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NBS TECHNICAL NOTE 593

Wire-Bond Electrical Connections: Testing, Fabrication and Degradation—

A Bibliography 1957–1971

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[3] Located at Boulder, Colorado 80302.

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Wire-Bond Electrical Connections: Testing, Fabrication and Degradation– A Bibliography 1957-1971

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Wire-Bond Electrical Connections: Testing, Fabrication and Degradation — A Bibliography 1957-1971

Harry A. Schafft

More than 245 papers relevant to wire-bond type electrical interconnections used in microelectronic and low-power discrete and hybrid devices are listed together with key words. The bibliographic search concentrated on compiling papers which appeared in the period from 1965 to 1970, inclusive. The selection of papers was generally limited to those that were pertinent to wire bonds where the wire diameter is less than about 50 μm (2 mils) and where the wire is bonded by either thermocompressive or ultrasonic means. Two indexes are provided: (1) an Author Index and (2) a Key Word Index. The latter includes a tabulation of the literature citations.

Key Words: bibliography; degradation (wire bond); discrete devices; electrical interconnection; fabrication (wire bond); failure (wire bond); hybrid circuits, integrated circuits; microelectronics; reliability; testing (wire bond); wire bond.

1. Introduction

Small-diameter (< 50 μm) wire is the principal means of making electrical connections (1) between the semiconductor die and the terminals leading outside the package of microelectronic and low-power discrete and hybrid devices, and (2) between different dice on a single device header of hybrid circuits. This *electrical interconnection* or *wire-bond,** as it will be referred to here, is considered to be the wire between two bonded points, the bonds, the bonding surface films, and the underlying material in the immediate vicinity of the bonds. *Failure* of a wire bond is one of the principal failure modes in these devices. As a result, great importance has been attached to the following three subject areas: (1) methods for testing and evaluating wire bonds, (2) optimization of the fabrication processes for making wire bonds, and (3) mechanisms of degradation and failure of wire bonds.

This bibliography is a *compilation* of more than 245 published articles, U. S. government reports, U. S. patents, and conference presentations relevant to wire bonds in these three subject areas of testing, fabrication, and degradation.

The *selection of papers* is generally limited to those that are pertinent to wire bonds that have wire diameters of less than about 50 μm (2 mils) and are bonded by either thermocompressive or ultrasonic means. This is the class of wire bonds that is of most interest in microelectronics. An attempt was made to make the collection of papers on test and evaluation methods complete while the collection of articles in the area of fabrication and degradation is meant to be representative. Some interesting papers could not be included because of restrictions on their distribution. It is quite possible that some papers which should have been included were overlooked. The compiler would appreciate having such omissions called to his attention.

Acknowledgement

The author is pleased to acknowledge the significant contributions made by Elaine C. W. Cohen who assisted in collecting much of the material and performed both expeditiously and cheerfully many of the tedious labors that the compilation of such a bibliography requires. Thanks also go out to Kathryn O. Leedy, Frank R. Kelly, Terry A. Schultz and especially to Ruth E. Joel for assisting in various stages of the preparation of the bibliography; to Kaye E. Dodson for typing the final draft with such dispatch; and to W. Murray Bullis, Frank F. Oettinger, and George J. Rogers for their assistance with various aspects of the format.

This work was performed under the Joint Program on Methods of Measurement for Semiconductor Materials, Process Control, and Devices and was supported in part by the National Bureau of Standards, the Defense Nuclear Agency, and the U.S. Navy Strategic Systems Project Office.

* Certain words or phrases are printed in script to assist in scanning.

2. Bibliography Format, In Brief

The two entries shown on the next page are used to indicate the various elements of the format which are encircled and numbered. The numbers refer to the explanatory notes listed below. A more complete description of the organization and format is given in Appendices A thru D.

Explanatory Notes:

1. *Identification code* for entry. The first two digits give the year of publication; the letter is the initial of the first author's surname; the last digit serves to distinguish entries which have the same first three alphanumerics. Entries are arranged in the bibliography (pp. 21-48) according to these codes.

2. *Author(s)*, editor(s), or organization (if no name(s) are provided). For *Author Index*, see page 4.

3. *First-level key word*† for general subject area. First-level key words are capitalized for identification purposes.

4. *Descriptors*†† to identify the kind(s) of wire bond(s) pertinent to or described under the subject of the first-level key word (in this example, DEGRADATION).

5. *Second-level key word*† to narrow the subject area of the first-level key word above it (in this example Mechanism modifies DEGRADATION). The first letter of a second-level key word is capitalized.

6. *Third-level key word*† to modify the second-level key word at its left (in this example intermetallics modifies Mechanism). All the letters are in lower-case. Some third-level key words include words in parentheses.

7. *Order* of first-level key words for subject area indicates the relative emphasis or importance given the respective areas in the entry. In this example, the main subject is degradation with test and fabrication following in that order.

8. *First-level key word* indicating approach or type of entry. Only one such key word is used per entry and it is listed last.

9. *Reading priority* is suggested by underlining the identification code and the appropriate key word(s) of those entries that are of such relative importance in a particular area that they should be seen first. The codes for these entries are also underlined in Section 4B (pp. 12-20).

10. *Title*

11. *Source*. See Appendix B (p. 49) and Table 1 (p. 50) for sources used. See Table 2 (p. 51) for *abbreviations* used for journals and conferences.

12. *Availability note* refers to an address listed in the Appendix. If the number is in brackets the address is one to which an order may be placed for a copy of the entry; if it is in parentheses the address is that of the first author's place of work at the time of publication.

13. *Availability note*. When the report citation is followed by a number preceded by the letters AD or PB, or by the letter N, the report is available from the National Technical Information Service (NTIS), Sills Building, 5285 Port Royal Road, Springfield, Virginia 22151 by using this NTIS accession number when ordering.

14. In some entries, additional *guidance* is provided in brackets. For example, reference may be made to the pages in the paper that are relevant to the subject.

