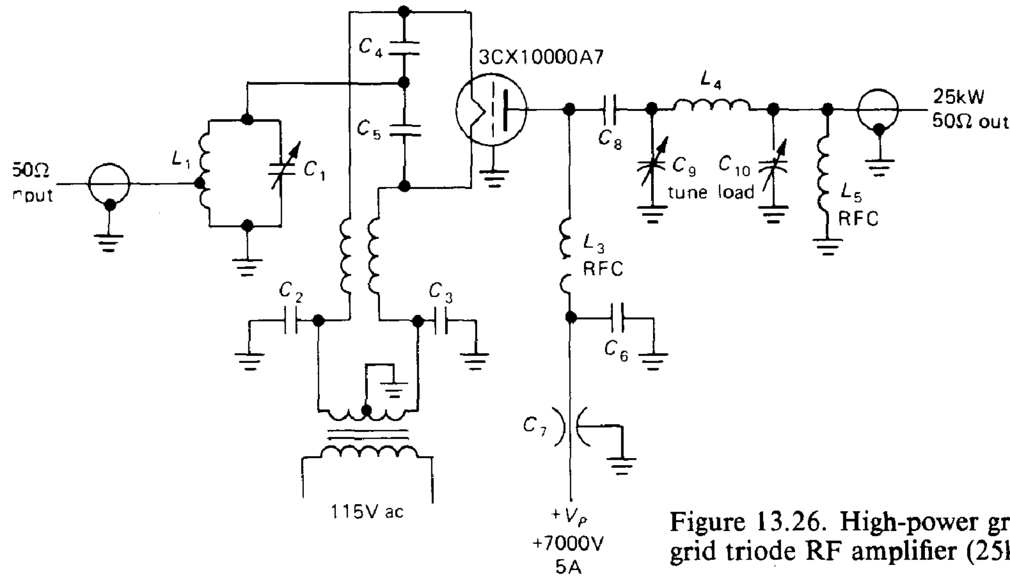


Figure 13.26. High-power grounded-grid triode RF amplifier (25kW output).

in the gigahertz range uses a dielectric "pill" resonator as the feedback element for a GaAs FET (or bipolar) oscillator. Oscillators using this "dielectrically stabilized" technique are simple and stable and have low noise.

For high stability, the best kind of oscillators use quartz crystals to set the operating frequency. With off-the-shelf garden-variety crystals, you can expect overall stabilities of a few parts per million, with tempco of order 1 ppm/degree or better. A temperature-compensated crystal oscillator (TCXO), which uses capacitors of controlled tempco to offset the crystal's frequency variation, can deliver frequency stability of 1 ppm over a temperature range of 0°C to 50°C or better. For the utmost in performance, oscillators with the crystal maintained in a constant-temperature "oven" are available, with stabilities of a few parts per billion over time and temperature. Even the so-called atomic oscillators (rubidium, cesium) actually use a high-stability quartz oscillator as the basic oscillating element, with frequency adjusted as necessary to agree with a particular atomic transition frequency.

Crystal oscillators are commercially available in frequencies ranging from about 10kHz to about 100MHz in all of the variations just mentioned. There are even little DIP and transistor can (TO-5) oscillators, with logic outputs. Only a slight electrical adjustment of frequency is possible, so the frequency must be specified when the oscillator or crystal is ordered.

To get both adjustability and high stability, a frequency synthesizer is the best choice. It uses tricks to generate any desired frequency from a single source of stable frequency, typically a 10MHz crystal oscillator. A synthesizer driven from a rubidium standard (stability of a few parts in $10^{12}$) makes a nice signal source.

#### *Mixers/modulators*

A circuit that forms the product of two analog waveforms is used in a variety of radiofrequency applications and is called, variously, a modulator, mixer, synchronous detector, or phase detector. The simplest form of modulation, as you will see shortly, is amplitude modulation (AM), in which the high-frequency *carrier* signal is varied in amplitude according to a slowly varying *modulating* signal. A multiplier obviously performs the right function. Such a circuit can also be used as a variable gain control, thinking of one of the inputs as a dc voltage. There are convenient ICs to do this job, e.g., the MC1495 and MC1496.

A mixer is a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies. From the trigonometric relationship

$$\cos\omega_1 t \cos\omega_2 t = \frac{1}{2}\cos(\omega_1+\omega_2)t + \frac{1}{2}\cos(\omega_1-\omega_2)t$$

it should be clear that a "four-quadrant multiplier," i.e., one that performs the product of two input signals of any polarity, is in fact a mixer. If you input two signals of frequency $f_1$ and $f_2$, you will get out signals at $f_1+f_2$ and $f_1-f_2$. A signal at frequency $f_0$ mixed with a band of signals near zero frequency (band-limited to a maximum frequency of $f_{\max}$) will produce a symmetrical band of frequencies around $f_0$, extending from $f_0-f_{\max}$ to $f_0+f_{\max}$ (the spectrum of amplitude modulation, see Section 13.15).

It is not necessary to form an accurate analog product in order to mix two signals. In fact, any nonlinear combination of the two signals will produce sum and difference frequencies. Take, for instance, a "square-law" nonlinearity applied to the sum of two signals:

$$(\cos\omega_1 t + \cos\omega_2 t)^2 = 1 + \frac{1}{2}\cos 2\omega_1 t + \frac{1}{2}\cos 2\omega_2 t + \cos(\omega_1+\omega_2)t + \cos(\omega_1-\omega_2)t$$

This is the sort of nonlinearity you would get (roughly) by applying two small signals to a forward-biased diode. Note that you get harmonics of the individual signals, as well as the sum and difference frequencies. The term "balanced mixer" is used to describe a circuit in which only the sum and difference signals, not the input signals and their harmonics, are passed through to the output. The four-quadrant multiplier is a balanced mixer, whereas the nonlinear diode is not.

Among the methods used to make mixers are the following: (a) simple nonlinear transistor or diode circuits, often using Schottky diodes; (b) dual-gate FETs, with one signal applied to each gate; (c) multiplier chips like the MC1495, MC1496, SL640, or AD630; (d) balanced mixers constructed from transformers and arrays of diodes, generally available as packaged "double-balanced mixers." The latter are typified by the popular M1 series of double-balanced mixers from Watkins-Johnson spanning the frequency range to 4000MHz with 20dB to 50dB of signal isolation, or the inexpensive SBL-1 mixer (1–500MHz) from Mini-Circuits Lab. Mixers are widely used in the generation of radiofrequency signals at arbitrary frequencies; they let you shift a signal up or down in frequency without changing its spectrum. You will see how it all works shortly.

The equations above show that the simple quadratic-law mixer produces outputs of equal amplitudes at both sum and difference frequencies. In communications applications (e.g., the "superheterodyne" receiver), where mixers are often used to shift frequency bands, it is sometimes desirable to suppress one of those mixer products. We'll see in Section 13.16 how to make such an *image-reject* mixer.

#### *Frequency multipliers*

A nonlinear circuit often is used to generate a signal at a multiple of the input signal's frequency. This is particularly handy if a signal of high stability is required at a very high frequency, above the range of good oscillators. One of the most common methods is to bias an amplifier stage for highly nonlinear operation, then use an *LC* output circuit tuned to some multiple of the input signal; this can be done with bipolar transistors, FETs, or even tunnel diodes. A multiplier like the 1496 can be used as an efficient doubler at low radiofrequencies by connecting the input

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SLOA060 - March 2001

# Sine-Wave Oscillator

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**ABSTRACT**

This note describes the operational amplifier (op-amp) sine-wave oscillator, together with the criteria for oscillation to occur using RC components. It delineates the roles of phase shift and gain in the circuit and then discusses considerations of the op amp. A brief analysis of a Wien-Bridge oscillator circuit is provided. Several examples of sine-wave oscillators are given, although it is recognized that there exist many additional types of oscillator to which the principles of this application note also apply.

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# 1 Introduction

Oscillators are circuits that produce specific, periodic waveforms such as square, triangular, sawtooth, and sinusoidal. They generally use some form of active device, lamp, or crystal, surrounded by passive devices such as resistors, capacitors, and inductors, to generate the output.

There are two main classes of oscillator: relaxation and sinusoidal. Relaxation oscillators generate the triangular, sawtooth and other nonsinuoidal waveforms and are not discussed in this note. Sinusoidal oscillators consist of amplifiers with external components used to generate oscillation, or crystals that internally generate the oscillation. The focus here is on sine wave oscillators, created using operational amplifiers op amps.

Sine wave oscillators are used as references or test waveforms by many circuits. A pure sine wave has only a single or fundamental frequency—ideally no harmonics are present. Thus, a sine wave may be the input to a device or circuit, with the output harmonics measured to determine the amount of distortion. The waveforms in relaxation oscillators are generated from sine waves that are summed to provide a specified shape.

# 2 Sine-Wave Oscillator Defined

Op-amp oscillators are circuits that are unstable—not the type that are sometimes unintentionally designed or created in the lab—but ones that are intentionally designed to remain in an unstable or oscillatory state. Oscillators are useful for generating uniform signals that are used as a reference in such applications as audio, function generators, digital systems, and communication systems.

Two general classes of oscillators exist: sinusoidal and relaxation. Sinusoidal oscillators consist of amplifiers with RC or LC circuits that have adjustable oscillation frequencies, or crystals that have a fixed oscillation frequency. Relaxation oscillators generate triangular, sawtooth, square, pulse, or exponential waveforms, and they are not discussed here.

Op-amp sine-wave oscillators operate without an externally-applied input signal. Instead, some combination of positive and negative feedback is used to drive the op amp into an unstable state, causing the output to cycle back and forth between the supply rails at a continuous rate. The frequency and amplitude of oscillation are set by the arrangement of passive and active components around a central op amp.

Op-amp oscillators are restricted to the lower end of the frequency spectrum because op amps do not have the required bandwidth to achieve low phase shift at high frequencies. Voltage-feedback op amps are limited to a low kHz range because their dominant, open-loop pole may be as low as 10 Hz. The new current-feedback op amps have a much wider bandwidth, but they are very hard to use in oscillator circuits because they are sensitive to feedback capacitance. Crystal oscillators are used in high-frequency applications up to the hundreds of MHz range.

# 3 Requirements for Oscillation

The canonical, or simplest, form of a negative feedback system is used to demonstrate the requirements for oscillation to occur. Figure 1 shows the block diagram for this system in which $V_{IN}$ is the input voltage, $V_{OUT}$ is the output voltage from the amplifier gain block (A), and $\beta$ is the signal, called the feedback factor, that is fed back to the summing junction. E represents the error term that is equal to the summation of the feedback factor and the input voltage.

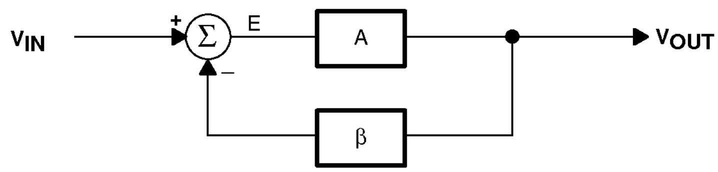



**Figure 1. Canonical Form of a Feedback System With Positive or Negative Feedback**

The corresponding classic expression for a feedback system is derived as follows. Equation 1 is the defining equation for the output voltage; equation 2 is the corresponding error:

$$V_{OUT} = E \times A \tag{1}$$

$$E = V_{IN} + \beta V_{OUT} \tag{2}$$

Eliminating the error term, E, from these equations gives

$$\frac{V_{OUT}}{A} = V_{IN} - \beta V_{OUT} \tag{3}$$

and collecting the terms in $V_{OUT}$ yields

$$V_{IN} = V_{OUT}\left(\frac{1}{A} + \beta\right) \tag{4}$$

Rearrangement of the terms produces equation 5, the classical form of feedback expression:

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \tag{5}$$

Oscillators do not require an externally-applied input signal; instead, they use some fraction of the output signal created by the feedback network as the input signal.

Oscillation results when the feedback system is not able to find a stable steady-state because its transfer function can not be satisfied. The system goes unstable when the denominator in equation 5 becomes zero, i.e., when $1 + A\beta = 0$, or $A\beta = -1$. The key to designing an oscillator is ensuring that $A\beta = -1$. This is called the *Barkhausen criterion*. Satisfying this criterion requires that the magnitude of the loop gain is unity with a corresponding phase shift of 180° as indicated by the minus sign. An equivalent expression using the symbology of complex algebra is $A\beta = 1\angle{-180°}$ for a negative feedback system. For a positive feedback system, the expression is $A\beta = 1\angle 0°$ and the sign of the $A\beta$ term is negative in equation 5.

As the phase shift approaches 180° and $|A\beta| \rightarrow 1$, the output voltage of the now-unstable system tends to infinity but, of course, is limited to finite values by an energy-limited power supply. When the output voltage approaches either power rail, the active devices in the amplifiers change gain. This causes the value of A to change and forces $A\beta$ away from the singularity; thus the trajectory towards an infinite voltage slows and eventually halts. At this stage, one of three things can occur: (i) Nonlinearity in saturation or cutoff causes the system to become stable and lock up at the current power rail. (ii) The initial change causes the system to saturate (or cutoff) and stay that way for a long time before it becomes linear and heads for the opposite power rail. (iii) The system stays linear and reverses direction, heading for the opposite power rail. The second alternative produces highly distorted oscillations (usually quasi-square waves), the resulting oscillators being called relaxation oscillators. The third produces a sine-wave oscillator.

# 4 Phase Shift in the Oscillator

The 180° phase shift in the equation $A\beta = 1\angle{-180°}$ is introduced by active and passive components. Like any well-designed feedback circuit, oscillators are made dependent on passive-component phase shift because it is accurate and almost drift-free. The phase shift contributed by active components is minimized because it varies with temperature, has a wide initial tolerance, and is device dependent. Amplifiers are selected so that they contribute little or no phase shift at the oscillation frequency. These constraints limit the op-amp oscillator to relatively low frequencies.

A single-pole RL or RC circuit contributes up to 90° phase shift per pole, and because 180° of phase shift is required for oscillation, at least two poles must be used in the oscillator design. An LC circuit has two poles, thus it contributes up to 180° phase shift per pole pair. But LC and LR oscillators are not considered here because low frequency inductors are expensive, heavy, bulky, and highly nonideal. LC oscillators are designed in high frequency applications, beyond the frequency range of voltage feedback op amps, where the inductor size, weight, and cost are less significant. Multiple RC sections are used in low frequency oscillator design in lieu of inductors.

Phase shift determines the oscillation frequency because the circuit oscillates at whatever frequency accumulates a 180° phase shift. The sensitivity of phase to frequency, $d\phi/d\omega$, determines the frequency stability. When buffered RC sections (an op amp buffer provides high input and low output impedance) are cascaded, the phase shift multiplies by the number of sections, *n* (see Figure 2).

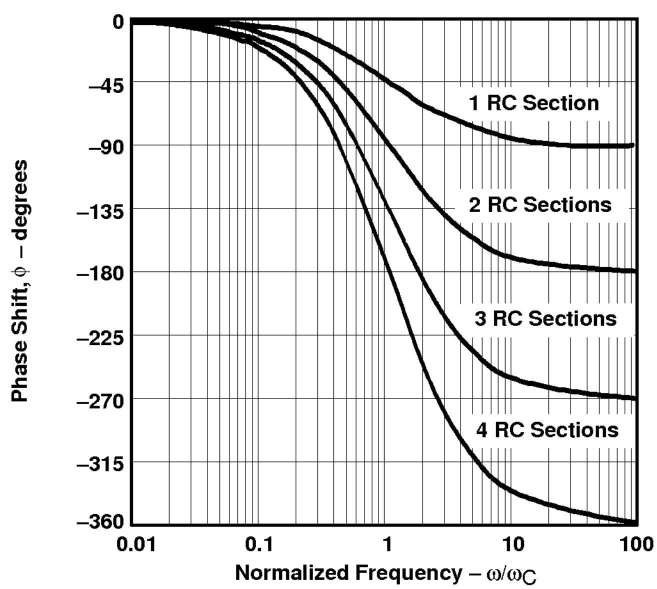



**Figure 2. Phase Plot of RC Sections**

In the region where the phase shift is 180°, the frequency of oscillation is very sensitive to the phase shift. Thus, a tight frequency specification requires that the phase shift, $d\phi$, be kept within exceedingly narrow limits for there to be only small variations in frequency, $d\omega$, at 180°. Figure 2 demonstrates that, although two cascaded RC sections eventually provide 180° phase shift, the value of $d\phi/d\omega$ at the oscillator frequency is unacceptably small. Thus, oscillators made with two cascaded RC sections have poor frequency stability. Three equal cascaded RC filter sections have a much higher dφ/dω (see Figure 2), and the resulting oscillator has improved frequency stability. Adding a fourth RC section produces an oscillator with an excellent dφ/dω (see Figure 2); thus, this is the most stable RC oscillator configuration. Four sections are the maximum number used because op amps come in quad packages, and the four-section oscillator yields four sine waves 45° phase shifted relative to each other. This oscillator can be used to obtain sine/cosine or quadrature sine waves.

Crystal or ceramic resonators make the most stable oscillators because resonators have an extremely high dφ/dω as a result of their nonlinear properties. Resonators are used for high-frequency oscillators, but low-frequency oscillators do not use resonators because of size, weight, and cost restrictions. Op amps are not generally used with crystal or ceramic resonator oscillators because op amps have low bandwidth. Experience shows that rather than using a low-frequency resonator for low frequencies, it is more cost effective to build a high frequency crystal oscillator, count the output down, and then filter the output to obtain the low frequency.

## 5 Gain in the Oscillator

The oscillator gain must be unity ($A\beta = 1\angle{-180°}$) at the oscillation frequency. Under normal conditions, the circuit becomes stable when the gain exceeds unity, and oscillations cease. However, when the gain exceeds unity with a phase shift of –180°, the nonlinearity of the active device reduces the gain to unity and the circuit oscillates. The nonlinearity becomes significant when the amplifier swings close to either power rail because cutoff or saturation reduces the active device (transistor) gain. The paradox is that worst-case design practice requires nominal gains exceeding unity for manufacturability, but excess gain causes increased distortion of the output sine wave.

When the gain is too low, oscillations cease under worst case conditions, and when the gain is too high, the output wave form looks more like a square wave than a sine wave. Distortion is a direct result of excessive gain overdriving the amplifier; thus, gain must be carefully controlled in low-distortion oscillators. Phase-shift oscillators have distortion, but they achieve low-distortion output voltages because cascaded RC sections act as distortion filters. Also, buffered phase-shift oscillators have low distortion because the gain is controlled and distributed among the buffers.

Most circuit configurations require an auxiliary circuit for gain adjustment when low-distortion outputs are desired. Auxiliary circuits range from inserting a nonlinear component in the feedback loop, to automatic gain control (AGC) loops, to limiting by external components such as resistors and diodes. Consideration must also be given to the change in gain resulting from temperature variations and component tolerances, and the level of circuit complexity is determined based on the required stability of the gain. The more stable the gain, the better the purity of the sine wave output.