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† The three levels of *key words* indicating subject area are listed in alphabetical order in Section 4A (pp. 8-11). Page numbers are provided to assist in locating these key words in Section 4B (pp. 12-20) where they are ordered by subject: test, fabrication, and degradation. With each key word in Section 4B is a tabulation of literature citations (using their identification codes). In both *Sections 4A and 4B*, each key word that may require additional definition is followed by an *explanatory phrase in brackets*. An exception is made for the test method key words. Key words for the test methods are listed in alphabetical order in *Table 4* (p. 54) with a brief description for each method. The descriptions are oriented to their function in testing wire bonds.

†† *Descriptors* are listed in Section 4B (pp. 12-20) with a tabulation of literature citations.

1 67P1 Parker, C. D.
2 INTEGRATED SILICON DEVICE TECHNOLOGY 10
VOLUME XV RELIABILITY
Contract No. AF 33(615)-8306,
May 1967. AD 655082 [see pp. 35-65] 14
3 DEGRADATION-bond: TC, US; wire: Al, Au;
film: Al, Au, Au/Mo; substrate: FeNiCo, 13
Si
Stress: process; thermal
Part: bond
5 Mechanism: contamination; intermetallics 6
Failure Rates
TEST
7 Screening Procedures
FABRICATION-bond: TC, US; wire: Au, Al;
film: Ag, Ag/Cr, Al, Au, Au/Mo;
substrate: Si
Evaluation: metal systems; metallization; wire
Procedure
8 REVIEW

9 68A3 Anderson, J. H., Jr. and W. P. Cox
AGING EFFECTS IN AU-AL AND AL-AL
BONDS USED IN MICROELECTRONICS
Proc. 7th Annual Reliability and
Maintainability Conf., pp. 533-536, 11
San Francisco, Calif., July 1968.
[7], (21) 12
DEGRADATION-bond: TC, US; wire: Al, Au; film:
Al 4
Stress: thermal
Part: wire; bond
Mechanism: anneal, intermetallics
Test: pull; resistance
FABRICATION-bond: TC; wire: Au; film: Al
Bonding Surface: film thickness
EXPERIMENTAL

3. Author Index

4. Key Word Index Introduction

The three levels of key words indicating subject area are listed in alphabetical order in Section 4A with page numbers where they are located in section 4B. In section 4B these key words and descriptors are listed by the three subject areas: test, fabrication, and degradation. By each key word and descriptor is a tabulation of identification codes of entries to which this key word or descriptor was assigned in the bibliography. Key words and descriptors that may require additional definition are followed by explanatory phrases, in brackets. An exception is made for the test method key words. They are listed in alphabetical order in Table 4 with brief descriptions for each method.

To help identify key words of different level: first-level key words are in uppercase, second-level key words have only the first letter capitalized, and third-level key words are in lower-case. Descriptors are also in lower-case and are listed immediately below the associated first-level key words in section 4B.

4A Alphabetical Key Word Listing

KEY WORD - [DESCRIPTIVE PHRASE]

PAGE NUMBER IN SUBJECT AREA LISTING OF KEY WORDS (Section 4B)

TEST

TEST [test, evaluation, and screening methods for wire bonds]

bond

TC [thermocompression]
64D1, 64H2, 65B1, 65C2, 67A1, 67G1, 67H1, 67S4, 68D2, 68F1, 68P1, 68R1, 69A1, 69K4, 69S1, 70A1, 70B1, 70H2, 71B3, 71H2, 71S1

US [ultrasonic]
59J1, 60J1, 61J1, 62J1, 64C2, 64W1, 66R1, 67P2, 67R1, 67R2, 68D2, 68F1, 68R1, 69B6, 69B7, 69K1, 69K4, 69P1, 70A1, 70B2, 70D2, 71B1, 71B4, 71G1

wire

Al [aluminum hardened with silicon]
64D1, 66R1, 67R1, 67R2, 68D2, 68R1, 69B5, 69B6, 69B7, 69K1, 69K4, 69P1, 70A1, 70B2, 70D2, 71B1, 71B4, 71G1

Al (pure) [pure aluminum]
67R2

Au [gold]
65C2, 67A1, 67G1, 67H1, 68D2, 68L1, 68P1, 69A1, 69B5, 69K4, 69S1, 70A1, 70B1, 70H2, 71B3, 71H2, 71S1

Au/Cu [gold plated copper]
67S4

film [metal or metal film(s) of bonding surface]

Ag [silver]
70B1, 71B3

Al [aluminum]
65C2, 67A1, 67R1, 67R2, 68D2, 68P1, 69B6, 69B7, 69K1, 69K4, 69P1, 70A1, 70B2, 70D2, 71B1, 71B4, 71G1, 71S1

Au [gold]
67A1, 67H1, 67S4, 68D2, 69P1, 69K4, 70A1, 70B1, 70D2, 71B3, 71S1

Au/Cr [gold on chromium]
66R1, 67R1, 67R2

Au/Mo [gold on molybdenum]
67G1

substrate [material underlying bonding surface film(s)]

alumina
66R1, 67R1, 67R2

beryllia
66R1, 67R1

ceramic
67S4

sapphire
66R1, 67R1, 67R2

Si [silicon]
67R1, 67R2

silica (96%)
67R1, 67R2

application

plastic devices
70B1, <u>70C2</u>, 70H2, 71B3, 71H2

hybrid devices
70S2, 71S1

Description [of the test method]

air blast
68D2

bond monitor
59J1, 60J1, <u>61J1</u>, 62J1, <u>64W1</u>, 67P2, 69B6, <u>69B7</u>, 71B4

centrifuge
63W1, 66L4, 66P1, 68B1, 68D2, 68I1, <u>69B2</u>, 69O1, 69S4, 70B7, 70D3

IR monitor
67B1, 67S4, 68B1

mechanical shock
63W1, 66P1, 67I1, 68D2, <u>69B2</u>, 69S4, 70D3, <u>71N2</u>, <u>71K1</u>

mechanical shock (radiation-induced)
<u>68F1</u>

metallurgical exam
68B1

MIL-STD-883
<u>68D2</u>, <u>69O1</u>, 70C2, 71N1

MIL-STD-750B
66P1

noise
65M1

pull
63W1, <u>65W1</u>, 67H1, 68B1, 68D2, 68P1, 69K1 69O1, <u>69S1</u>, <u>70A1</u>, <u>70B7</u>, 71N1, <u>71N2</u>

pull (nondestructive)
65B1, <u>69S1</u>

resistance
66M1, 68D2, 70B2, 70H2, 71H2, 71N1, <u>71N2</u>

shear
67A1, 68D2

temperature cycle
66L4, 66P1, 68D2, 69O1, 69S4, 70H2, 71H2

thermal shock
63W1, 68D2, 69B2, 69S4, 70D3

US probe
59R1, 67B4

US stress
<u>69K4</u>, 70B7

vibration (fatigue)
<u>66I1</u>, 68D2, 69S4, 70D3

vibration (monitored)
66L4, 68D2, 70D3

vibration (variable frequency)
63W1, <u>66I1</u>, 66P1, 68D2, 69S4, 70D3

TEST - FABRICATION

visual inspection
66P1, 66L4, 68D2, 68R1, 69O1, 71N1

visual inspection (SEM)
69S1, 71N1

x-ray
66L4, 68D2, 68L1, 69S1

Evaluation [of the test method]
air blast
69P1

centrifuge
66L4, 67G1, 68H4, 69O1

IR monitor
67S4

mechanical shock
68F1, 68H4

mechanical shock (radiation-induced)
68F1

MIL-STD 883
70S2

noise
68B1

pull
67R2, 68H4, 70B8, 71B1

pull (nondestructive)
64D1

resistance
67R2, 68B1, 70H2, 71H2

shear
67G1

temperature cycle
66L4, 68H4, 69B1, 70H2, 71H2

thermal shock
65H3, 68H4, 69B1, 69P1, 70B1, 71B3

vibration (monitored)
66L4

vibration (variable frequency)
69S4

visual inspection
64H2, 66L4, 67G1, 68H4, 69K1, 69O1, 69P1, 69S4

x-ray
66L4, 67G1, 68H4

Correlation [between methods for the same type of wire bond]
bond monitor
69B7

centrifuge
65B1

mechanical shock-(radiation-induced)
69P1, 70D2

pull
65B1, 66R1, 67R1, 67R2, 69A1, 69B7, 69K1, 69P1, 70D2, 71G1

pull (nondestructive)
69A1

resistance
66R1, 67R1, 67R2

visual inspection
67B7, 67G1, 69K1, 69P1, 70D2, 71G1

Application [information relevant to a particular test method]
bond monitor
64C2, 70B7, 71K2

mechanical shock
61A2, 69K2

mechanical shock (radiation-induced)
67G2, 70M2

MIL-STD-883
69B8, 69D3, 71N1

pull
67S3, 68A1, 69B5, 69D1, 70A6, 70B8, 71B4

temperature cycle
69K2, 70P2, 70V1

thermal shock
69K2, 70P2

US probe
69D2

vibration (fatigue)
69K2

visual inspection
68H1

Precautions [in the use of a test method]
resistance
65C2, 68E1

Screening Procedures [where a series of tests is used to cull out unsatisfactory wire bonds]
66P1, 67G1, 67P1, 68D2, 69D3, 69L1, 70S2, 71N1, 71S1

FABRICATION
bond
TC [thermocompression]
57A1, 57A2, 58C1, 61A1, 62M1, 63M1, 63P1, 63W1, 64A1, 64D1, 64H1, 64H2, 64J1, 64M1, 65B1, 65C1, 65C5, 65H1, 65H2, 65R1, 65S1, 65S3, 66A1, 66A2, 66B1, 66B3, 66B4, 66B6, 66C1, 66E1, 66G2, 66H1, 66K3, 66L1, 67A2, 67B2, 67C1, 67H1, 67K1, 67P1, 67R4, 67S1, 67S5, 68A2, 68A3, 68B1, 68D1, 68G1, 68H3, 68H5, 68J1, 68K1, 68M1, 68M2, 68M3, 68P1, 68R2, 68T2, 69A2, 69B3, 69G2, 69O2, 69S1, 69S2, 69S5, 69T2, 70A2, 70D4, 71B2, 71M1, 71P1, 71R1

US [ultrasonic]
59A1, 59J1, 59W1, 60J1, 60J2, 60W1, 61D1, 61J1, 62P1, 63W1, 64D2, 65D1, 65J1, 65N1, 66B1, 66B6, 66E1, 66H1, 66L3, 66R1, 67B2, 67H2, 67J1, 67L1, 67P1, 67R1, 67R2, 67S1, 67T1, 68B1, 68D1, 68H3, 68K1, 68M1, 68M2,

FABRICATION

68S1, 68T2, 68U1, 68U2, 68U3, 68U4, 68U5, 69B2, 69B3, 69B5, 69B6, 69K1, 69K3, 69L2, 69O2, 69P1, 69S1, 69S2, 69S5, 69T2, 69U1, 69U2, 70B2, 70B3, 70B5, 70B6, 70B7, 70B8, 70C1, 70D2, 70D4, 70P1, 70W1, 71B1, 71B2, 71B4, 71D1, 71G1, 71H1, 71J1, 71M1, 71P1, 71P2, 71R1

wire

Ag [silver]
57A1, 57A2, 58C1, 61A1, 62M1, 63W1, 64A1, 66A1, 66C1, 66G2

Al [aluminum hardened with silicon]
57A1, 57A2, 58C1, 61A1, 63M1, 63W1, 64A1, 64D1, 64S1, 65B1, 65D1, 65R1, 66A1, 66B4, 66G2, 66R1, 67B2, 67C1, 67K1, 67L1, 67P1, 67R1, 67R2, 67S1, 67S5, 67V1, 68G1, 68H3, 68K1, 68M2, 68R2, 68T2, 68U1, 69B2, 69B3, 69B5, 69B6, 69K1, 69K3, 69O2, 69P1, 69S1, 69S2, 69U1, 70B2, 70B3, 70C1, 70D2, 70D4, 70P1, 71B1, 71B2, 71G1, 71J1, 71P1, 71P2, 71R1