# 6 Effect of the Active Element (Op Amp) on the Oscillator

Until now, it has been assumed that the op amp has infinite bandwidth and the output is frequency independent. In reality, the op amp has many poles, but it has been compensated so that they are dominated by a single pole over the specified bandwidth. Thus, $A\beta$ must now be considered frequency dependent via the op-amp gain term, A. Equation 6 shows this dependence, where *a* is the maximum open loop gain, $\omega_a$ is the dominant pole frequency, and $\omega$ is the frequency of the signal. Figure 3 depicts the frequency dependence of the op-amp gain and phase. The closed-loop gain, $A_{CL} = 1/\beta$, does not contain any poles or zeros and is, therefore, constant with frequency to the point where it affects the op-amp open-loop gain at $\omega_{3dB}$. Here, the signal amplitude is attenuated by 3 dB and the phase shift introduced by the op amp is 45°. The amplitude and phase really begin to change one decade below this point, at $0.1 \times \omega_{3dB}$, and the phase continues to shift until it reaches 90° at 10 $\omega_{dB}$, one decade beyond the 3-dB point. The gain continues to roll off at –20 dB/decade until other poles and zeros come into play. The higher the closed-loop gain, $A_{CL}$, the earlier it intercepts the op-amp gain.

$$A = \frac{a}{1 + j\frac{\omega}{\omega_a}} \qquad (6)$$

The phase shift contributed by the op amp affects the performance of the oscillator circuit by lowering the oscillation frequency, and the reduction in $A_{CL}$ can make $A\beta < 1$ and the oscillator then ceases to oscillate.

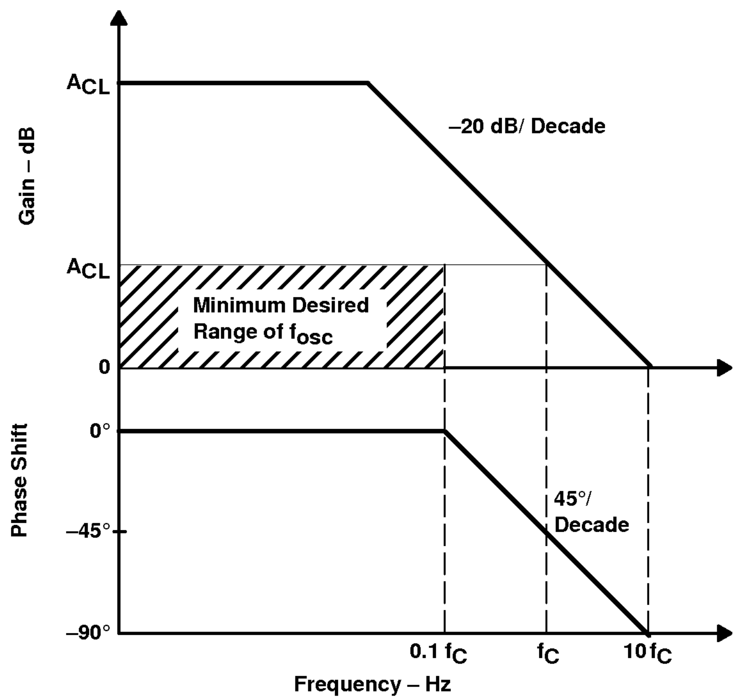



**Figure 3. Op-Amp Frequency Response**

Most op amps are compensated and may have more than the 45° of phase shift at the $\omega_{3dB}$ point. Therefore, the op amp should be chosen with a gain bandwidth at least one decade above the oscillation frequency, as shown by the shaded area of Figure 3. The Wien bridge requires a gain bandwidth greater than 43 $\omega_{OSC}$ to maintain the gain and frequency within 10% of the ideal values [2]. Figure 4 compares the output distortion vs frequency curves of an LM328, a TLV247x, and a TLC071 op amp, which have bandwidths of 0.4 MHz, 2.8 MHz, and 10 MHz, respectively, in a Wein bridge oscillator circuit with nonlinear feedback (see section 7.1 for the circuit and transfer function). The oscillation frequency ranges from 16 Hz to 160 kHz. The graph illustrates the importance of choosing the correct op amp for the application. The LM328 achieves a maximum oscillation of 72 kHz and is attenuated more than 75%, while the TLV247x achieves 125 kHz with 18% attenuation. The wide bandwidth of the TLC071 provides a 138 kHz oscillation frequency with a mere 2% attenuation. The op amp must be chosen with the correct bandwidth or else the output will oscillate at a frequency well below the design specification.

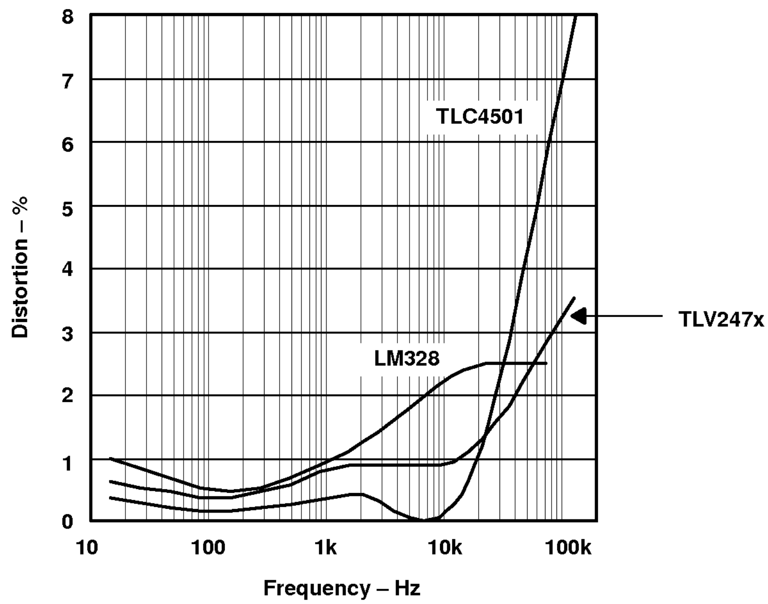



**Figure 4. Distortion vs Oscillation Frequency for Various Op-Amp Bandwidths**

Care must be taken when using large feedback resistors because they interact with the input capacitance of the op amp to create poles with negative feedback, and both poles and zeros with positive feedback. Large resistor values can move these poles and zeros into the neighborhood of the oscillation frequency and affect the phase shift [3].

Final consideration is given to the op amp's slew-rate limitation. The slew rate must be greater than $2\pi V_P f_0$, where $V_P$ is the peak output voltage and $f_0$ is the oscillation frequency; otherwise, distortion of the output signal results.

## 7 Analysis of Oscillator Operation (Circuit)

Oscillators are created using various combinations of positive and negative feedback. Figure 5a shows the basic negative feedback amplifier block diagram with a positive feedback loop added. When positive and negative feedback are used, the gain of the negative feedback path is combined into a single gain term (representing closed-loop gain). Figure 5a reduces to Figure 5b, the positive feedback network is then represented by $\beta = \beta_2$, and subsequent analysis is simplified. When negative feedback is used, the positive-feedback loop can be ignored because $\beta_2$ is zero.

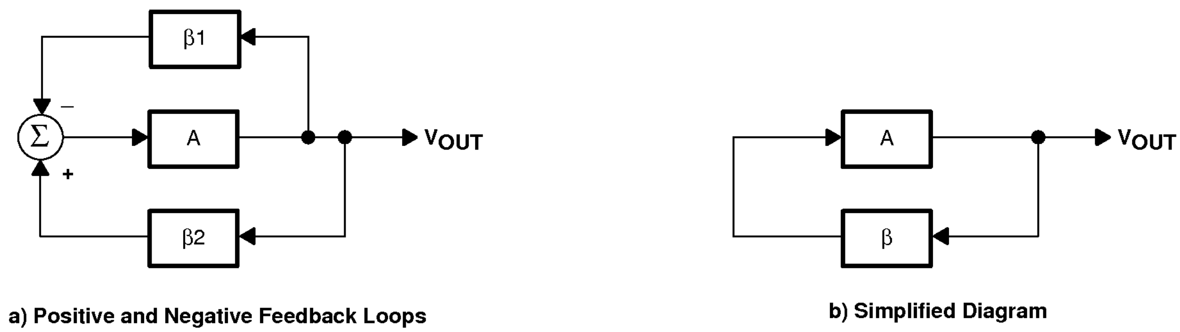



**Figure 5. Block Diagram of an Oscillator**

The general form of an op amp with positive and negative feedback is shown in Figure 6 (a). The first step in analysis is to break the loop at some point without altering the gain of the circuit. The positive feedback loop is broken at the point marked with an X. A test signal ($V_{TEST}$) is applied to the broken loop and the resulting output voltage ($V_{OUT}$) is measured with the equivalent circuit shown in Figure 6 (b).

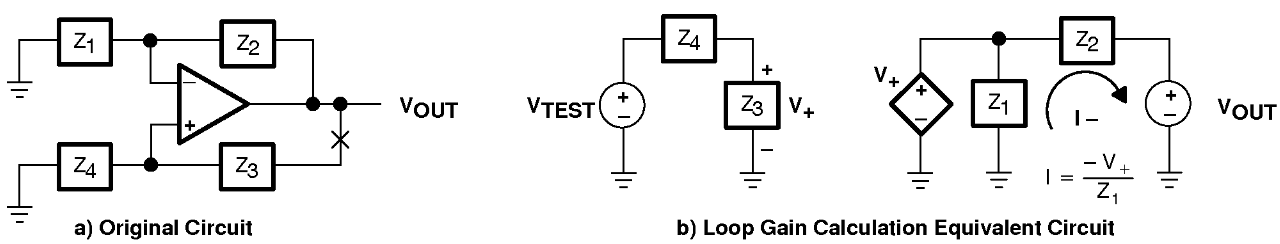



**Figure 6. Amplifier With Positive and Negative Feedback**

First, $V_+$ is calculated using equation 7; then it is treated as an input signal to a noninverting amplifier, resulting in equation 8. Substituting equation 7 for $V_+$ in equation 8 gives the transfer function in equation 9. The actual circuit elements are then substituted for each impedance and the equation is simplified. These equations are valid when the op-amp open-loop gain is large and the oscillation frequency is less than 0.1 $\omega_{3dB}$.

$$V_+ = V_{TEST}\left(\frac{Z_3}{Z_3 + Z_4}\right) \tag{7}$$

$$V_{OUT} = V_+\left(\frac{Z_1 + Z_2}{Z_1}\right) \tag{8}$$

$$\frac{V_{OUT}}{V_{TEST}} = \left(\frac{Z_3}{Z_3 + Z_4}\right)\left(\frac{Z_1 + Z_2}{Z_1}\right) \tag{9}$$

Phase-shift oscillators generally use negative feedback, so the positive feedback factor ($\beta_2$) becomes zero. Oscillator circuits such as the Wien bridge use both negative ($\beta_1$) and positive ($\beta_2$) feedback to achieve a constant state of oscillation. Equation 9 is used to analyze this circuit in detail in section 8.1.

# 8 Sine Wave Oscillator Circuits

There are many types of sine wave oscillator circuits and variants—in an application, the choice depends on the frequency and the desired monotonicity of the output waveform. The focus of this section is on the more prominent oscillator circuits: Wien bridge, phase shift, and quadrature. The transfer function is derived for each case using the techniques described in section 6 of this note and in references 4, 5, and 6.

## 8.1 Wein Bridge Oscillator

The Wien bridge is one of the simplest and best known oscillators and is used extensively in circuits for audio applications. Figure 7 shows the basic Wien bridge circuit configuration. On the positive side, this circuit has only a few components and good frequency stability. The major drawback of the circuit is that the output amplitude is at the rails, which saturates the op-amp output transistors and causes high output distortion. Taming this distortion is more challenging than getting the circuit to oscillate. There are a couple of ways to minimize this effect. These will be covered later; first the circuit is analyzed to obtain the transfer function.

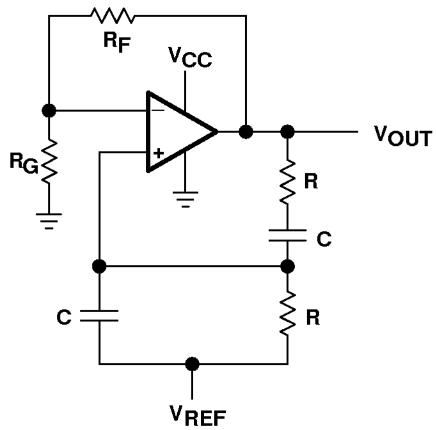



**Figure 7. Wein-Bridge Circuit Schematic**

The Wien bridge circuit has the form already detailed in section 6, and the transfer function for the circuit is derived using the technique described there. It is readily apparent that $Z_1 = R_G$, $Z_2 = R_F$, $Z_3 = (R_1 + 1/sC_1)$ and $Z_4 = (R_2 \| 1/sC_2)$. The loop is broken between the output and $Z_1$, $V_{TEST}$ is applied to $Z_1$, and $V_{OUT}$ is calculated. The positive feedback voltage, $V_+$, is calculated first in equations 10 through 12. Equation 10 shows the simple voltage divider at the noninverting input. Each term is then multiplied by $(R_2C_2s + 1)$ and divided by $R_2$ to get equation 11.

$$V_+ = V_{TEST}\left(\frac{Z_2}{Z_3 + Z_4}\right) = V_{TEST}\left[\frac{\left(\frac{R_2}{R_2C_2s+1}\right)}{\left(\frac{R_2}{R_2C_2s+1}\right) + \left(R_1 + \frac{1}{C_1s}\right)}\right] \qquad (10)$$

$$\frac{V_+}{V_{TEST}} = \frac{1}{1 + R_1C_2s + \frac{R_1}{R_2} + \frac{1}{R_2C_1s} + \frac{C_2}{C_1}} \qquad (11)$$

Substituting $s = j\omega_0$, where $\omega_0$ is the oscillation frequency, $\omega_1 = 1/R_1C_2$, and $\omega_2 = 1/R_2C_1$, gives equation 12.

$$\frac{V_+}{V_{TEST}} = \frac{1}{1 + \frac{R_1}{R_2} + \frac{C_2}{C_1} + j\left(\frac{\omega_0}{\omega_1} - \frac{\omega_2}{\omega_0}\right)} \qquad (12)$$

Some interesting relationships now become apparent. The capacitor at the zero, represented by $\omega_1$, and the capacitor at the pole, represented by $\omega_2$, must each contribute 90° of phase shift toward the 180° required for oscillation at $\omega_0$. This requires that $C_1 = C_2$ and $R_1 = R_2$. Setting $\omega_1$ and $\omega_2$ equal to $\omega_0$ cancels the frequency terms, ideally removing any change in amplitude with frequency because the pole and zero negate one another. This results in an overall feedback factor of $\beta = 1/3$ (equation 13).

$$\frac{V_+}{V_{TEST}} = \frac{1}{1 + \frac{R}{R} + \frac{C}{C} + j\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)} = \frac{1}{3 + j\left(\frac{\omega_0}{\omega_0} - \frac{\omega_0}{\omega_0}\right)} = \frac{1}{3} \qquad (13)$$

The gain, A, of the negative feedback portion of the circuit must then be set such that $|A\beta| = 1$, requiring A = 3. $R_F$ must be set to twice the value of $R_G$ to satisfy this condition. The op amp in Figure 7 is single supply, so a dc reference voltage, $V_{REF}$, must be applied to bias the output for full-scale swing and minimal distortion. Applying $V_{REF}$ to the positive input through $R_2$ restricts dc current flow to the negative feedback leg of the circuit. $V_{REF}$ was set at 0.833V to bias the output at the midrail of the single supply, rail-to-rail input and output amplifier, or 2.5 V. (see reference [7]. $V_{REF}$ is shorted to ground for split supply applications.

The final circuit is shown in Figure 8, with component values selected to provide an oscillation frequency of $\omega_0 = 2\pi f_0$, where $f_0 = 1/(2\pi RC) = 1.59$ kHz. The circuit oscillated at 1.57 kHz, caused by varying component values with 2.8% distortion. This high value results from the extensive clipping of the output signal at both supply rails, producing several large odd and even harmonics. The feedback resistor was then adjusted ±1%. Figure 9 shows the output voltage waveforms. The distortion grew as the saturation increased with increasing $R_F$, and oscillations ceased when $R_F$ was decreased by a mere 0.8%.

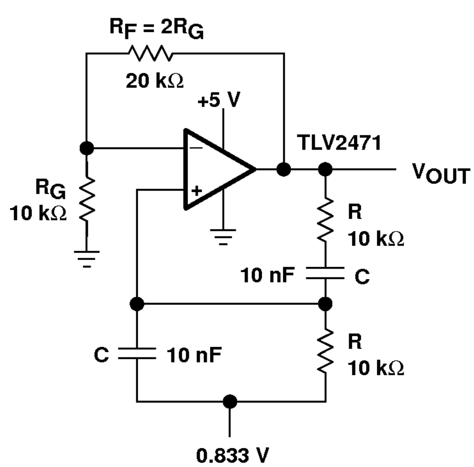



**Figure 8. Final Wein-Bridge Oscillator Circuit**

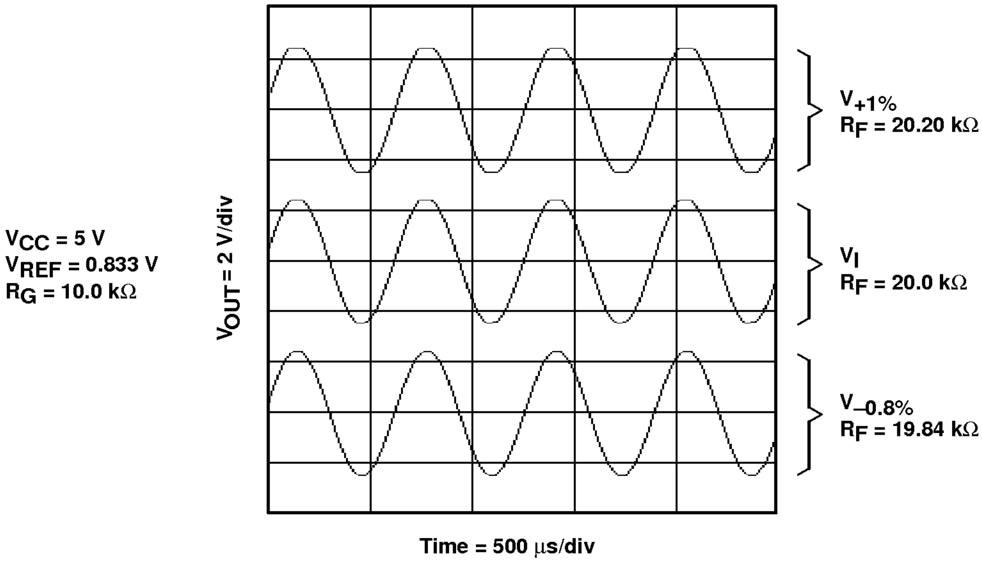



**Figure 9. Wein-Bridge Output Waveforms: Effects of $R_F$ on Distortion**

Applying nonlinear feedback can minimize the distortion inherent in the basic Wien bridge circuit. A nonlinear component such as an incandescent lamp can be substituted into the circuit for $R_G$ as shown in Figure 10. The lamp resistance, $R_{LAMP}$, is nominally selected at one half the feedback resistance, $R_F$, at the lamp current established by $R_F$ and $R_{LAMP}$. When the power is first applied the lamp is cool and its resistance is small, so the gain is large (> 3). The current heats up the filament and the resistance increases, lowering the gain. The nonlinear relationship between the lamp current and resistance keeps output voltage changes small—a small change in voltage means a large change in resistance. Figure 11 shows the output of this amplifier with a distortion of less than 0.1% for $f_{OSC}$ = 1.57 kHz. The distortion for this variation is greatly reduced over the basic circuit by avoiding hard saturation of the op amp transistors.