Al/Mg [aluminum hardened with magnesium]
67V1, 68U1, 69U1, 70P1

Al (pure) [pure aluminum]
67R2, 67V1, 69O2

Au [gold]
57A1, 57A2, 58C1, 61A1, 62M1, 63M1, 63P1, 63W1, 64A1, 64C1, 64H1, 64H2, 64M1, 64S1, 65B1, 65C5, 65D1, 65H1, 65H2, 65R1, 65S1, 66A1, 66B3, 66B4, 66C1, 66G2, 66L1, 66W1, 67B2, 67C1, 67H1, 67K1, 67P1, 67S1, 67S5, 67T1, 68A3, 68H3, 68K1, 68M2, 68M3, 68P1, 68R2, 68S1, 68T2, 68U1, 69A2, 69B3, 69G2, 69P1, 69S1, 69S2, 69S3, 69U1, 70A2, 70A3, 70D4, 71B2, 71P1

Au/Ag [gold with silver added]
66W1

Au/Cu [gold plated copper]
61A1, 66C1

Au/CuBeO [gold plated CuBeO]
71D1

Au/Ga [gold with gallium added]
68S1

Au/Ni [gold covered nickel]
64C1

Au/Pt [gold covered platinum]
64C1

Au/W [gold covered tungsten]
64C1

Cu [copper]
57A1, 57A2, 61A1, 62M1, 63M1

Cu/Ni [gold plated nickel]
66C1

Pb [lead]
57A2

Pl [palladium]
63W1

Pt [platinum]
57A2, 63M1, 65C1

Sn [tin]
57A2

Sn/Cu [tinned copper]
61A1

Ti [titanium]
63M1

Zr [zirconium]
63M1

film

Ag [silver]
63W1, 66G2, 67P1

Ag/Al [silver on aluminum]
63W1, 68T2

Ag/Cr [silver on chromium]
63W1, 64S1, 66G2, 67K1, 67P1, 67S5, 68K1

Ag/Cr-Al [silver on chromium-aluminum alloy]
63WI

Al [aluminum]
62M1, 63M1, 63W1, 64D1, 64H1, 64H2, 64M1, 64S1, 65B1, 65C5, 65H1, 65H2, 65R1, 65R2, 65S1, 66A1, 66B3, 66B4, 66G2, 66H1, 66W1, 67B2, 67C1, 67H1, 67K1, 67L1, 67P1, 67R1, 67R2, 67S1, 67S5, 68A3, 68G1, 68H3, 68K1, 68M2, 68M3, 68P1, 68R2, 68T2, 69A2, 69B2, 69B5, 69B6, 69K1, 69O2, 69P1, 69S1, 69S2, 69U1, 70A2, 70B2, 70B3, 70C1, 70D2, 70D4, 71B1, 71G1, 71J1, 71P1, 71P2

Al/Cr [aluminum on chromium]
63P1, 66H1, 67B2, 67R2

Au [gold]
63W1, 64D1, 64S1, 64B1, 65C5, 65R1, 66A1, 66B4, 66G2, 66H1, 67B2, 67H1, 67K1, 67P1, 67S1, 68H3, 68K1, 68R2, 69A3, 69B2, 69B3, 69K3, 69O2, 69P1, 69S1, 69U1, 70D2, 70D4, 71G1, 71J1, 71P1

Au/Ag [gold on silver]
65C5

Au/Ag/Cr [gold on silver on chromium]
69S3

Au/Ag/Cr-Al [gold on silver on chromium-aluminum alloy]
63W1

Au/Al [gold on aluminum]
63M1

$AuAl_2$ [gold-aluminum compound]
68T2

Au/Co [gold on cobalt]
65C5

Au/Cr [gold on chromium]
63P1, 63M1, 65C5, 66H1, 66R1, 67B2, 67L1, 67R1, 68M2, 69S2

FABRICATION

Au/Cu [gold plated copper]
71D1

Au/Cu/Ti [gold on copper on titanium]
68M2

Au/Cr/Al [gold on chromium on aluminum]
68K1

Au/Mo [gold on molybdenum]
65C6, 66G2, 67C1, 67P1, 67S1, 67S5, 68M2, 69S2, 69S3

Au/Mo/Al [gold on molybdenum on aluminum]
67S5, 70A2

Au/Mo/Mn [gold on molybdenum on manganese]
69B3

Au/Mo/Pt [gold on molybdenum on platinum]
67C1, 67K1, 68K1

Au/Ni [gold on nickel]
65C5, 68M2

Au/NiCr [gold on nichrome]
65S1

Au/Pl [gold in palladium]
63W1

Au/Pt/Ti [gold on platinum on titanium]
67S5, 68M2

Au/Pt/Ti/Pt [gold on platinum on titanium on platinum]
69S3

Au/Ti/Al [gold on titanium on aluminum]
69S3, 70A2

Bi [bismuth]
62M1

Cr [chromium]
68H3, 68T2

Cr/Al [chromium on aluminum]
64S1, 67S5, 69S3

Cu/NiCr [copper or nichrome]
65S1

Ga [gallium]
62M1

In [indium]
62M1

Ni [nickel]
66A1

NiCr [nichrome]
63M1

Pl [palladium]
64S1

Pt [platinum]
64H2, 64S1

Pt/Ti [platinum on titanium]
68M2

Sb [antimony]
62M1

Ta [tantalum]
63M1

Ti [titanium]
63M1

thick film

Ag [silver]
69B3

Ag/Pd [silver-palladium composition]
69B3

Au [gold]
69B3

Au/Pd [gold-palladium composition]
69B3

Au/Pd/Pt [gold-palladium-platinum composition]
69B3

Au/Pt [gold-platinum composition]
69B3

Pd/Ag [palladium-silver composition]
69B3

substrate

Al [aluminum]
66B4

alumina
65R2, 65S1, 66C1, 66R1, 67L1, 67R1, 67R2, 68H3

beryllia
66R1, 67L1, 67R1

BN [boron nitride]
65R2

ceramic
63P1, 66H1

epoxy
71D1

Fe/Ni/Co [iron-nickel-cobalt alloy]
65B1, 66B4, 69K3, 71G1, 71J1

Ge [germanium]
57A1, 57A2, 57C1, 61A1, 62M1, 65D1

glass
63P1, 65D1, 65H1, 65H2, 65R2, 66C1, 66H1, 67L1, 68H3

sapphire
66R1, 67L1, 67R2

Si [silicon]
57A1, 57A2, 57C1, 61A1, 62M1, 63M1, 64A1, 64H2, 65C1, 65C5, 65D1, 65R2, 65S1, 66A1, 66B4, 67L1, 67P1, 67R2, 68H3, 68T2

silica (96%)
67L1, 67R1, 67R2

application

hybrid devices
67L1, 67R1, 68H3, 68M3, 69T2

Theory [of bonding]

TC [thermocompression]
57A2, 61A1, 63M1, 64A1, 66A1, 66B4, 66B6, 67B2, 68B1, 69S1

FABRICATION

US [ultrasonic]
59A1, 59J1, 59W1, 60J1, 60J2, 60W1, 61J1, 62P1, 65D1, 65J1, 65N1, 65P1, 66B6, 67B2, 67J1, 68B1, 68U2, 68U3, 68U4, 69P1, 69S1, 69U1, 70B3, 70B8, 71P2

Evaluation [of]
TC [thermocompression bonding]
63P1, 63W1, 66B1, 66C1, 66E1, 67B2, 67S1, 68H3, 68K1, 68M1, 69C1, 69S1, 69T2, 70D4, 71B2

US [ultrasonic bonding]
60J2, 61J1, 62P1, 63W1, 66B1, 66E1, 66R1, 67B2, 67L1, 67R1, 67S1, 68H3, 68K1, 68M1, 69C1, 69S1, 69T2, 70D4, 71B2, 71P2

wire bond [wire bonds, in general, and versus other bonding methods]
67L1, 69B2, 69B3, 69C1, 69S5, 70D4, 70M1, 71B2, 71M1

apparatus (US) [ultrasonic bonding equipment]
61D1

bond (adhesion)
57A2, 63M1, 63P1

bond (ball)
64M1, 65B1, 65R1, 66B4, 66E1, 66G2, 66L1, 67B2, 67C1, 67K1, 68M3, 68R2, 69B6, 69C1

bond (stitch)
65D1, 65R1, 66E1, 66L1, 67B2, 68M3, 68R2, 69C1

bond (wedge)
65B1, 65R1, 66B4, 66E1, 66G2, 66L1, 67B2, 67C1, 67K1, 68R2, 69C1

bond (general)
66C2

metal system [of the wire bond, i.e. wire-metallization-substrate, for]

(TC) [thermocompression bonds]
63W1, 64S1, 65C5, 65R2, 66G2, 67K1, 67P1, 67S5, 68M2, 68T2, 70A2

(US) [ultrasonic bonds]
61J1, 67P1, 67R2, 68M2, 68T2

(general) [bond type not specified]
66W1, 69S3

metallization
65C5, 66H1, 67C1, 67P1, 68T2, 69B3, 69S2

package
67G1

temperature control [for thermocompression bonding]
66L1, 67K1, 68H3, 71B2

tool
(TC) [to make thermocompression bonds]
63W1, 64M1, 65B1, 66B4, 68H3

(US) [to make ultrasonic bonds]
63W1

wire
(TC) [for thermocompression wire bonds]
65B1, 65R1, 65R2, 66G2, 67P1, 68H3, 68R2, 71R1

(US) [for ultrasonic wire bonds]
63W1, 67P1, 68U1, 69U1, 70C1, 70P1, 71R1

(ribbon)
65B5, 69B6

(general)
66W1

Procedure [for making a wire bond]
TC [thermocompression]
57A1, 57C1, 60J2, 61A1, 62M1, 64H2, 64M1, 65C1, 65R1, 65S1, 66A2, 66L1, 67A2, 67B2, 67H1, 67K1, 67P1, 68A2, 68B1, 68H5, 68K1, 68R2, 69G2, 69S1, 71B2

US [ultrasonic]
60J1, 65J1, 65N1, 67B2, 67P1, 67R2, 67T1, 68B1, 68K1, 69K2, 69K3, 69S1

Schedule [optimization of procedures and processes for making wire bonds]
TC [thermocompression]
57A1, 63M1, 63P1, 64A1, 64H2, 65B1, 66A1, 66C1, 67B2, 67H1, 68B1, 68K1

US [ultrasonic]
59A1, 59W1, 60J1, 60W1, 61J1, 63W1, 65J1, 66R1, 67J1, 67L1, 67R1, 67R2, 68K1, 68U1, 68U4, 69P1, 69U1, 70B8, 70D2

Variables [effects of process and material variables on quality of wire bond]
TC [thermocompression bond]
57A1, 57C1, 59A1, 61A1, 63M1, 63P1, 64A1, 64H2, 65H1, 65H2, 66A1, 66B1, 66C1, 66L1, 67B2, 67H1, 67K1, 68P1, 69B3

US [ultrasonic bond]
59W1, 60J1, 60J2, 60W1, 61J1, 63W1, 65D1, 65J1, 65N1, 66B1, 67J1, 67R1, 69B3, 69P1, 70D2, 71J1

Apparatus [of bonding machines and accessories]
adjustment (TC) [of thermocompression bonding apparatus]
67H1, 63W1

adjustment (US) [of ultrasonic bonding apparatus]
64D2, 68U5, 69B6, 69P1, 69U1, 70B3, 70D2, 71B4, 71H1

description (TC) [of thermocompression bonding apparatus]
68D1, 68H3

description (US) [of ultrasonic bonding apparatus]
60J1, 62P1, 63W1, 67B2, 67L1, 67R2, 68D1, 69U1