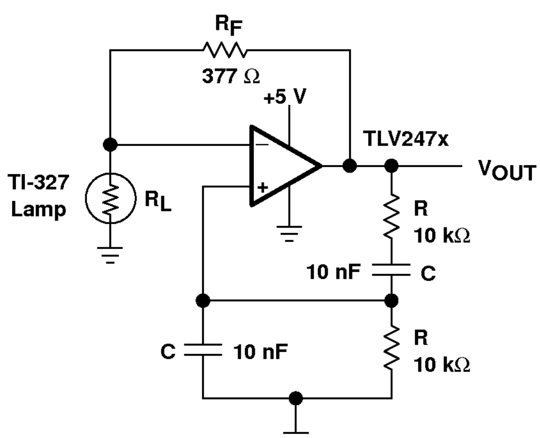



**Figure 10. Wein-Bridge Oscillator With Nonlinear Feedback**

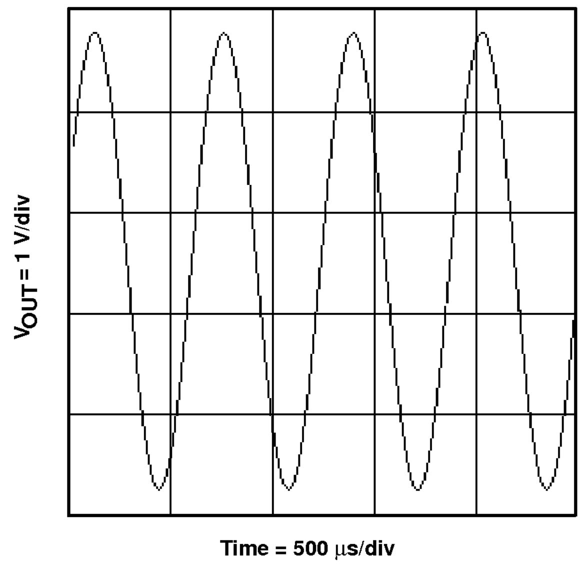



**Figure 11. Output of the CIrcuit in Figure 10**

The impedance of the lamp is mostly caused by thermal effects. The output amplitude is very temperature sensitive and tends to drift. The gain must then be set higher than 3 to compensate for any temperature variations, and this increases the distortion in the circuit [4]. This type of circuit is useful when the temperature does not fluctuate over a wide range or when used in conjunction with an amplitude-limiting circuit.

The lamp has an effective low-frequency thermal time constant, $t_{thermal}$ [5]. As $f_{OSC}$ approaches $t_{thermal}$, distortion greatly increases. Several lamps can be placed in series to increase $t_{thermal}$ and reduce distortion. The drawbacks are that the time required for oscillations to stabilize increases and the output amplitude reduces.

An automatic gain-control (AGC) circuit must be used when neither of the two previous circuits yields low enough distortion. A typical Wien bridge oscillator with an AGC circuit is shown in Figure 12; Figure 13 shows the output waveform of the circuit. The AGC is used to stabilize the magnitude of the sinusoidal output to an optimum gain level. The JFET serves as the AGC element, providing excellent control because of the wide range of the drain-to-source resistance, which is controlled by the gate voltage. The JFET gate voltage is zero when the power is applied, and thus turns on with a low drain-to-source resistance ($R_{DS}$). This places $R_{G2}$+$R_S$+$R_{DS}$ in parallel with $R_{G1}$, raising the gain to 3.05, and oscillations begin, gradually building up. As the output voltage grows, the negative swing turns the diode on and the sample is stored on $C_1$, providing a dc potential to the gate of $Q_1$. Resistor $R_1$ limits the current and establishes the time constant for charging $C_1$ (which should be much greater than $f_{OSC}$). When the output voltage drifts high, $R_{DS}$ increases, lowering the gain to a minimum of 2.87 ($1+R_F/R_{G1}$). The output stabilizes when the gain reaches 3. The distortion of the AGC is less than 0.2%.

The circuit of Figure 12 is biased with $V_{REF}$ for a single-supply amplifier. A zener diode can be placed in series with D1 to limit the positive swing of the output and reduce distortion. A split supply can be easily implemented by grounding all points connected to $V_{REF}$. There is a wide variety of Wien bridge variants to control the amplitude more precisely and allow selectable or even variable oscillation frequencies. Some circuits use diode limiting in place of a nonlinear feedback component. Diodes reduce distortion by providing a soft limit for the output voltage.

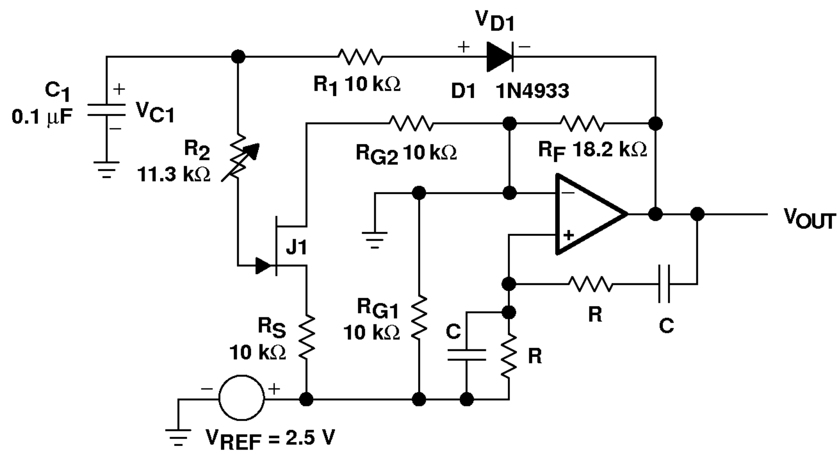



Figure 12. Wein-Bridge Oscillator With AGC

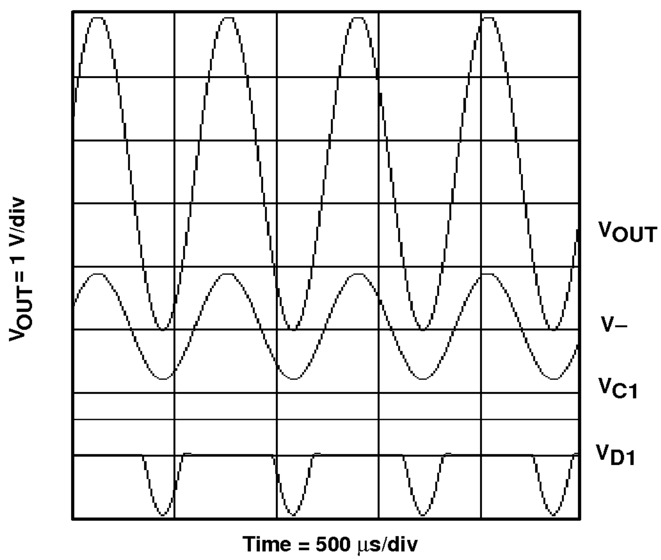



Figure 13. Output of the Circuit in Figure 12

## 8.2 Phase-Shift Oscillator, Single Amplifier

Phase-shift oscillators have less distortion than the Wien bridge oscillator, coupled with good frequency stability. A phase-shift oscillator can be built with one op amp as shown in Figure 14. Three RC sections are cascaded to get the steep slope, $d\phi/d\omega$, required for a stable oscillation frequency, as described in section 3. Fewer RC sections results in high oscillation frequency and interference with the op-amp BW limitations.

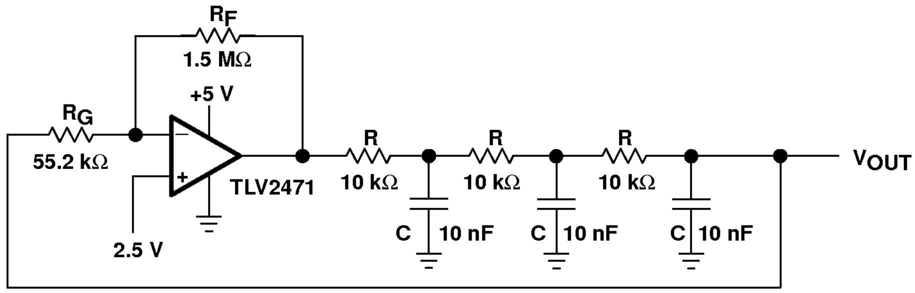



**Figure 14. Phase-Shift Oscillator (Single Op Amp)**

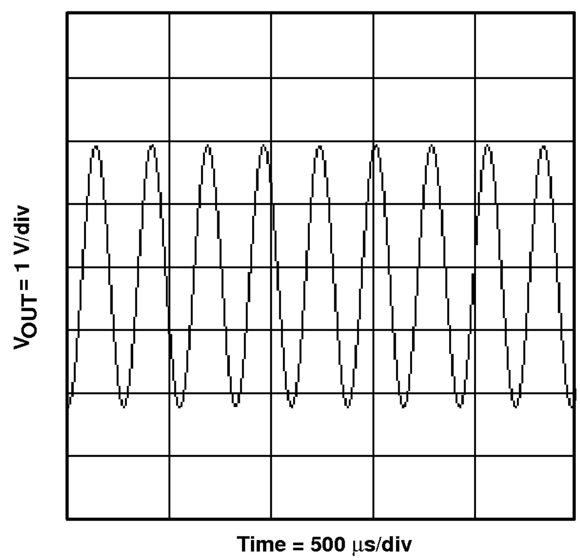



**Figure 15. Output of the Circuit in Figure 14**

The usual assumption is that the phase shift sections are independent of each other, allowing equation 14 to be written. The loop phase shift is –180° when the phase shift of each section is –60°. This occurs when $\omega = 2\pi f = 1.732/RC$ (tan 60° = 1.732…). The magnitude of β at this point is $(1/2)^3$, so the gain, A, must be 8 for the system gain of unity.

$$A\beta = A\left(\frac{1}{RCs + 1}\right)^3 \tag{14}$$

The oscillation frequency with the component values shown in Figure 14 is 3.76 kHz rather than the calculated oscillation frequency of 2.76 kHz. Also, the gain required to start oscillation is 27 rather than the calculated gain of 8. These discrepancies are partially due to component variations, however, the biggest factor is the incorrect assumption that the RC sections do not load each other. This circuit configuration was very popular when active components were large and expensive. But now op amps are inexpensive, small, and come four-to-a-package, so the single-op-amp phase-shift oscillator is losing popularity. The output distortion is a low 0.46%, considerably less than the Wien bridge circuit without amplitude stabilization.

## 8.3 Phase-Shift Oscillator, Buffered

The buffered phase-shift oscillator is much improved over the unbuffered version, the penalty being a higher component count. Figures 16 and 17 show the buffered phase-shift oscillator and the resulting output waveform, respectively. The buffers prevent the RC sections from loading each other, hence the buffered phase-shift oscillator performs more nearly at the calculated frequency and gain. The gain-setting resistor, $R_G$, loads the third RC section. If the fourth buffer in a quad op amp buffers this RC section, the performance becomes ideal. Low-distortion sine waves can be obtained from either phase-shift oscillator design, but the purest sine wave is taken from the output of the last RC section. This is a high-impedance node, so a high impedance input is mandated to prevent loading and frequency shifting with load variations.

The circuit oscillated at 2.9 kHz compared to an ideal frequency of 2.76 kHz, and it oscillated with a gain of 8.33 compared to an ideal gain of 8. The distortion was 1.2%, considerably more than the unbuffered phase-shift oscillator. The discrepancies and higher distortion are due to the large feedback resistor, $R_F$, which created a pole with $C_{IN}$ of approximately 5 kHz. Resistor $R_G$ still loaded down the lost RC section. Adding a buffer between the last RC section and $V_{OUT}$ lowered the gain and the oscillation frequency to the calculated values.

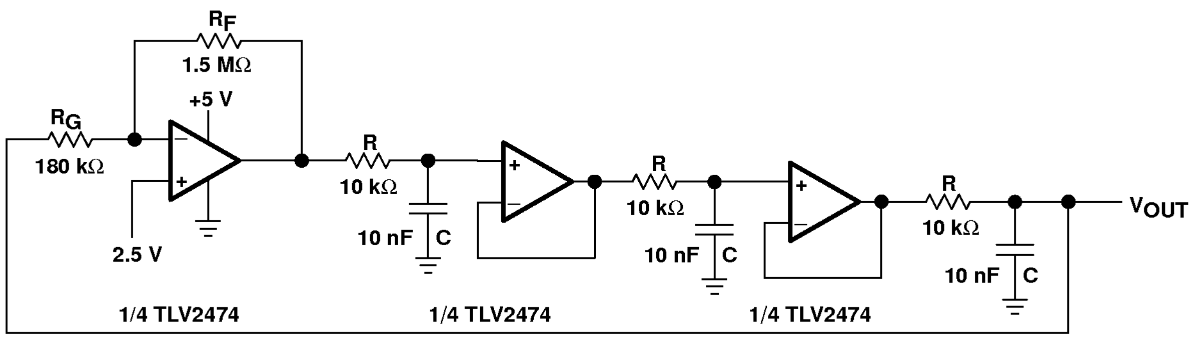



**Figure 16. Phase-Shift Oscillator, Buffered**

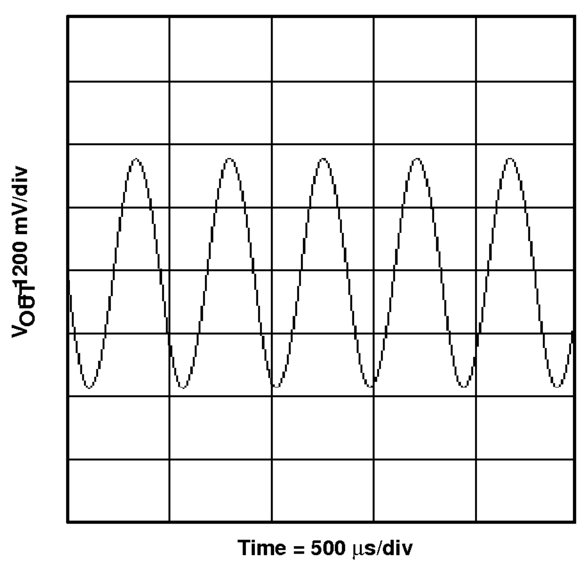



**Figure 17. Output of the Circuit Figure 16**

## 8.4 Bubba Oscillator

The bubba oscillator in Figure 18 is another phase-shift oscillator, but it takes advantage of the quad op-amp package to yield some unique advantages. Four RC sections require 45° phase shift per section, so this oscillator has an excellent d$\phi$/dt resulting in minimal frequency drift. The RC sections each contribute 45° phase shift, so taking outputs from alternate sections yields low-impedance quadrature outputs. When an output is taken from each op amp, the circuit delivers four 45° phase-shifted sine waves. The loop equation is given in equation 15. When $\omega = 1/RCs$, equation 15 reduces to equations 16 and 17.

$$A\beta = A\left(\frac{1}{RCs + 1}\right)^4 \tag{15}$$

$$|\beta| = \left|\left(\frac{1}{j + 4}\right)^4 = \frac{1}{\sqrt{2}^4} = \frac{1}{4}\right| \tag{16}$$

$$\phi = \tan^{-1}(1) = 45° \tag{17}$$

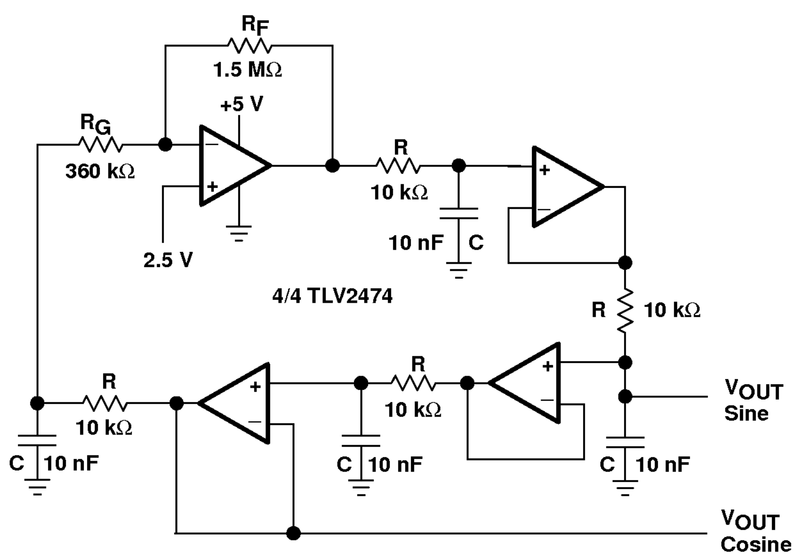



Figure 18. Bubba Oscillator

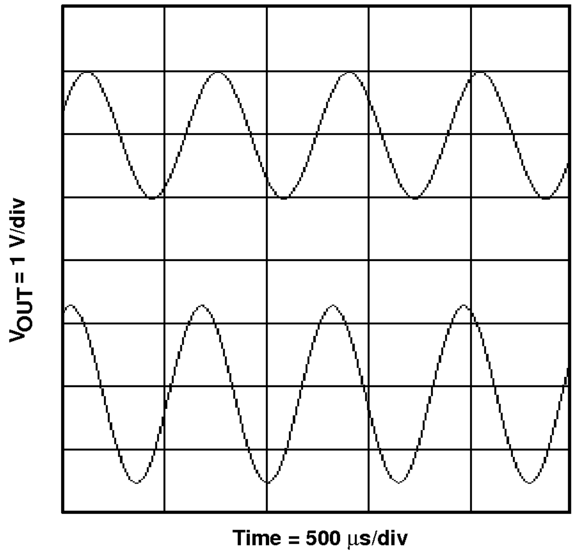



**Figure 19. Output of the Circuit in Figure 18**

The gain, A, must equal 4 for oscillation to occur. The test circuit oscillated at 1.76 kHz rather than the ideal frequency of 1.72 kHz when the gain was 4.17 rather than the ideal gain of 4. The output waveform is shown in Figure 19. Distortion was 1.1% for $V_{OUTSINE}$ and 0.1% for $V_{OUTCOSINE}$. With low gain, A, and using low bias-current op amps, the gain-setting resistor, $R_G$, did not load the last RC section, thus ensuring oscillator frequency accuracy. Very low distortion sine waves can be obtained from the junction of R and $R_G$. When low-distortion sine waves are required at all outputs, the gain should be distributed among all the op amps. The noninverting input of the gain op amp is biased at 0.5 V to set the quiescent output voltage at 2.5 V for single-supply operation, and it should be ground for split-supply op amps. Gain distribution requires biasing of the other op amps, but it has no effect on the oscillator frequency.

## 8.5 Quadrature Oscillator

The quadrature oscillator shown in Figure 20 is another type of phase-shift oscillator, but the three RC sections are configured so each section contributes 90° of phase shift. This provides both sine and cosine waveform outputs (the outputs are *quadrature*, or 90° apart), which is a distinct advantage over other phase-shift oscillators. The idea of the quadrature oscillator is to use the fact that the double integral of a sine wave is a negative sine wave of the same frequency and phase, in other words, the original sine wave 180° phase shifted. The phase of the second integrator is then inverted and applied as positive feedback to induce oscillation [6].