FABRICATION

design (TC) [of thermocompression bonding apparatus]
63M1, 63W1, 64J1, 64M1, 65S3, 66A2, 66K3, 67A2, 67R4, 68H5

design (US) [of ultrasonic bonding apparatus]
59A1, 59W1, 60J2, 60W1, 63W1, 65D1, 65J1, 65N1, 67H2, 67J1, 67S1, 68B1, 68U5, 69L2, 69U1, 69U2, 70B2, 70B3, 70B6, 70D2, 70W1, 71B4, 71J1

Control [importance of control of]
force (TC) [applied in making thermocompression bond]
68P1

force (US) [applied in making ultrasonic bond]
68U4, 70C1

power (US) [used in making ultrasonic bond]
68U4, 70C1

temperature (TC) [in making thermocompression bond]
64H2, 65H1, 65H2, 65S1, 66C1, 66L1, 68B1, 68H3, 68J1, 68M3, 68P1

temperature (US) [in making ultrasonic bond]
68B1

time (US) [for making ultrasonic bond]
68U4, 70C1

Tool [bonding]
adjustment (US) [for ultrasonic bonding]
69U1, 70B2, 70B3, 71H1, 70D2

design (TC) [for thermocompression bonding]
63W1, 64H2, 65B1, 65S3, 66B4, 66C1, 67B2, 67R3, 67S1, 68B1, 68H3, 69G1, 71B2

design (US) [for ultrasonic bonding]
59W1, 60W1, 63W1, 65D1, 67R1, 67R3, 67S1, 67T1, 68U1, 69G1, 69P1, 70B2, 70B7, 70D2, 71B1, 71D1, 71G1, 71J1

oscillation (US) [of the ultrasonic bonding tool]
69B6, 70B2, 70B3, 70D2, 70W1, 71B1, 71D1, 71H1

wear (TC) [of the thermocompression bonding tool]
68H3

wear (US) [of the ultrasonic bonding tool]
67R1, 71J1

Rigidity [importance of in]
apparatus
67R2, 68U5, 69P1, 69U1, 70B2, 70B3, 70B7, 70B8, 70D2, 71B1, 71B4, 71J1

terminal [device]
68U5, 69P1, 70D2, 71B2

package
69U1, 70D2, 71J1

Wire
care
64C1, 67B2, 68S1, 70A3

contamination
65K1, 70A3, 70B3

electrical characteristics
66R1, 67R1, 69O2, 70A7

fabrication
69O2, 70S1

mechanical characteristics
63W1, 64C1, 65K1, 66L3, 67R2, 67V1, 68G1, 68S1, 68U1, 69D2, 69O2, 69U1, 70A3, 70A4, 70B3, 70B5, 71B4, 71R1

size
66C1, 66K2, 68B2, 70A3, 70A4, 70A5

topography [of the surface]
65K1, 69O2

Bonding Surface [of film(s) or metal substrate]
contamination
59W1, 60W1, 64H2, 65B1, 66B4, 66C1, 69A3, 69H1, 69P1, 70D2, 71G1

film thickness
64H1, 65C5, 65H1, 65H2, 66B3, 66G2, 66R1, 67L1, 67R1, 67R2, 68A3, 69A2, 69A3, 69K1, 69K3, 70D2, 71G1, 71P1

mechanical characteristics
59W1, 60W1, 69A3, 69P1, 71H3

metal system
67C1, 68T2, 71G1

orientation [with respect to the bonding tool]
68S1

preparation
59W1, 60W1, 63P1, 64H1, 65H1, 65H2, 65R2, 66H1, 67C1, 67L1, 67R2, 68T2, 69A3, 69B3, 70A2, 70B3, 71G1

topography
59W1, 60W1, 63P1, 64H2, 65D1, 66R1, 67L1, 67R1, 67R2, 69A3, 69P1, 70D2, 70P1, 71J1, 71P2

Test [used to evaluate fabrication procedures and processes]
bond monitor
59A1, 59W1, 61J1, 65J1, 65P1, 67J1

bond temperature
61J1

centrifuge
63W1, 64M1, 65B1, 65R1, 67K1, 68R2, 69B2

interferometer
70B2, 70W1

mechanical shock
63W1, 64M1, 65R1, 68R2, 69B2

metallurgical exam
59W1, 60J1, 60J2, 60W1, 61J1, 65H2, 65J1, 66C2, 67J1

photoelastic stress analysis
61J1

FABRICATION - DEGRADATION

pull
57C1, 59W1, 60W1, 61A1, 63M1, 63P1, 63W1, 64H2, 65B1, 65C5, 65H1, 65H2, 65J1, 65S1, 66B4, 66C1, 66G2, 66R1, 66W1, 67H1, 67K1, 67L1, 67R2, 68B1, 68U1, 69B3, 6902, 69P1, 69S1, 69U1, 70B3, 70B7, 70B8, 70C1, 70D2, 71D1, 71G1

pull (nondestructive)
65B1, 66B4

radiotracer
61J1, 69H1

resistance
63M1, 63P1, 66G2, 66R1, 67R2, 70C1

shear
61D1, 64A1, 66A1

temperature cycle
63P1, 69B2

thermal shock
63P1, 63W1, 64M1, 66C1, 67R2

US probe
69D2

vibration (variable frequency)
63W1, 64M1, 65R1, 68R2

visual inspection
57A1, 60J1, 61A1, 63M1, 63P1, 67L1, 67R2, 68U1, 69P1, 69U1, 70C1, 70D2, 71G1

visual inspection (SEM)
69C2, 70B7, 70B8

Trouble Shooting [methods for locating and correcting deficiencies in fabricating procedures]
69U1, 71H1

DEGRADATION [degradation or failure]
bond
TC [thermocompression]
61G1, 64P1, 64S1, 64U1, 65C3, 65C4, 65C5, 65H1, 65H2, 65R1, 65R2, 65S2, 66B2, 66B3, 66B4, 66B5, 66G2, 66L2, 67A1, 67A3, 67B3, 67C1, 67G1, 67K1, 67K2, 67P1, 67S1, 67S5, 68A3, 68F1, 68G1, 68G2, 68H2, 68M1, 68M2, 68P1, 68R2, 69A2, 69B3, 69B4, 69K4, 69L1, 6901, 6902, 69S1, 69T1, 70A1, 70A2, 70B1, 70D1, 70H2, 70R1, 70S2, 70V1, 71B3, 71H2, 71P1, 71R1, 71S1

US [ultrasonic]
59W1, 60W1, 66K1, 66L3, 66R1, 67A3, 67C3, 67P1, 67L1, 67R1, 67R2, 67S1, 68A3, 68F1, 68M1, 68U1, 69B5, 69K3, 69K4, 69L1, 6901, 6902, 69P1, 69U1, 70A1, 70B2, 70B8, 70C1, 70P1, 70V1, 71B1, 71B4, 71G1, 71G2, 71P1, 71R1

wire
Al [aluminum hardened with silicon or so implied]
64S1, 64U1, 65C5, 65R1, 66B4, 66K1, 66R1, 67A3, 67C1, 67L1, 67P1, 67R1, 67R2, 67S1, 67S2, 67S5, 68F1, 68G1, 68G2, 68M1, 68R2, 68U1, 69B4, 69B5, 69K3, 69K4, 69L1, 6901, 6902, 69P1, 69S3, 69U1, 70A1, 70B2, 70C1, 70P2, 70V1, 71B1, 71B4, 71G2, 71P1, 71R1

Al (pure) [pure aluminum]
67R2, 70P2

Al/Mg [aluminum hardened with magnesium]
69P1, 70P1

Au [gold]
61G1, 64P1, 64S1, 64U1, 65C3, 65C4, 65C5, 65H1, 65H2, 65R1, 65R2, 65S2, 66B2, 66B3, 66B4, 66B5, 66G2, 66L2, 67A1, 67B3, 67C1, 67C3, 67G1, 67K1, 67K2, 67P1, 67S1, 67S5, 67A3, 68F1, 68G1, 68H2, 68L1, 68M1, 68M2, 68P1, 68R2, 69A2, 69B3, 69B4, 69K4, 69L1, 6901, 69S1, 69S3, 69T1, 70A1, 70A2, 70B1, 70D1, 70H2, 70P2, 70R1, 70V1, 71B3, 71G1, 71H2, 71P1, 71S1

film
Ag [silver]
69T1

Ag/Cr [silver or chromium]
67S5

Al [aluminum]
64P1, 64S1, 64U1, 65C3, 65C4, 65C5, 65H1, 65H2, 65R1, 65R2, 65S2, 66B2, 66B3, 66B5, 66B7, 66G2, 66K1, 67A1, 67B3, 67C1, 67C3, 67K1, 67K2, 67L1, 67P1, 67R1, 67R2, 67S1, 67S5, 67A3, 68G1, 68G2, 68H2, 68M2, 68P1, 68R2, 68U1, 69A2, 69B4, 69B5, 69K4, 69L1, 6901, 6902, 69S1, 69S3, 69T1, 70A1, 70A2, 70B2, 70C1, 70D1, 70R1, 70V1, 71B1, 71B4, 71P1, 71S1

Au [gold]
64S1, 64U1, 65C5, 65R1, 65S2, 67A1, 67P1, 67S1, 68H2, 68M2, 68R2, 69K3, 69K4, 69L1, 6901, 6902, 69S3, 69T1, 70A1, 70B1, 71B3, 71P1, 71S1

Au/Cr [gold on chromium]
66R1, 67L1, 67R1, 67R2

Au/Mo [gold on molybdenum]
65C5, 67C1, 67G1, 67P1, 67S1, 67S5, 69B4

Au/Mo/Al [gold on molybdenum on aluminum]
67S5, 70A2

Au/Mo/Pt [gold on molybdenum on platinum]
67C1

Au/Pt/Ti [gold on platinum on titanium]
67S5

Au/Ti/Al [gold on titanium on aluminum]
70A2

Cr/Al [chromium on aluminum]
67S5

Ni [nickel]
69T1

thick film
Ag/Pd [silver-palladium composition]
69B3

DEGRADATION

Au [gold]
69B3, 71G2

substrate
alumina
65R2, 66R1, 67L1, 67R2

beryllia
66R1, 67L1

BN [boron nitride]
65R2

FeNiCo [iron-nickel-cobalt alloy]
64S1, 66B4, 66K1, 67P1, 69K3

glass
65H1, 65H2, 65R2

sapphire
66R1, 67L1, 67R2

Si [silicon]
61G1, 64S1, 65R2, 65S2, 67L1, 67P1, 67R2, 69U1

silica (95%)
67R2, 67L1

application
plastic device
68L1, 69T1, 70B1, 70B4, 70H1, 70H2, 71B3, 71H2

hybrid devices
67L1, 70S2, 71L1, 71S1

Stress [that produces a weakened wire bond as a result of the fabrication process or that results in degradation or failure of an already completed wire bond]
electrical
67B3

mechanical
70W2

moisture
66B7, 69T1, 70B4, 70H2, 71H2, 71L1

process
59W1, 60W1, 61G1, 64P1, 64U1, 65R2, 65S2, 66B2, 66B5, 66G1, 66K1, 66L3, 67A3, 67C2, 67G1, 67P1, 67L1, 67R1, 67R2, 67S1, 67S5, 68H2, 68L1, 68M2, 68P1, 68U1, 69L1, 69U1, 70B4, 70B8, 70C1, 71B1, 71B4, 71G1

radiation
66L2, 66O1

test (centrifuge)
64P1, 64U1, 65S2, 67G1, 67S1, 71S1

test (mechanical shock)
65U1, 71S1

test (mechanical shock (radiation-induced))
68F1

test (mechanical shock)
71S1

test (pull)
70A1, 70B8

test (temperature cycle)
66K1, 70B4, 70H1, 70H2, 71H2, 71L1, 71P1, 71S1

test (thermal shock)
64U1, 67G1, 67R2, 69T1, 70B1, 70B4, 70H1, 71B3, 71S1

test (US stress)
69K4

thermal
61B1, 64S1, 64U1, 65C3, 65C4, 65C5, 65H1, 65H2, 65R1, 65R2, 65S2, 66B3, 66B4, 66B5, 66G2, 66K1, 66R1, 67A1, 67B3, 67C1, 67C3, 67G1, 67K2, 67L1, 67P1, 67R1, 67R2, 67S1, 67S2, 67S5, 67A3, 68G1, 68G2, 68P1, 68R2, 68T1, 69A2, 69B3, 69B4, 69B5, 69K3, 69L1, 69O1, 69O2, 69P1, 69S1, 69S3, 69T1, 70A1, 70A2, 70B2, 70C1, 70P1, 70P2, 70R1, 70V1, 71G2, 71P1, 71R1