The loop gain is calculated from equation 18. When $R_1C_1 = R_2C_2 = R_3C_3$, equation 18 reduces to equation 19. When $\omega = 1/RC$, equation 18 reduces to $1\angle{-180}$, so oscillation occurs at $\omega = 2\pi f = 1/RC$. The test circuit oscillated at 1.65 kHz rather than the calculated 1.59 kHz, as shown in Figure 21. This discrepancy is attributed to component variations. Both outputs have relatively high distortion that can be reduced with a gain-stabilizing circuit. The sine output had 0.846% distortion and the cosine output had 0.46% distortion. Adjusting the gain can increase the amplitudes. The penalty is reduced bandwidth.

$$A\beta = A\left(\frac{1}{R_1C_1s}\right)\left[\frac{R_3C_3s + 1}{R_3C_3s\left(R_2C_2s + 1\right)}\right] \tag{18}$$

$$A\beta = A\left(\frac{1}{RCs}\right)^2 \tag{19}$$

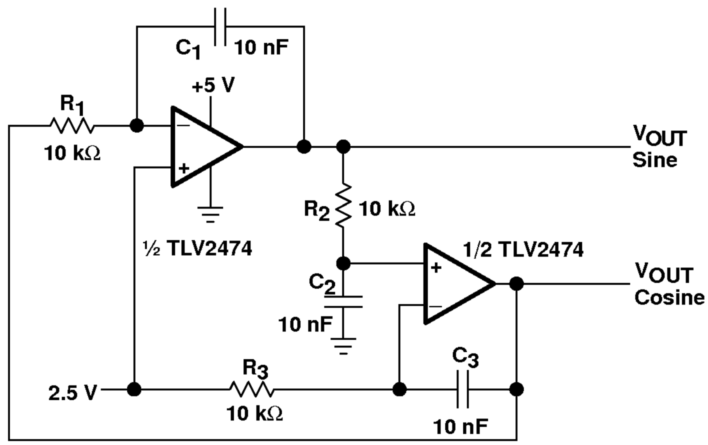



**Figure 20. Quadrature Oscillator**

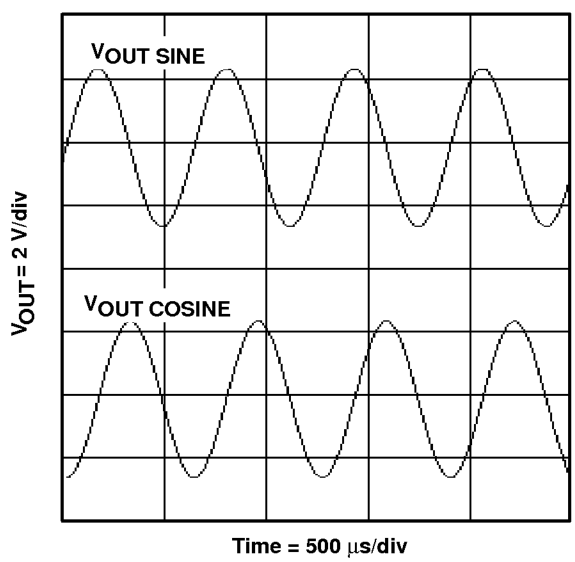



**Figure 21. Output of the Circuit in Figure 20**

# 9 Conclusion

Op-amp oscillators are restricted to the lower end of the frequency spectrum because they do not have the required bandwidth to achieve low phase shift at high frequencies. The new current-feedback op amps have a much greater bandwidth than their voltage-feedback counterparts, but thay are very difficult to use in oscillator circuits because of their sensitivity to feedback capacitance. Voltage-feedback op amps are limited to a few hundred kHz (at the most) because of their low frequency rolloff. The bandwidth is reduced when op amps are cascaded due to the multiple contribution of phase shift.

The Wien-bridge oscillator has few parts and good frequency stability, but the basic circuit has high output distortion. AGC improves the distortion considerably, particularly in the lower frequency range. Nonlinear feedback offers the best performance over the mid- and upper-frequency ranges. The phase-shift oscillator has high output distortion and, without buffering, requires a high gain, which limits its use to very low frequencies. The decreasing cost of op amps and components has reduced the popularity of phase-shift oscillators. The quadrature oscillator only requires two op amps, has reasonable distortion, and offers both sine and cosine waveforms. The drawback is the low amplitude, which can be increased using an additional gain stage, but with the penalty of greatly reduced bandwidth.

# 10 References


1. Graeme, Jerald, *Optimizing Op Amp Performance*, McGraw Hill Book Company, 1997.
2. Gottlieb, Irving M., *Practical Oscillator Handbook*, Newnes, 1997.
3. Kennedy, E. J., *Operational Amplifier Circuits, Theory and Applications,* Holt Rhienhart and Winston, 1988.
4. Philbrick Researches, Inc., *Applications Manual for Computing Amplifiers*, Nimrod Press, Inc., 1966.
5. Graf, Rudolf F., *Oscillator Circuits*, Newnes, 1997.
6. Graeme, Jerald, *Applications of Operational Amplifiers, Third Generation Techniques*, McGraw Hill Book Company, 1973.
7. *Single Supply Op Amp Design Techniques*, Application Note, Texas Instruments Literature Number SLOA030.

## IMPORTANT NOTICE



Mailing Address:

Texas Instruments
Post Office Box 655303
Dallas, Texas 75265

# LM13700 Dual Operational Transconductance Amplifiers with Linearizing Diodes and Buffers

**Check for Samples: LM13700**

## FEATURES

- **$g_m$ Adjustable over 6 Decades**
- **Excellent $g_m$ Linearity**
- **Excellent Matching between Amplifiers**
- **Linearizing Diodes**
- **High Impedance Buffers**
- **High Output Signal-to-Noise Ratio**

## APPLICATIONS

- **Current-Controlled Amplifiers**
- **Current-Controlled Impedances**
- **Current-Controlled Filters**
- **Current-Controlled Oscillators**
- **Multiplexers**
- **Timers**
- **Sample-and-Hold circuits**

## DESCRIPTION

The LM13700 series consists of two current controlled transconductance amplifiers, each with differential inputs and a push-pull output. The two amplifiers share common supplies but otherwise operate independently. Linearizing diodes are provided at the inputs to reduce distortion and allow higher input levels. The result is a 10 dB signal-to-noise improvement referenced to 0.5 percent THD. High impedance buffers are provided which are especially designed to complement the dynamic range of the amplifiers. The output buffers of the LM13700 differ from those of the LM13600 in that their input bias currents (and hence their output DC levels) are independent of $I_{ABC}$. This may result in performance superior to that of the LM13600 in audio applications.

## Connection Diagram

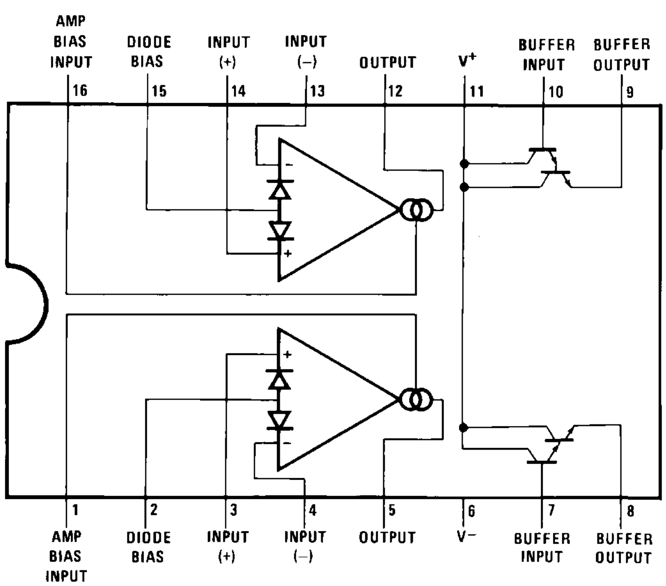



**Figure 1. PDIP and SOIC Packages-Top View**
**See Package Number D0016A or NFG0016E**

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

## Absolute Maximum Ratings [1]

| | |
|---|---|
| Supply Voltage | |
| LM13700 | 36 $V_{DC}$ or ±18V |
| Power Dissipation [2] $T_A$ = 25°C | |
| LM13700N | 570 mW |
| Differential Input Voltage | ±5V |
| Diode Bias Current ($I_D$) | 2 mA |
| Amplifier Bias Current ($I_{ABC}$) | 2 mA |
| Output Short Circuit Duration | Continuous |
| Buffer Output Current [3] | 20 mA |
| Operating Temperature Range | |
| LM13700N | 0°C to +70°C |
| DC Input Voltage | $+V_S$ to $-V_S$ |
| Storage Temperature Range | −65°C to +150°C |
| Soldering Information | |
| PDIP Package | |
| Soldering (10 sec.) | 260°C |
| SOIC Package | |
| Vapor Phase (60 sec.) | 215°C |
| Infrared (15 sec.) | 220°C |

(1) "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not ensure specific performance limits.
(2) For operation at ambient temperatures above 25°C, the device must be derated based on a 150°C maximum junction temperature and a thermal resistance, junction to ambient, as follows: LM13700N, 90°C/W; LM13700M, 110°C/W.
(3) Buffer output current should be limited so as to not exceed package dissipation.

## Electrical Characteristics (1)

| Parameter | Test Conditions | LM13700 | | | Units |
|---|---|---|---|---|---|
| | | Min | Typ | Max | |
| Input Offset Voltage ($V_{OS}$) | Over Specified Temperature Range | | 0.4 | 4 | mV |
| | $I_{ABC}$ = 5 µA | | 0.3 | 4 | |
| $V_{OS}$ Including Diodes | Diode Bias Current ($I_D$) = 500 µA | | 0.5 | 5 | mV |
| Input Offset Change | 5 µA ≤ $I_{ABC}$ ≤ 500 µA | | 0.1 | 3 | mV |
| Input Offset Current | | | 0.1 | 0.6 | µA |
| Input Bias Current | Over Specified Temperature Range | | 0.4 | 5 | µA |
| | | | 1 | 8 | |
| Forward Transconductance ($g_m$) | | 6700 | 9600 | 13000 | µmho |
| | Over Specified Temperature Range | 5400 | | | |
| $g_m$ Tracking | | | 0.3 | | dB |
| Peak Output Current | $R_L$ = 0, $I_{ABC}$ = 5 µA | | 5 | | µA |
| | $R_L$ = 0, $I_{ABC}$ = 500 µA | 350 | 500 | 650 | |
| | $R_L$ = 0, Over Specified Temp Range | 300 | | | |
| Peak Output Voltage | | | | | |
| Positive | $R_L$ = ∞, 5 µA ≤ $I_{ABC}$ ≤ 500 µA | +12 | +14.2 | | V |
| Negative | $R_L$ = ∞, 5 µA ≤ $I_{ABC}$ ≤ 500 µA | −12 | −14.4 | | V |
| Supply Current | $I_{ABC}$ = 500 µA, Both Channels | | 2.6 | | mA |
| $V_{OS}$ Sensitivity | | | | | |
| Positive | **$\Delta V_{OS}/\Delta V^+$** | | 20 | 150 | µV/V |
| Negative | **$\Delta V_{OS}/\Delta V^-$** | | 20 | 150 | µV/V |
| CMRR | | 80 | 110 | | dB |
| Common Mode Range | | ±12 | ±13.5 | | V |
| Crosstalk | Referred to Input (2)<br>20 Hz < f < 20 kHz | | 100 | | dB |
| Differential Input Current | $I_{ABC}$ = 0, Input = ±4V | | 0.02 | 100 | nA |
| Leakage Current | $I_{ABC}$ = 0 (Refer to Test Circuit) | | 0.2 | 100 | nA |
| Input Resistance | | 10 | 26 | | kΩ |
| Open Loop Bandwidth | | | 2 | | MHz |
| Slew Rate | Unity Gain Compensated | | 50 | | V/µs |
| Buffer Input Current | (2) | | 0.5 | 2 | µA |
| Peak Buffer Output Voltage | (2) | 10 | | | V |

(1) These specifications apply for $V_S$ = ±15V, $T_A$ = 25°C, amplifier bias current ($I_{ABC}$) = 500 µA, pins 2 and 15 open unless otherwise specified. The inputs to the buffers are grounded and outputs are open.
(2) These specifications apply for $V_S$ = ±15V, $I_{ABC}$ = 500 µA, $R_{OUT}$ = 5 kΩ connected from the buffer output to $-V_S$ and the input of the buffer is connected to the transconductance amplifier output.

## Schematic Diagram

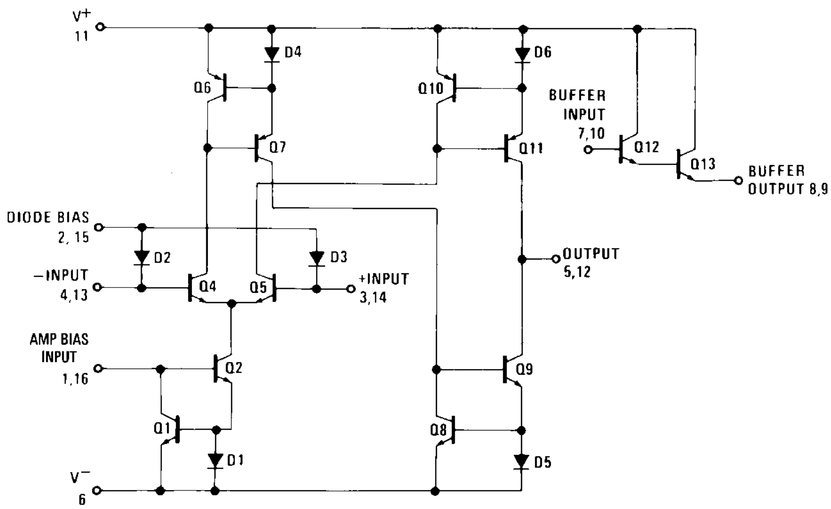



**Figure 2. One Operational Transconductance Amplifier**

## Typical Application

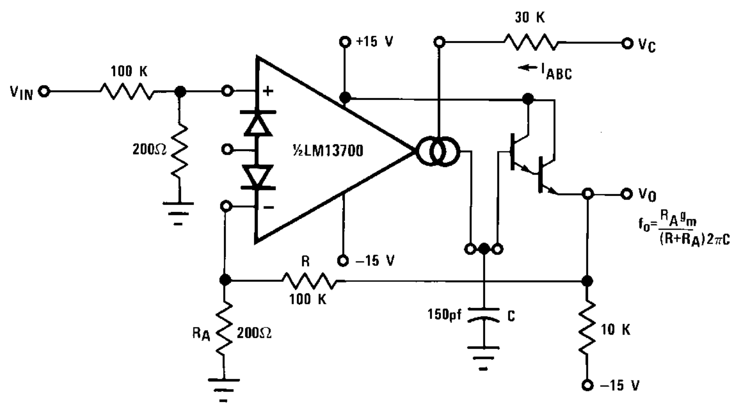



**Figure 3. Voltage Controlled Low-Pass Filter**

## Typical Performance Characteristics

**Input Offset Voltage**

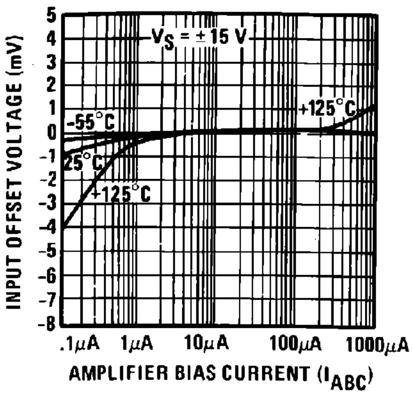



**Figure 4.**

**Input Offset Current**

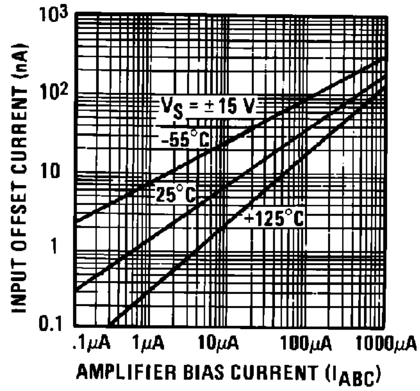



**Figure 5.**

**Input Bias Current**

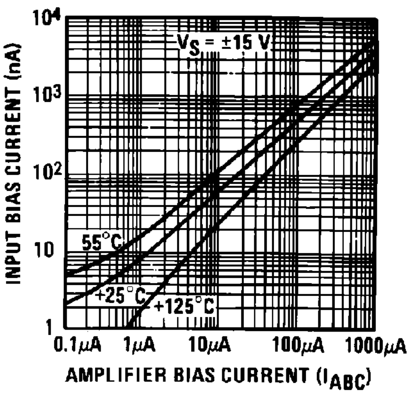



**Figure 6.**

**Peak Output Current**

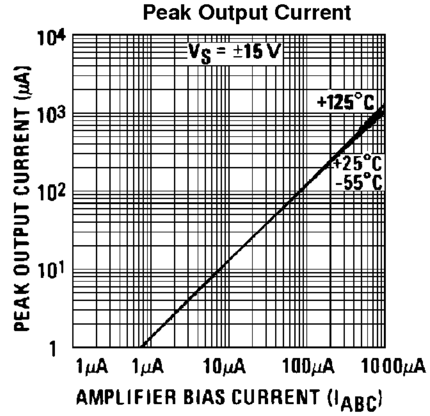



**Figure 7.**

**Peak Output Voltage and Common Mode Range**

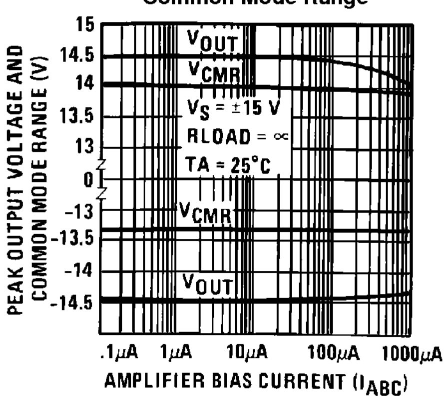



**Figure 8.**

**Leakage Current**

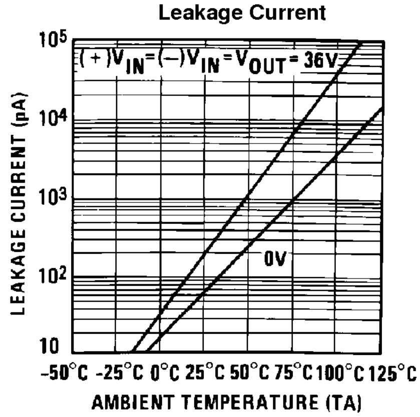



**Figure 9.**

## Typical Performance Characteristics (continued)

**Input Leakage**

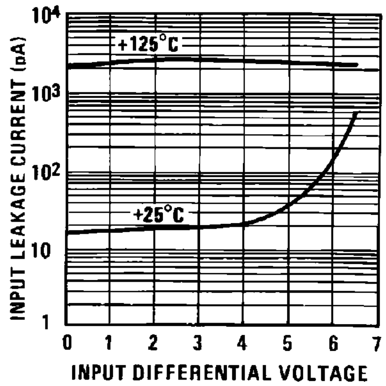



Figure 10.

**Transconductance**

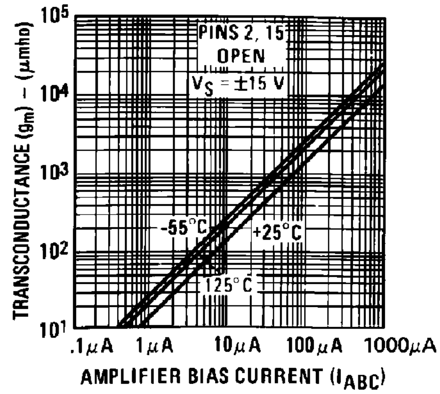



Figure 11.

**Input Resistance**

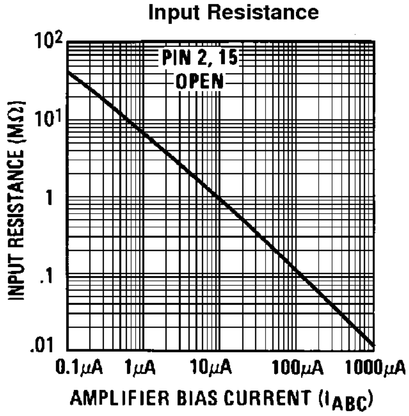



Figure 12.

**Amplifier Bias Voltage vs. Amplifier Bias Current**

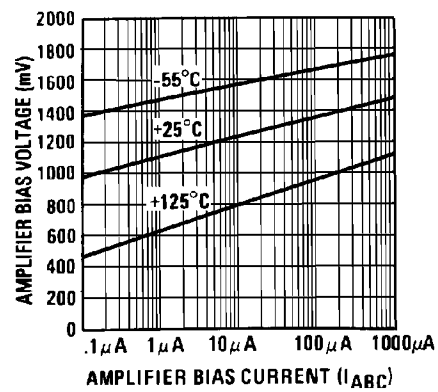



Figure 13.

**Input and Output Capacitance**

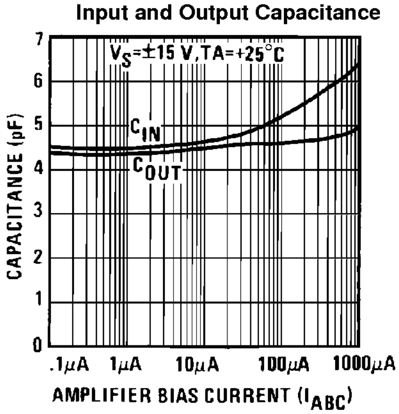



Figure 14.

**Output Resistance**

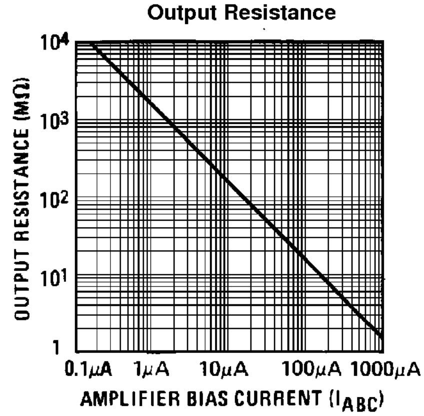



Figure 15.

## Typical Performance Characteristics (continued)

**Distortion vs. Differential Input Voltage**

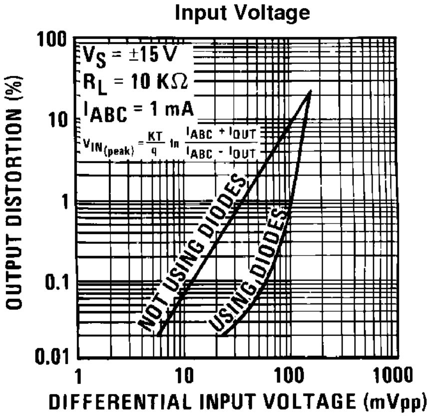



Figure 16.

**Voltage vs. Amplifier Bias Current**

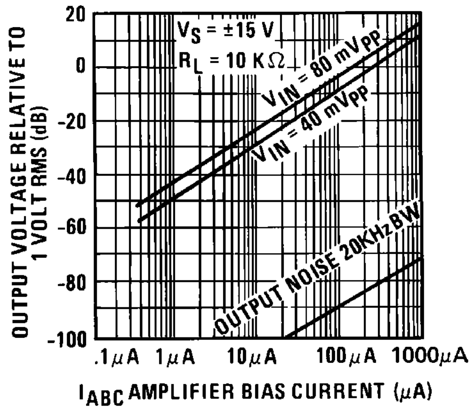



Figure 17.

**Output Noise vs. Frequency**

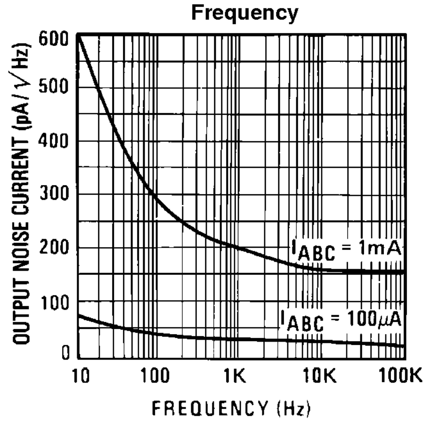



Figure 18.

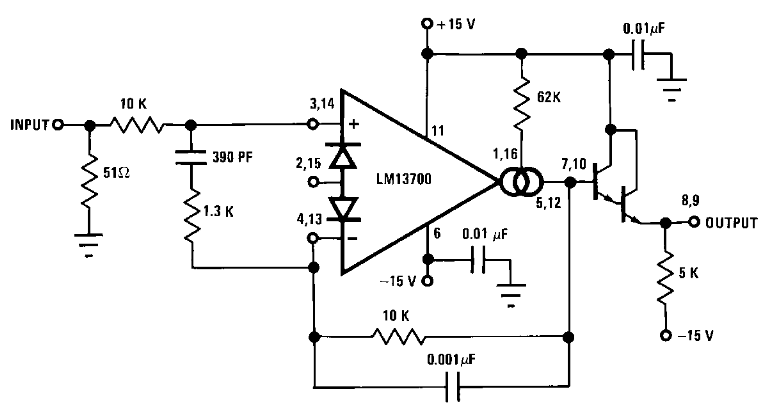



Figure 19. Unity Gain Follower

## Typical Performance Characteristics (continued)

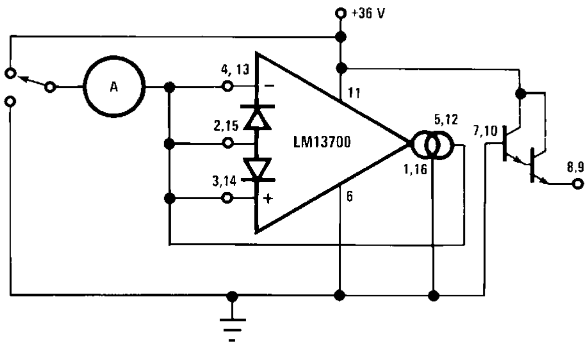



**Figure 20. Leakage Current Test Circuit**

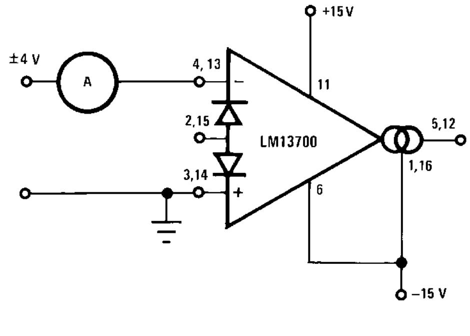



**Figure 21. Differential Input Current Test Circuit**

## Circuit Description

The differential transistor pair $Q_4$ and $Q_5$ form a transconductance stage in that the ratio of their collector currents is defined by the differential input voltage according to the transfer function:

$$V_{IN} = \frac{kT}{q} \ln \frac{I_5}{I_4} \tag{1}$$

where $V_{IN}$ is the differential input voltage, kT/q is approximately 26 mV at 25°C and $I_5$ and $I_4$ are the collector currents of transistors $Q_5$ and $Q_4$ respectively. With the exception of $Q_{12}$ and $Q_{13}$, all transistors and diodes are identical in size. Transistors $Q_1$ and $Q_2$ with Diode $D_1$ form a current mirror which forces the sum of currents $I_4$ and $I_5$ to equal $I_{ABC}$:

$$I_4 + I_5 = I_{ABC} \tag{2}$$

where $I_{ABC}$ is the amplifier bias current applied to the gain pin.

For small differential input voltages the ratio of $I_4$ and $I_5$ approaches unity and the Taylor series of the ln function can be approximated as:

$$\frac{kT}{q} \ln \frac{I_5}{I_4} \approx \frac{kT}{q} \frac{I_5 - I_4}{I_4}$$

$$I_4 \approx I_5 \approx \frac{I_{ABC}}{2} \tag{3}$$

$$V_{IN} \left[\frac{I_{ABC}q}{2kT}\right] = I_5 - I_4 \tag{4}$$

Collector currents $I_4$ and $I_5$ are not very useful by themselves and it is necessary to subtract one current from the other. The remaining transistors and diodes form three current mirrors that produce an output current equal to $I_5$ minus $I_4$ thus:

$$V_{IN} \left[\frac{I_{ABC}q}{2kT}\right] = I_{OUT} \tag{5}$$

The term in brackets is then the transconductance of the amplifier and is proportional to $I_{ABC}$.

## Linearizing Diodes

For differential voltages greater than a few millivolts, Equation 3 becomes less valid and the transconductance becomes increasingly nonlinear. Figure 22 demonstrates how the internal diodes can linearize the transfer function of the amplifier. For convenience assume the diodes are biased with current sources and the input signal is in the form of current $I_S$. Since the sum of $I_4$ and $I_5$ is $I_{ABC}$ and the difference is $I_{OUT}$, currents $I_4$ and $I_5$ can be written as follows:

$$I_4 = \frac{I_{ABC}}{2} - \frac{I_{OUT}}{2}, \; I_5 = \frac{I_{ABC}}{2} + \frac{I_{OUT}}{2} \tag{6}$$

Since the diodes and the input transistors have identical geometries and are subject to similar voltages and temperatures, the following is true:

$$\frac{kT}{q}\ \ln\frac{\frac{I_D}{2}+I_S}{\frac{I_D}{2}-I_S}=\frac{kT}{q}\ \ln\frac{\frac{I_{ABC}}{2}+\frac{I_{OUT}}{2}}{\frac{I_{ABC}}{2}-\frac{I_{OUT}}{2}}$$

$$\therefore I_{OUT}=I_S\left(\frac{2I_{ABC}}{I_D}\right)\ \text{for}\ |I_S|<\frac{I_D}{2} \tag{7}$$

Notice that in deriving Equation 7 no approximations have been made and there are no temperature-dependent terms. The limitations are that the signal current not exceed $I_D/2$ and that the diodes be biased with currents. In practice, replacing the current sources with resistors will generate insignificant errors.

## APPLICATIONS

### Voltage Controlled Amplifiers

Figure 23 shows how the linearizing diodes can be used in a voltage-controlled amplifier. To understand the input biasing, it is best to consider the 13 kΩ resistor as a current source and use a Thevenin equivalent circuit as shown in Figure 24. This circuit is similar to Figure 22 and operates the same. The potentiometer in Figure 23 is adjusted to minimize the effects of the control signal at the output.

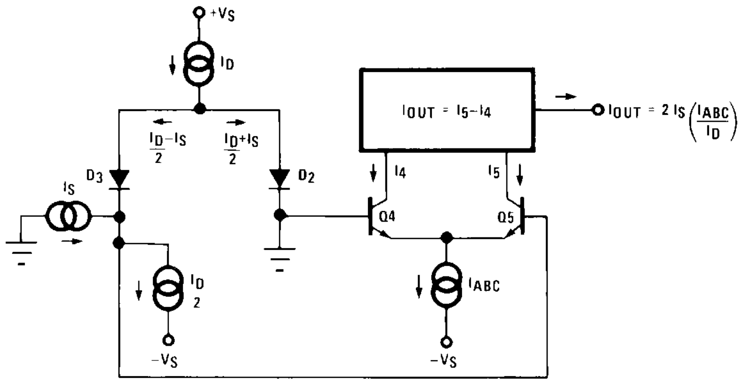



**Figure 22. Linearizing Diodes**

For optimum signal-to-noise performance, $I_{ABC}$ should be as large as possible as shown by the Output Voltage vs. Amplifier Bias Current graph. Larger amplitudes of input signal also improve the S/N ratio. The linearizing diodes help here by allowing larger input signals for the same output distortion as shown by the Distortion vs. Differential Input Voltage graph. S/N may be optimized by adjusting the magnitude of the input signal via $R_{IN}$ (Figure 23) until the output distortion is below some desired level. The output voltage swing can then be set at any level by selecting $R_L$.

Although the noise contribution of the linearizing diodes is negligible relative to the contribution of the amplifier's internal transistors, $I_D$ should be as large as possible. This minimizes the dynamic junction resistance of the diodes ($r_e$) and maximizes their linearizing action when balanced against $R_{IN}$. A value of 1 mA is recommended for $I_D$ unless the specific application demands otherwise.

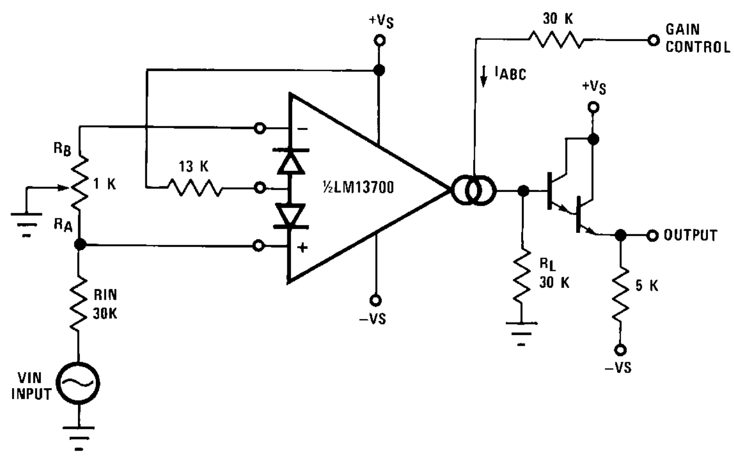



**Figure 23. Voltage Controlled Amplifier**

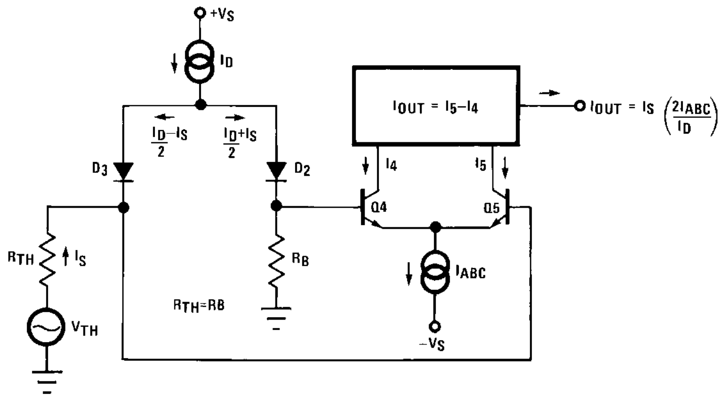



**Figure 24. Equivalent VCA Input Circuit**

## Stereo Volume Control

The circuit of Figure 25 uses the excellent matching of the two LM13700 amplifiers to provide a Stereo Volume Control with a typical channel-to-channel gain tracking of 0.3 dB. $R_P$ is provided to minimize the output offset voltage and may be replaced with two 510Ω resistors in AC-coupled applications. For the component values given, amplifier gain is derived for Figure 23 as being:

$$\frac{V_O}{V_{IN}} = 940 \times I_{ABC} \quad (8)$$

If $V_C$ is derived from a second signal source then the circuit becomes an amplitude modulator or two-quadrant multiplier as shown in Figure 26, where:

$$I_O = \frac{-2I_S}{I_D}(I_{ABC}) = \frac{-2I_S}{I_D}\frac{V_{IN2}}{R_C} - \frac{2I_S}{I_D}\frac{(V^- + 1.4V)}{R_C} \quad (9)$$

The constant term in the above equation may be cancelled by feeding $I_S \times I_D R_C/2(V- + 1.4V)$ into $I_O$. The circuit of Figure 27 adds $R_M$ to provide this current, resulting in a four-quadrant multiplier where $R_C$ is trimmed such that $V_O = 0V$ for $V_{IN2} = 0V$. $R_M$ also serves as the load resistor for $I_O$.

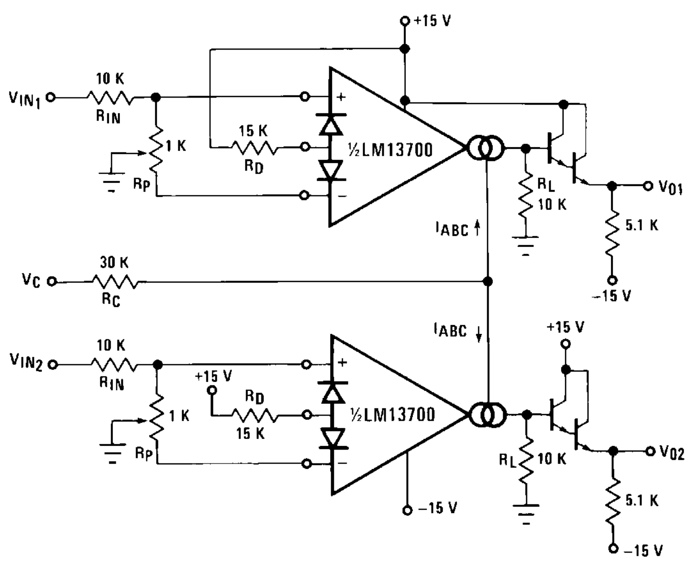



**Figure 25. Stereo Volume Control**

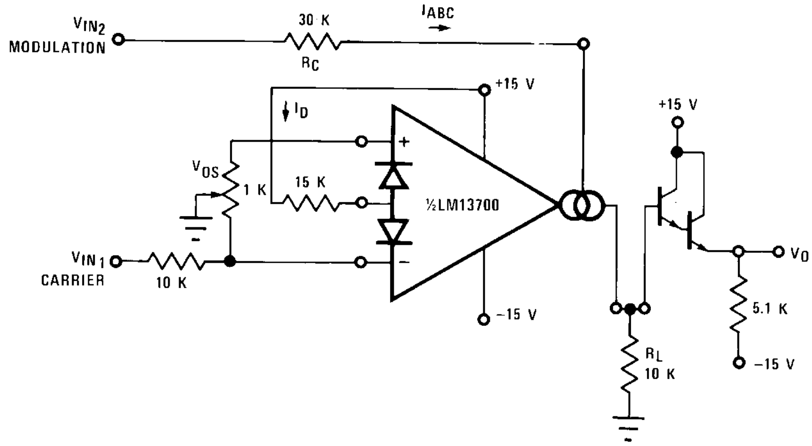



**Figure 26. Amplitude Modulator**

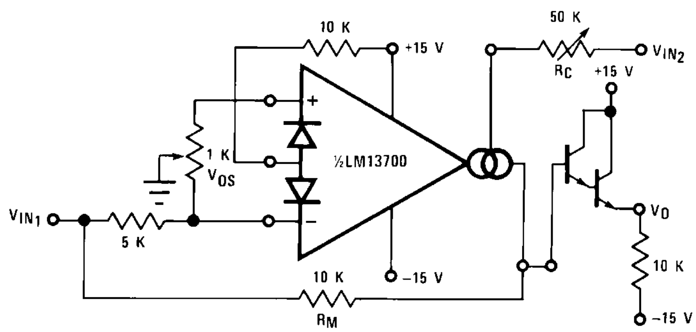



**Figure 27. Four-Quadrant Multiplier**

Noting that the gain of the LM13700 amplifier of Figure 24 may be controlled by varying the linearizing diode current $I_D$ as well as by varying $I_{ABC}$, Figure 28 shows an AGC Amplifier using this approach. As $V_O$ reaches a high enough amplitude ($3V_{BE}$) to turn on the Darlington transistors and the linearizing diodes, the increase in $I_D$ reduces the amplifier gain so as to hold $V_O$ at that level.

## Voltage Controlled Resistors

An Operational Transconductance Amplifier (OTA) may be used to implement a Voltage Controlled Resistor as shown in Figure 29. A signal voltage applied at $R_X$ generates a $V_{IN}$ to the LM13700 which is then multiplied by the $g_m$ of the amplifier to produce an output current, thus:

$$R_X = \frac{R + R_A}{g_m R_A} \tag{10}$$

where $g_m \approx 19.2 I_{ABC}$ at 25°C. Note that the attenuation of $V_O$ by R and $R_A$ is necessary to maintain $V_{IN}$ within the linear range of the LM13700 input.

Figure 30 shows a similar VCR where the linearizing diodes are added, essentially improving the noise performance of the resistor. A floating VCR is shown in Figure 31, where each “end” of the “resistor” may be at any voltage within the output voltage range of the LM13700.

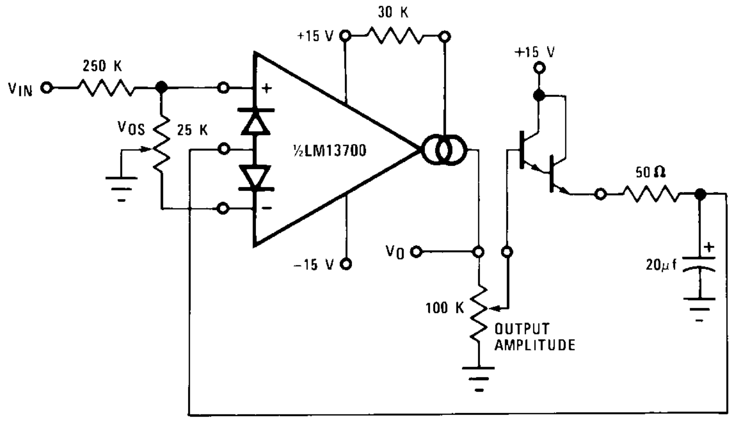
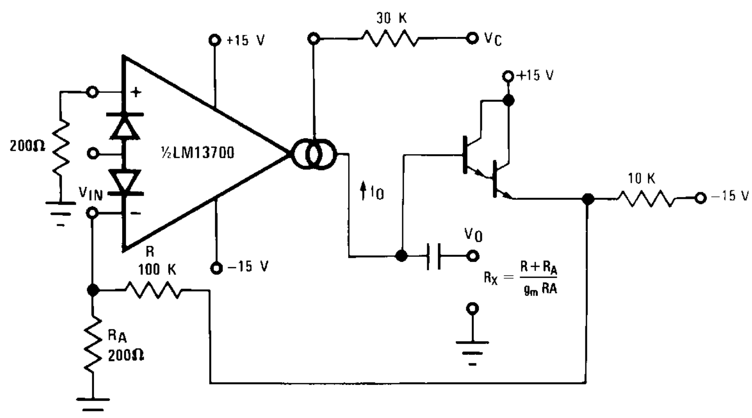



**Figure 28. AGC Amplifier**




$$R_X = \frac{R + R_A}{g_m R_A}$$

**Figure 29. Voltage Controlled Resistor, Single-Ended**

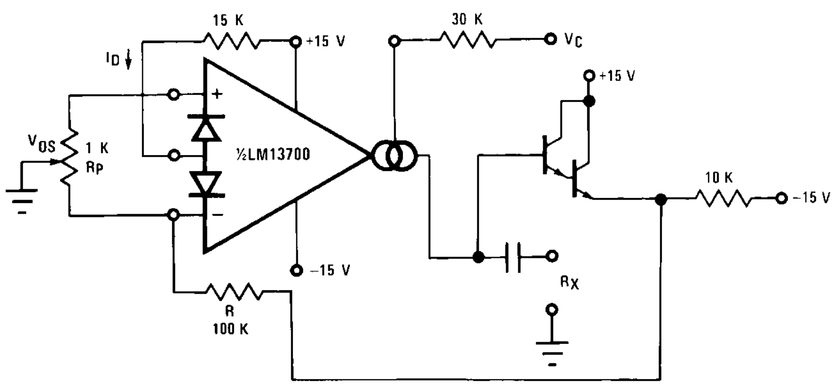



**Figure 30. Voltage Controlled Resistor with Linearizing Diodes**

## Voltage Controlled Filters

OTA's are extremely useful for implementing voltage controlled filters, with the LM13700 having the advantage that the required buffers are included on the I.C. The VC Lo-Pass Filter of Figure 32 performs as a unity-gain buffer amplifier at frequencies below cut-off, with the cut-off frequency being the point at which $X_C/g_m$ equals the closed-loop gain of $(R/R_A)$. At frequencies above cut-off the circuit provides a single RC roll-off (6 dB per octave) of the input signal amplitude with a −3 dB point defined by the given equation, where $g_m$ is again $19.2 \times I_{ABC}$ at room temperature. Figure 33 shows a VC High-Pass Filter which operates in much the same manner, providing a single RC roll-off below the defined cut-off frequency.

Additional amplifiers may be used to implement higher order filters as demonstrated by the two-pole Butterworth Lo-Pass Filter of Figure 34 and the state variable filter of Figure 35. Due to the excellent $g_m$ tracking of the two amplifiers, these filters perform well over several decades of frequency.

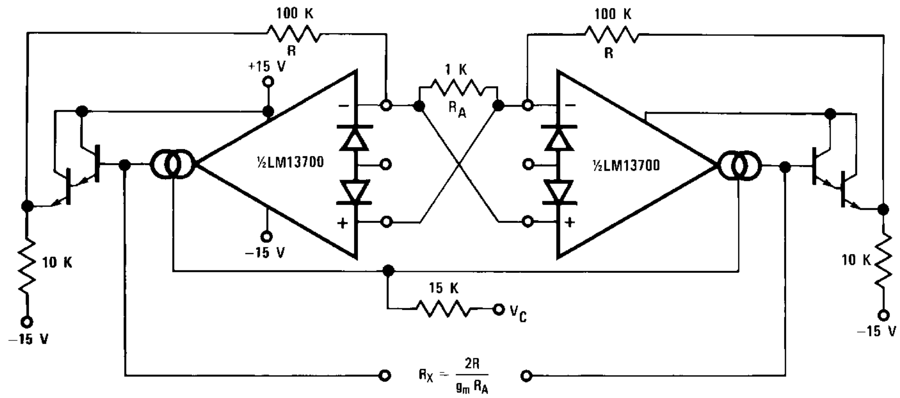



**Figure 31. Floating Voltage Controlled Resistor**

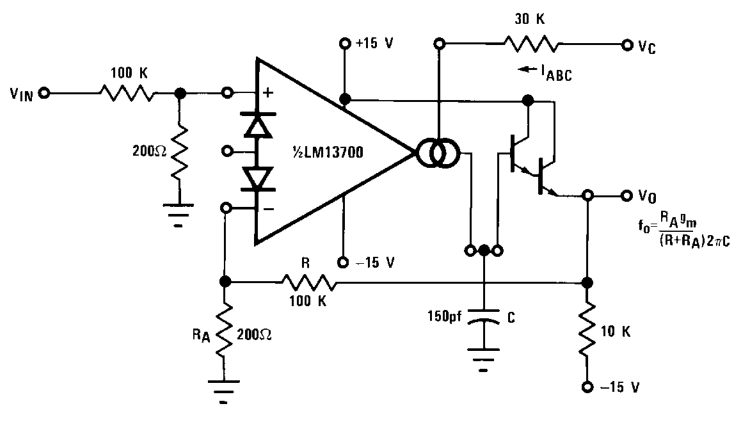
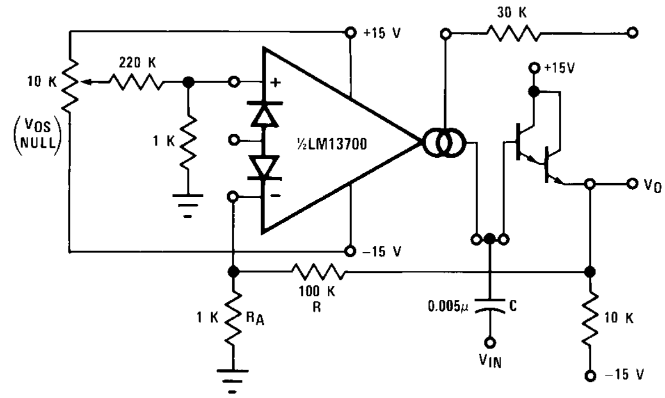


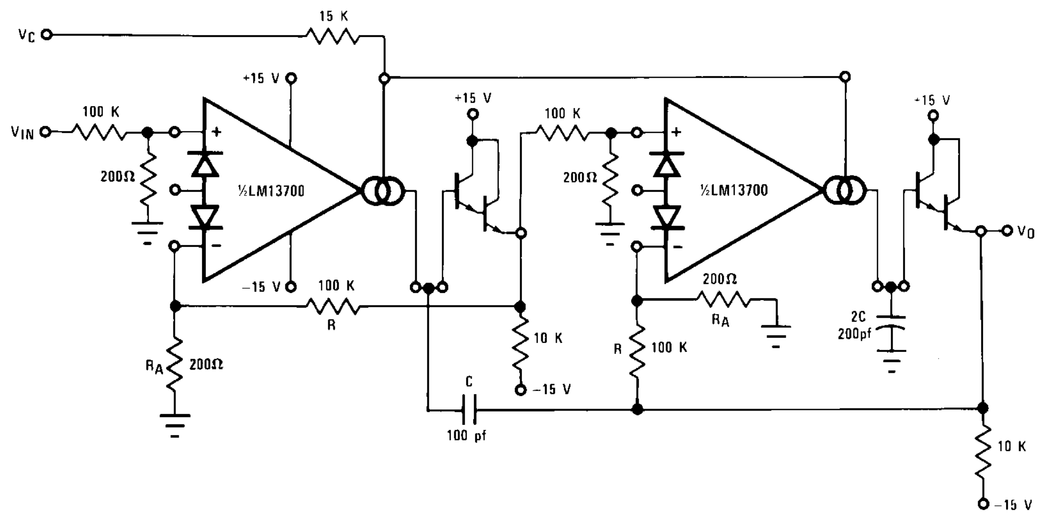

**Figure 32. Voltage Controlled Low-Pass Filter**




$$f_o = \frac{R_A g_m}{(R + R_A) 2\pi C}$$

**Figure 33. Voltage Controlled Hi-Pass Filter**




$$f_o = \frac{R_A g_m}{(R + R_A) 2\pi C}$$

**Figure 34. Voltage Controlled 2-Pole Butterworth Lo-Pass Filter**

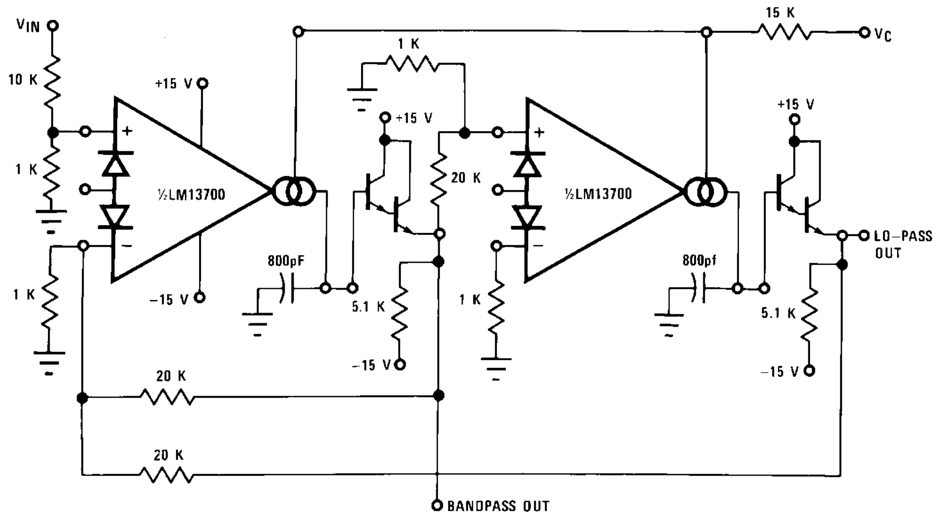


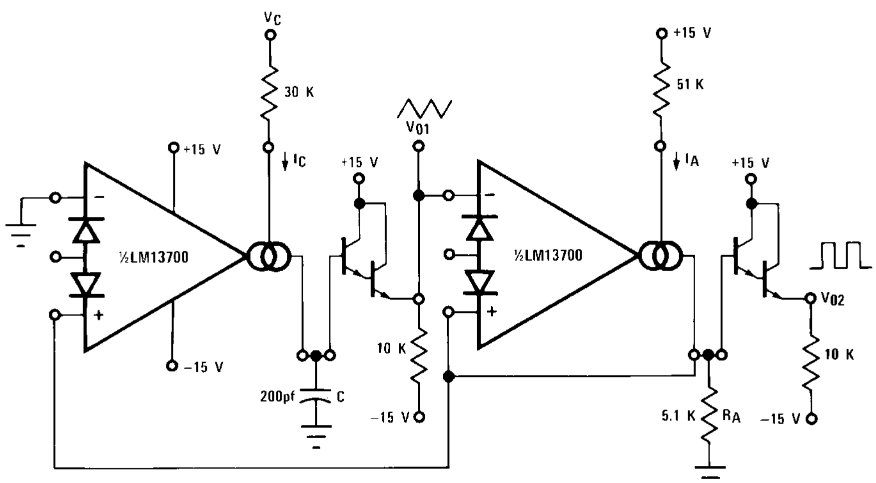

**Figure 35. Voltage Controlled State Variable Filter**

## Voltage Controlled Oscillators

The classic Triangular/Square Wave VCO of Figure 36 is one of a variety of Voltage Controlled Oscillators which may be built utilizing the LM13700. With the component values shown, this oscillator provides signals from 200 kHz to below 2 Hz as $I_C$ is varied from 1 mA to 10 nA. The output amplitudes are set by $I_A \times R_A$. Note that the peak differential input voltage must be less than 5V to prevent zenering the inputs.

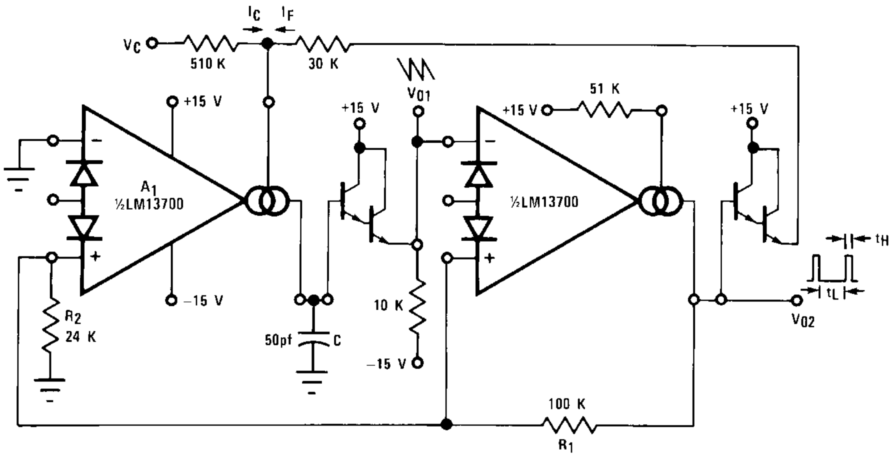
A few modifications to this circuit produce the ramp/pulse VCO of Figure 37. When $V_{O2}$ is high, $I_F$ is added to $I_C$ to increase amplifier A1's bias current and thus to increase the charging rate of capacitor C. When $V_{O2}$ is low, $I_F$ goes to zero and the capacitor discharge current is set by $I_C$.

The VC Lo-Pass Filter of Figure 32 may be used to produce a high-quality sinusoidal VCO. The circuit of Figure 37 employs two LM13700 packages, with three of the amplifiers configured as lo-pass filters and the fourth as a limiter/inverter. The circuit oscillates at the frequency at which the loop phase-shift is 360° or 180° for the inverter and 60° per filter stage. This VCO operates from 5 Hz to 50 kHz with less than 1% THD.




$$f_{OSC} = \frac{I_C}{4CI_AR_A}$$

**Figure 36. Triangular/Square-Wave VCO**




$$V_{PK} = \frac{(V^+ \pm 0.8V)\,R_2}{R_1 + R_2}$$

$$t_H \approx \frac{2V_{PK}C}{I_F}$$

$$t_L = \frac{2V_{PK}C}{I_C}$$

$$f_0 \approx \frac{I_C}{2V_{PK}C} \text{ for } I_C << I_F$$

**Figure 37. Ramp/Pulse VCO**

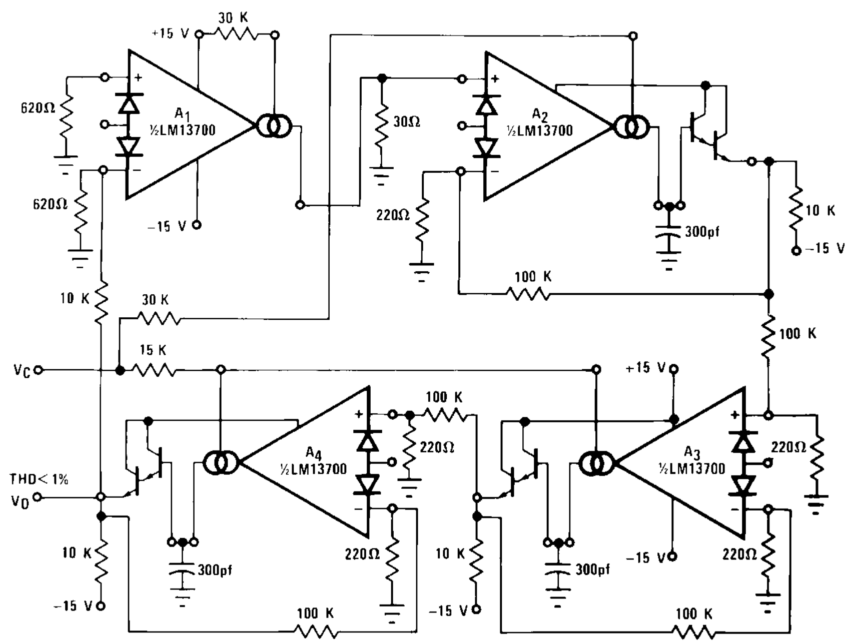



**Figure 38. Sinusoidal VCO**

Figure 39 shows how to build a VCO using one amplifier when the other amplifier is needed for another function.

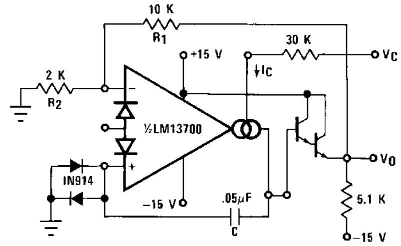



**Figure 39. Single Amplifier VCO**

## Additional Applications

Figure 40 presents an interesting one-shot which draws no power supply current until it is triggered. A positive-going trigger pulse of at least 2V amplitude turns on the amplifier through $R_B$ and pulls the non-inverting input high. The amplifier regenerates and latches its output high until capacitor C charges to the voltage level on the non-inverting input. The output then switches low, turning off the amplifier and discharging the capacitor. The capacitor discharge rate is speeded up by shorting the diode bias pin to the inverting input so that an additional discharge current flows through $D_I$ when the amplifier output switches low. A special feature of this timer is that the other amplifier, when biased from $V_O$, can perform another function and draw zero stand-by power as well.

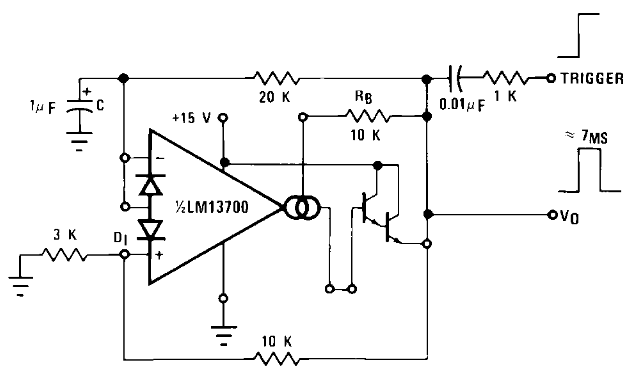



**Figure 40. Zero Stand-By Power Timer**

The operation of the multiplexer of Figure 41 is very straightforward. When A1 is turned on it holds $V_O$ equal to $V_{IN1}$ and when A2 is supplied with bias current then it controls $V_O$. $C_C$ and $R_C$ serve to stabilize the unity-gain configuration of amplifiers A1 and A2. The maximum clock rate is limited to about 200 kHz by the LM13700 slew rate into 150 pF when the ($V_{IN1}$–$V_{IN2}$) differential is at its maximum allowable value of 5V.

The Phase-Locked Loop of Figure 42 uses the four-quadrant multiplier of Figure 27 and the VCO of Figure 39 to produce a PLL with a ±5% hold-in range and an input sensitivity of about 300 mV.

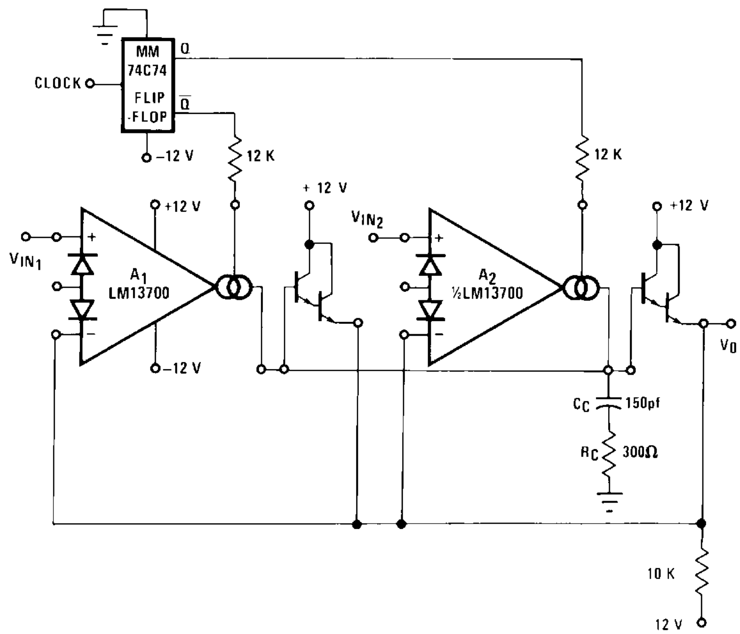



Figure 41. Multiplexer

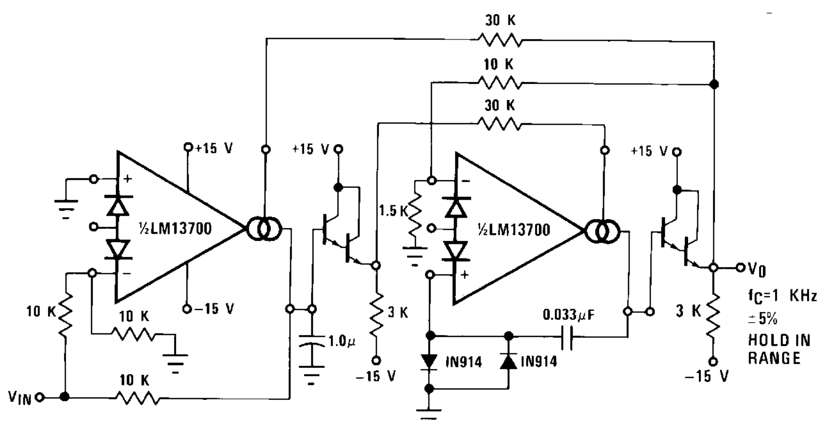



Figure 42. Phase Lock Loop

The Schmitt Trigger of Figure 43 uses the amplifier output current into R to set the hysteresis of the comparator; thus $V_H = 2 \times R \times I_B$. Varying $I_B$ will produce a Schmitt Trigger with variable hysteresis.

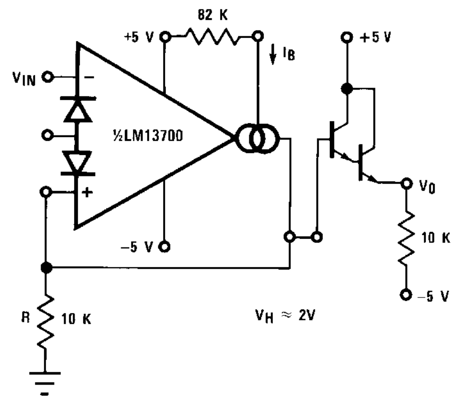



Figure 43. Schmitt Trigger

Figure 44 shows a Tachometer or Frequency-to-Voltage converter. Whenever A1 is toggled by a positive-going input, an amount of charge equal to $(V_H–V_L)$ $C_t$ is sourced into $C_f$ and $R_t$. This once per cycle charge is then balanced by the current of $V_O/R_t$. The maximum $F_{IN}$ is limited by the amount of time required to charge $C_t$ from $V_L$ to $V_H$ with a current of $I_B$, where $V_L$ and $V_H$ represent the maximum low and maximum high output voltage swing of the LM13700. D1 is added to provide a discharge path for $C_t$ when A1 switches low.

The Peak Detector of Figure 45 uses A2 to turn on A1 whenever $V_{IN}$ becomes more positive than $V_O$. A1 then charges storage capacitor C to hold $V_O$ equal to $V_{IN}$ PK. Pulling the output of A2 low through D1 serves to turn off A1 so that $V_O$ remains constant.

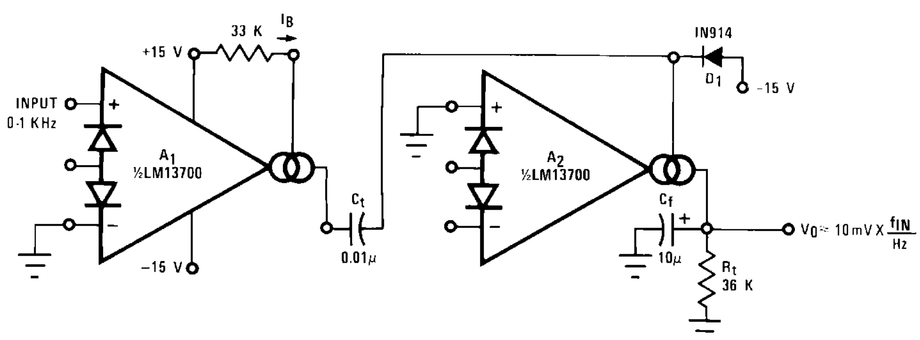



Figure 44. Tachometer

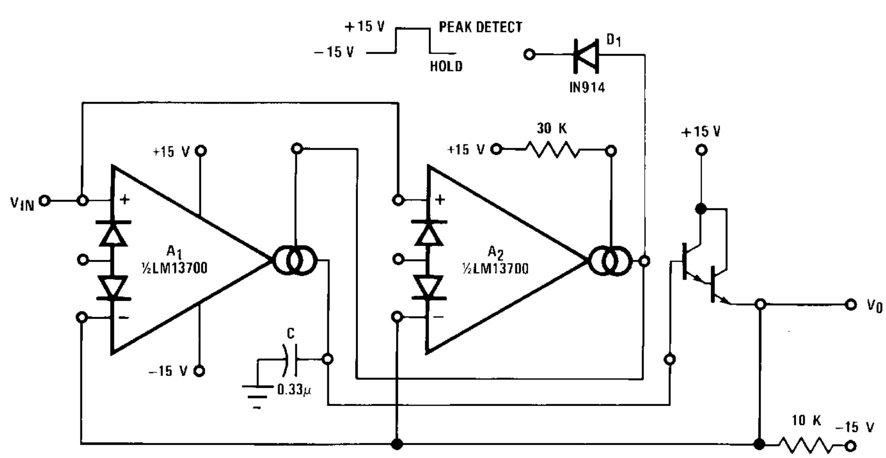



Figure 45. Peak Detector and Hold Circuit

The Ramp-and-Hold of Figure 47 sources $I_B$ into capacitor C whenever the input to A1 is brought high, giving a ramp-rate of about 1V/ms for the component values shown.

The true-RMS converter of Figure 48 is essentially an automatic gain control amplifier which adjusts its gain such that the AC power at the output of amplifier A1 is constant. The output power of amplifier A1 is monitored by squaring amplifier A2 and the average compared to a reference voltage with amplifier A3. The output of A3 provides bias current to the diodes of A1 to attenuate the input signal. Because the output power of A1 is held constant, the RMS value is constant and the attenuation is directly proportional to the RMS value of the input voltage. The attenuation is also proportional to the diode bias current. Amplifier A4 adjusts the ratio of currents through the diodes to be equal and therefore the voltage at the output of A4 is proportional to the RMS value of the input voltage. The calibration potentiometer is set such that $V_O$ reads directly in RMS volts.

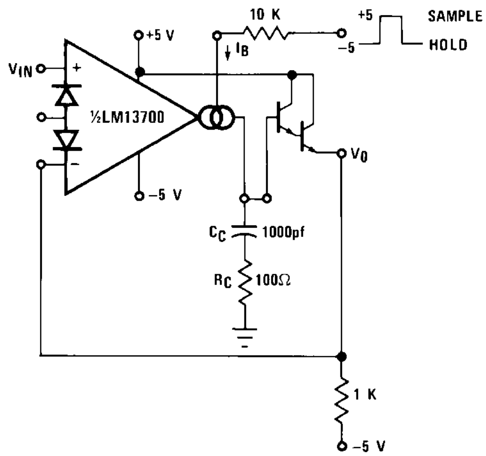



**Figure 46. Sample-Hold Circuit**

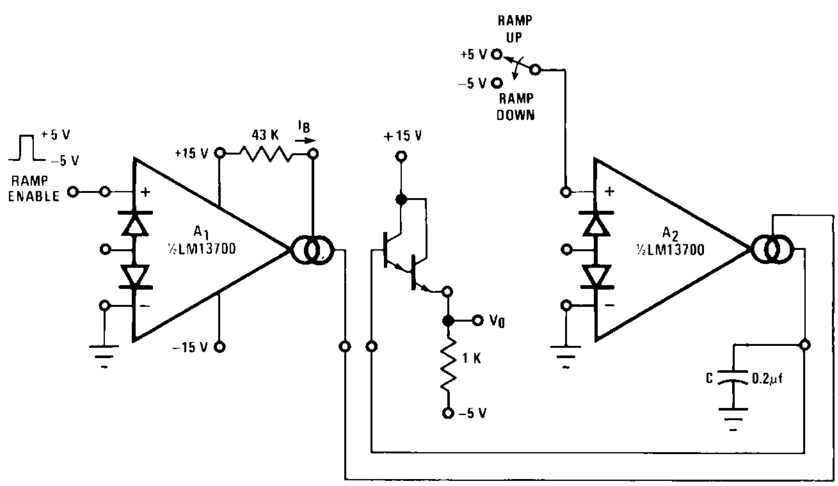



**Figure 47. Ramp and Hold**

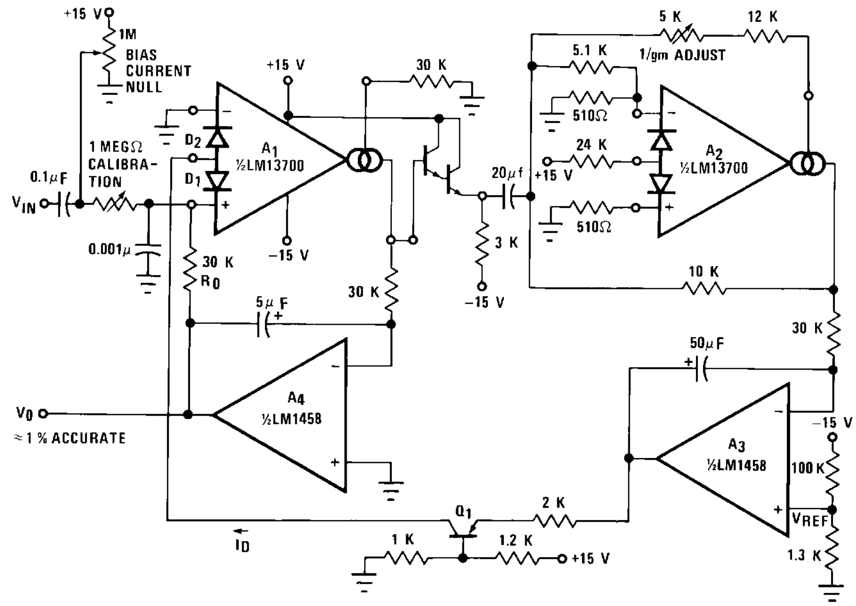



**Figure 48. True RMS Converter**

The circuit of Figure 49 is a voltage reference of variable Temperature Coefficient. The 100 kΩ potentiometer adjusts the output voltage which has a positive TC above 1.2V, zero TC at about 1.2V, and negative TC below 1.2V. This is accomplished by balancing the TC of the A2 transfer function against the complementary TC of D1.

The wide dynamic range of the LM13700 allows easy control of the output pulse width in the Pulse Width Modulator of Figure 50.

For generating $I_{ABC}$ over a range of 4 to 6 decades of current, the system of Figure 51 provides a logarithmic current out for a linear voltage in.

Since the closed-loop configuration ensures that the input to A2 is held equal to 0V, the output current of A1 is equal to $I_3 = -V_C/R_C$.

The differential voltage between Q1 and Q2 is attenuated by the R1,R2 network so that A1 may be assumed to be operating within its linear range. From Equation 5, the input voltage to A1 is:

$$V_{IN}1 = \frac{-2kTI_3}{qI_2} = \frac{-2kTV_C}{qI_2R_C} \tag{11}$$

The voltage on the base of Q1 is then

$$V_B1 = \frac{(R_1 + R_2)\, V_{IN}1}{R_1} \tag{12}$$

The ratio of the Q1 and Q2 collector currents is defined by:

$$V_B1 = \frac{kT}{q} \ln \frac{I_{C2}}{I_{C1}} \approx \frac{kT}{q} \ln \frac{I_{ABC}}{I_1} \tag{13}$$

Combining and solving for $I_{ABC}$ yields:

$$I_{ABC} = I_1 \exp \frac{2(R_1 + R_2)\, V_C}{R_1\, I_2\, R_C} \tag{14}$$

This logarithmic current can be used to bias the circuit of Figure 25 to provide temperature independent stereo attenuation characteristic.

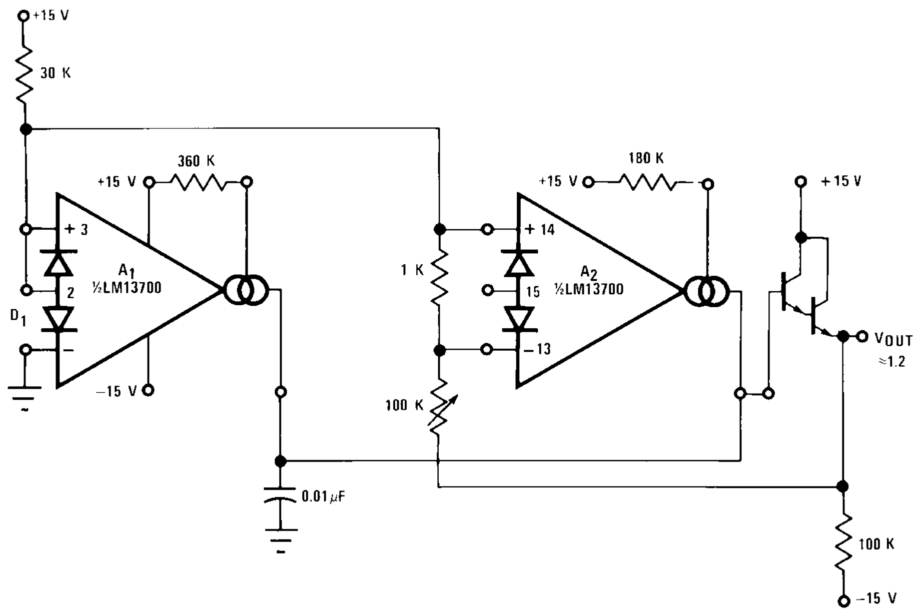



**Figure 49. Delta VBE Reference**

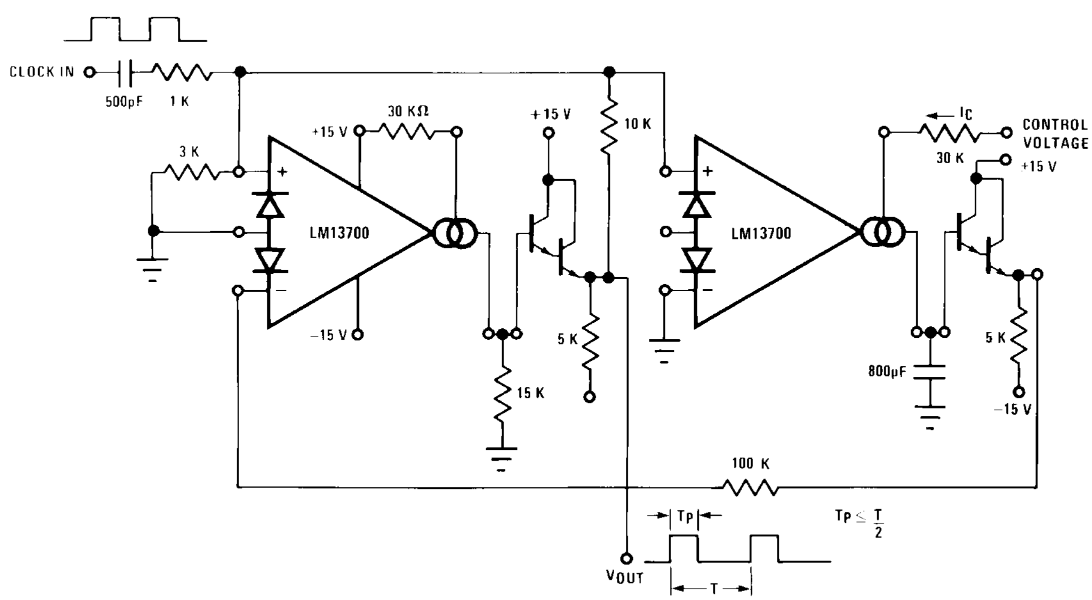
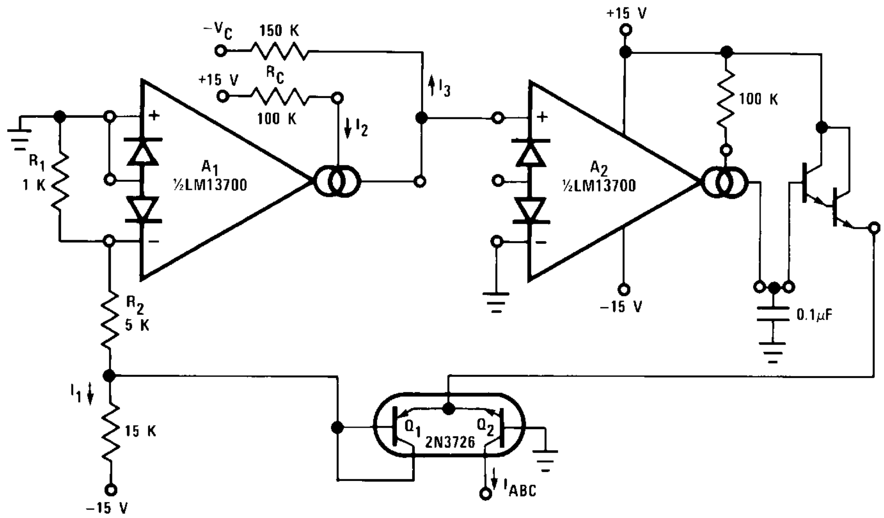



**Figure 50. Pulse Width Modulator**




$I_{ABC} = I_1 \exp \frac{-CI_3}{I_2}$

**Figure 51. Logarithmic Current Source**

## REVISION HISTORY

| Changes from Revision D (March 2013) to Revision E | Page |
| --- | --- |
| • Changed layout of National Data Sheet to TI format | 24 |

## PACKAGING INFORMATION

| Orderable Device | Status (1) | Package Type | Package Drawing | Pins | Package Qty | Eco Plan (2) | Lead/Ball Finish (6) | MSL Peak Temp (3) | Op Temp (°C) | Device Marking (4/5) | Samples |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LM13700M | NRND | SOIC | D | 16 | 48 | TBD | Call TI | Call TI | 0 to 70 | LM13700M | |
| LM13700M/NOPB | ACTIVE | SOIC | D | 16 | 48 | Green (RoHS & no Sb/Br) | CU SN | Level-1-260C-UNLIM | 0 to 70 | LM13700M | Samples |
| LM13700MX | NRND | SOIC | D | 16 | 2500 | TBD | Call TI | Call TI | 0 to 70 | LM13700M | |
| LM13700MX/NOPB | ACTIVE | SOIC | D | 16 | 2500 | Green (RoHS & no Sb/Br) | CU SN | Level-1-260C-UNLIM | 0 to 70 | LM13700M | Samples |
| LM13700N | NRND | PDIP | NFG | 16 | 25 | TBD | Call TI | Call TI | 0 to 70 | LM13700N | |
| LM13700N/NOPB | ACTIVE | PDIP | NFG | 16 | 25 | Pb-Free (RoHS) | CU SN | Level-1-NA-UNLIM | 0 to 70 | LM13700N | Samples |

(1) The marketing status values are defined as follows:
**ACTIVE:** Product device recommended for new designs.
**LIFEBUY:** TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
**NRND:** Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
**PREVIEW:** Device has been announced but is not in production. Samples may or may not be available.
**OBSOLETE:** TI has discontinued the production of the device.

(2) Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check http://www.ti.com/productcontent for the latest availability information and additional product content details.
**TBD:** The Pb-Free/Green conversion plan has not been defined.
**Pb-Free (RoHS):** TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.
**Pb-Free (RoHS Exempt):** This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.
**Green (RoHS & no Sb/Br):** TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

[6] Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

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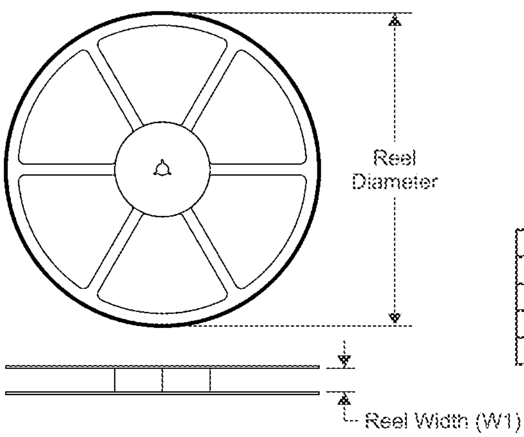
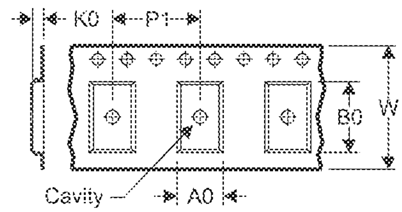
REEL DIMENSIONS

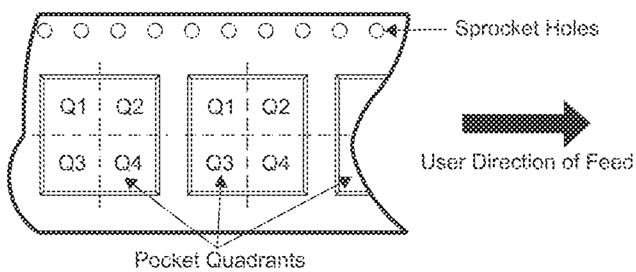



TAPE DIMENSIONS




| | |
|---|---|
| A0 | Dimension designed to accommodate the component width |
| B0 | Dimension designed to accommodate the component length |
| K0 | Dimension designed to accommodate the component thickness |
| W | Overall width of the carrier tape |
| P1 | Pitch between successive cavity centers |

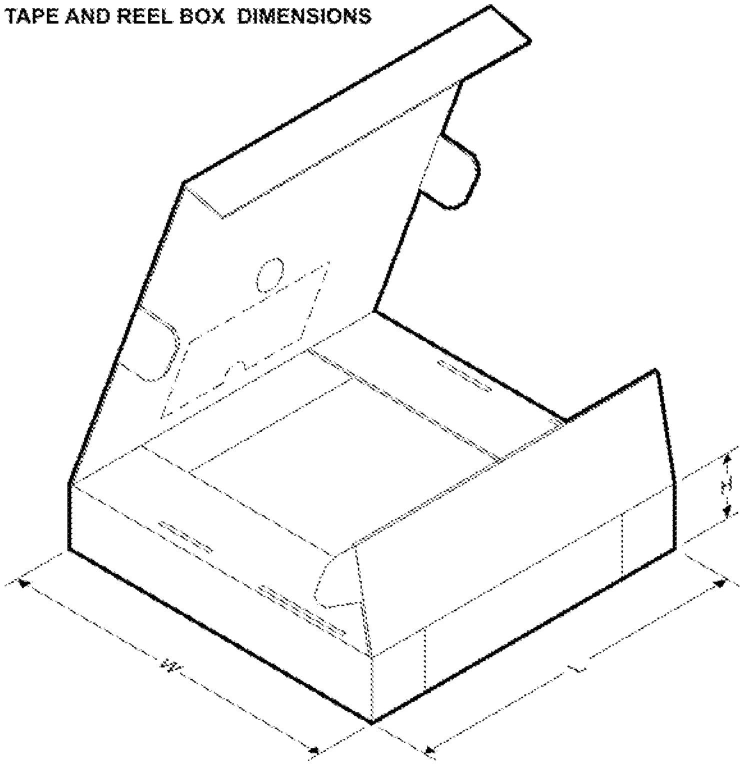
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE




*All dimensions are nominal

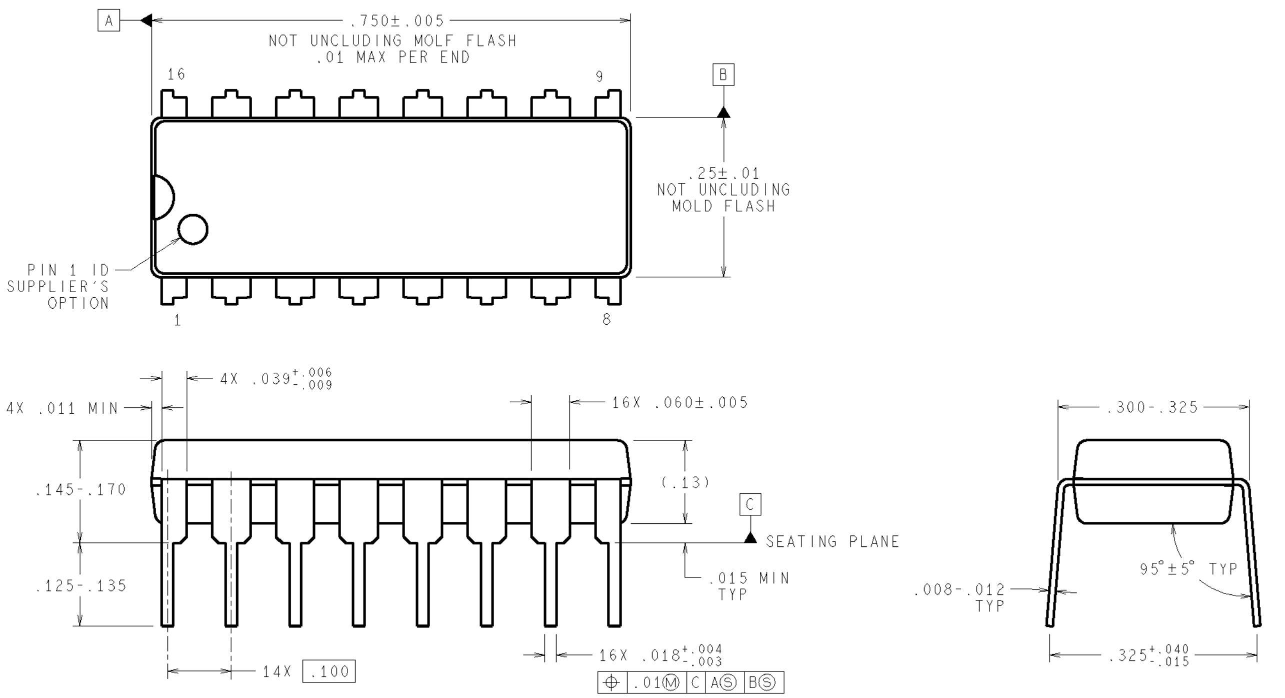
| Device | Package Type | Package Drawing | Pins | SPQ | Reel Diameter (mm) | Reel Width W1 (mm) | A0 (mm) | B0 (mm) | K0 (mm) | P1 (mm) | W (mm) | Pin1 Quadrant |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LM13700MX | SOIC | D | 16 | 2500 | 330.0 | 16.4 | 6.5 | 10.3 | 2.3 | 8.0 | 16.0 | Q1 |
| LM13700MX/NOPB | SOIC | D | 16 | 2500 | 330.0 | 16.4 | 6.5 | 10.3 | 2.3 | 8.0 | 16.0 | Q1 |

TAPE AND REEL BOX DIMENSIONS




*All dimensions are nominal

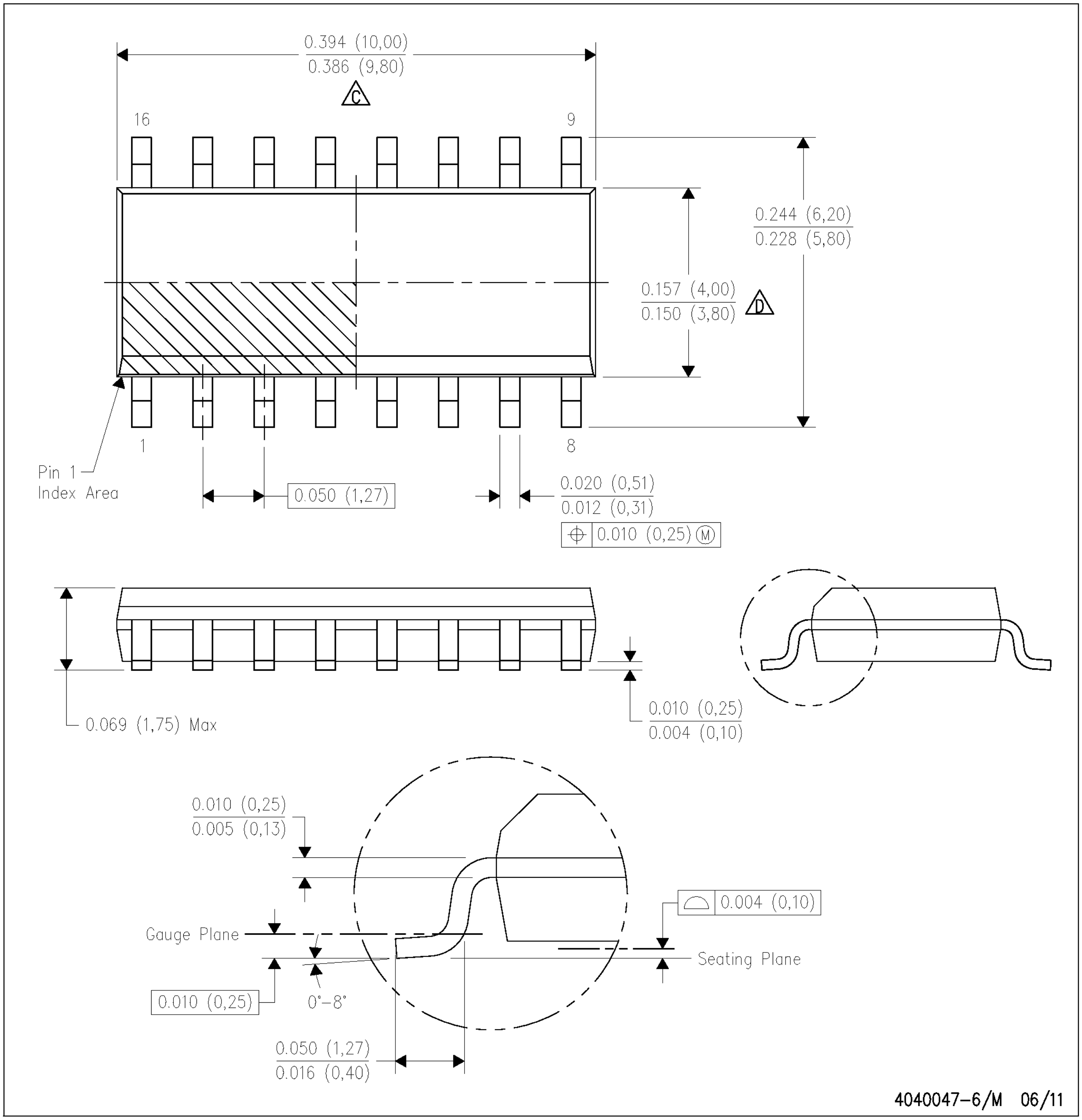
| Device | Package Type | Package Drawing | Pins | SPQ | Length (mm) | Width (mm) | Height (mm) |
|---|---|---|---|---|---|---|---|
| LM13700MX | SOIC | D | 16 | 2500 | 367.0 | 367.0 | 35.0 |
| LM13700MX/NOPB | SOIC | D | 16 | 2500 | 367.0 | 367.0 | 35.0 |




DIMENSIONS ARE IN INCHES
DIMENSIONS IN ( ) FOR REFERENCE ONLY

N16E (Rev G)

D (R–PDSO–G16) PLASTIC SMALL OUTLINE




NOTES:
A. All linear dimensions are in inches (millimeters).
B. This drawing is subject to change without notice.
C. Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.006 (0,15) each side.
D. Body width does not include interlead flash. Interlead flash shall not exceed 0.017 (0,43) each side.
E. Reference JEDEC MS-012 variation AC.

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# Electronic Patent Application Fee Transmittal

| | |
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| **Application Number:** | |
| **Filing Date:** | |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Filer:** | Jed Margolin |
| **Attorney Docket Number:** | |

Filed as Small Entity

## Utility under 35 USC 111(a) Filing Fees

| Description | Fee Code | Quantity | Amount | Sub-Total in USD($) |
|---|---|---|---|---|
| **Basic Filing:** | | | | |
| Utility filing Fee (Electronic filing) | 4011 | 1 | 70 | 70 |
| Utility Search Fee | 2111 | 1 | 300 | 300 |
| Utility Examination Fee | 2311 | 1 | 360 | 360 |
| **Pages:** | | | | |
| **Claims:** | | | | |
| Independent Claims in Excess of 3 | 2201 | 2 | 210 | 420 |
| **Miscellaneous-Filing:** | | | | |
| **Petition:** | | | | |

| Description | Fee Code | Quantity | Amount | Sub-Total in USD($) |
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| **Patent-Appeals-and-Interference:** | | | | |
| **Post-Allowance-and-Post-Issuance:** | | | | |
| **Extension-of-Time:** | | | | |
| **Miscellaneous:** | | | | |
| | **Total in USD ($)** | | | **1150** |

# Electronic Acknowledgement Receipt

| | |
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| **EFS ID:** | 19427869 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 26-JUN-2014 |
| **Filing Date:** | |
| **Time Stamp:** | 18:15:39 |
| **Application Type:** | Utility under 35 USC 111(a) |

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| 1 | Transmittal of New Application | jm_flame_transmittal_aia0015.pdf | 275299<br>70972ad62f44cc681fc3f1f463c6f05947a5cba8 | no | 2 |

**Warnings:**

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| 2 | Application Data Sheet | jm_flame_ads_aia0014.pdf | 1560956<br>c610e5aa5ea83d4ab905b134689b12320990692b | no | 7 |
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| 3 | Miscellaneous Incoming Letter | jm_flame_fees_sb17.pdf | 256792<br>670fa74fb329a8bc13b4119771b0afad9a381a19 | no | 2 |
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| 4 | Oath or Declaration filed | jm_flame_declare_aia01.pdf | 68222<br>3866e7e14537cf976b9d810a1474eff72c82705f | no | 1 |
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| 5 | Information Disclosure Statement (IDS) Form (SB08) | jm_flame_ids.pdf | 418129<br>41bc5f0f7a130154ecc5e15a8253f8261cb04cf5 | no | 4 |
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| 10 | Non Patent Literature | npl_08_Mphale_2007.pdf | 233694<br>656fbc519e90cd719e2dcc47263fffb545dddc11 | no | 12 |

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| 16 | Non Patent Literature | npl_14_Alkali_meta_halide_Wikipedia.pdf | 72382<br>041db037cd4185e944d420f6937ea81b77de7c3c | no | 2 |
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| 27 | Non Patent Literature | npl_30_horowitz_mixer.pdf | 496009<br>3ce8619ffd42219a7ff27442d51cfe28be321b0c | no | 4 |
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**<u>National Stage of an International Application under 35 U.S.C. 371</u>**
**If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.**

**<u>New International Application Filed with the USPTO as a Receiving Office</u>**
**If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.**

# Electronic Patent Application Fee Transmittal

| | |
|---|---|
| **Application Number:** | 14316489 |
| **Filing Date:** | |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Filer:** | Jed Margolin |
| **Attorney Docket Number:** | |

Filed as Small Entity

## Utility under 35 USC 111(a) Filing Fees

| Description | Fee Code | Quantity | Amount | Sub-Total in USD($) |
|---|---|---|---|---|
| **Basic Filing:** | | | | |
| Utility filing Fee (Electronic filing) | 4011 | 1 | 70 | 70 |
| Utility Search Fee | 2111 | 1 | 300 | 300 |
| Utility Examination Fee | 2311 | 1 | 360 | 360 |
| **Pages:** | | | | |
| **Claims:** | | | | |
| Independent Claims in Excess of 3 | 2201 | 2 | 210 | 420 |
| **Miscellaneous-Filing:** | | | | |
| **Petition:** | | | | |

| Description | Fee Code | Quantity | Amount | Sub-Total in USD($) |
|---|---|---|---|---|
| **Patent-Appeals-and-Interference:** | | | | |
| **Post-Allowance-and-Post-Issuance:** | | | | |
| **Extension-of-Time:** | | | | |
| **Miscellaneous:** | | | | |
| | **Total in USD ($)** | | | **1150** |

# Electronic Acknowledgement Receipt

| | |
|---|---|
| **EFS ID:** | 19428582 |
| **Application Number:** | 14316489 |
| **International Application Number:** | |
| **Confirmation Number:** | 1025 |
| **Title of Invention:** | Flame Sensing System |
| **First Named Inventor/Applicant Name:** | Jed Margolin |
| **Customer Number:** | 23497 |
| **Filer:** | Jed Margolin |
| **Filer Authorized By:** | |
| **Attorney Docket Number:** | |
| **Receipt Date:** | 26-JUN-2014 |
| **Filing Date:** | |
| **Time Stamp:** | 19:14:39 |
| **Application Type:** | Utility under 35 USC 111(a) |

## Payment information:

| | |
|---|---|
| Submitted with Payment | yes |
| Payment Type | Credit Card |
| Payment was successfully received in RAM | $1150 |
| RAM confirmation Number | 5884 |
| Deposit Account | |
| Authorized User | |

## File Listing:

| Document Number | Document Description | File Name | File Size(Bytes)/ Message Digest | Multi Part /.zip | Pages (if appl.) |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| 1 | Fee Worksheet (SB06) | fee-info.pdf | 35583<br>813a1d7528bc9dca418b212b68b78c1fbab9a2dd | no | 2 |
| **Warnings:** | | | | | |
| **Information:** | | | | | |
| | | **Total Files Size (in bytes):** | 35583 | | |

**This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.**

**New Applications Under 35 U.S.C. 111**
**If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.**

**National Stage of an International Application under 35 U.S.C. 371**
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**New International Application Filed with the USPTO as a Receiving Office**
**If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.**