Part [part affected, primarily of the wire bond]
bond
59W1, 60W1, 61B1, 64P1, 64S1, 64U1, 65C3, 65C4, 65C5, 65H1, 65H2, 65R1, 65R2, 65S2, 66B2, 66B3, 66B4, 66B5, 66G1, 66G2, 66K1, 66L2, 66O1, 67A1, 67A3, 67B3, 67C1, 67C2, 67C3, 67G1, 67K2, 67L1, 67P1, 67R1, 67R2, 67S1, 67S5, 68A3, 68F1, 68H2, 68M2, 68P1, 68T1, 69A2, 69B4, 69K3, 69K4, 69S1, 69S3, 69T1, 70A2, 70B1, 70B8, 70D1, 70R1, 70H2, 71B3, 71B4, 71G2, 71H2, 71P1, 71S1

metallization
64U1, 65S2, 66B7, 66R1, 67G1, 67L1, 67R1, 67R2, 68M2, 69A2, 70B4, 70H2, 71H2, 71L1

substrate
61G1, 65S2, 67G1, 68M2, 68U1, 69U1, 70C1

wire
64P1, 64U1, 65H1, 65H2, 65K1, 65S2, 66B2, 66B4, 66G1, 66G2, 66K1, 66L3, 67A3, 67G1, 67L1, 67R2, 67S1, 67S5, 67A3, 68G1, 68G2, 68H2, 68L1, 69B5, 69K4, 69O2, 69P1, 69T1, 70A1, 70B1, 70B2, 70B4, 70C1, 70H2, 70V1, 70W2, 71B1, 71B3, 71B4, 71G1, 71G2, 71H2, 71L1, 71P1, 71R1, 71S1

device [the device of which the wire bond is a part]
67S2, 69P1, 70P1

Mechanism
anneal [wire anneal]
66K1, 67S5, 68A3, 69P1, 69B5, 69L1, 69O1, 69O2, 69P1, 70A1, 70B2, 70C1, 71B4, 71R1

contamination [on or in the parts of the wire bond before or after bonding]
65S2, 66G1, 66K1, 67C2, 67G1, 67P1, 67S2, 68H2, 68M2, 69L1, 69P1, 70D1, 70P1, 71L1

corrosion
65S2, 66B7, 67C1, 69T1, 70B4, 70H2, 71H2, 71L1

fatigue [metal fatigue]
59W1, 60W1, 65K1, 68G1, 68G2, 70B4, 70V1, 70W2, 71L1, 71P1, 71R1

DEGRADATION

electromigration
67B3

grain growth
66G2, 66K1, 68P1, 69O2, 70A1, 71R1

hardening [of the wire]
59W1, 60W1, 66L3

intermetallics [intermetallic compounds and the Kirkendall effect]
61B1, 64P1, 64S1, 64U1, 65C3, 65C4, 65C5, 65H1, 65H2, 65R1, 65R2, 65S2, 66B2, 66B3, 66B4, 66B5, 66G1, 66G2, 66W1, 67A1, 67A3, 67B2, 67B3, 67C1, 67C3, 67C4, 67K1, 67K2, 67L1, 67P1, 67R1, 67R2, 67S1, 67S5, 68A3, 68H2, 68M2, 68P1, 68R2, 68T1, 69A2, 69B4, 69K3, 69L1, 69O1, 69S1, 69S3, 70A2, 70P2, 70R1, 71L1, 71P1

spallation [separation of a material or interface caused by stress-wave interactions]
66O1, 68F1

thermal mismatch
65S2, 68H2, 69T1, 70B1, 70B4, 70H2, 71B3, 71H2

Test [used to determine degradation or failure]

centrifuge
65C5, 65S2, 66G1, 67G1

electron microprobe
67C2

electrical parameter
67S2, 69P1

metallurgical exam
59W1, 60W1, 65C3, 65C4, 65H1, 65H2, 66B3, 66B5, 69K3, 70P2

pull
59W1, 60W1, 64S1, 65C4, 65C5, 65H1, 65H2, 66B4, 66G2, 66K1, 66R1, 67C3, 67R1, 67R2, 67S5, 67A3, 67L1, 68P1, 69B3, 69B5, 69L1, 69O1, 69O2, 69P1, 70A2, 70B2, 70C1, 70P2, 70R1, 70V1, 71B4, 71G1, 71R1

resistance
65H2, 65S2, 66B3, 66B5, 66G2, 66R1, 67C3, 67K2, 67L1, 67R1, 67R2, 67A3, 69K3, 70A2, 70B4, 70C1, 70R1, 71G2, 71L1

shear
67A1, 67G1, 69L1

temperature cycle
65C5, 66G1

vibration (fatigue)
65C5

vibration (variable frequency)
66G1

visual inspection
65C3, 70C1

visual inspection (SEM)
67A3, 67G1, 68P1, 69S1, 70A1, 70B8, 70D1, 70V1

x-ray
68L1, 70B4

Failure Rates [general reliability data; relative percentages of failure modes]

TC [thermocompression wire bonds]
64U1, 66B2, 67G1, 67P1, 67S1, 68H2, 68M1, 68R2, 69B4, 69K4, 69L1, 69O1, 70S2, 70V1

US [ultrasonic wire bonds]
67P1, 67S1, 68M1, 69K4, 69L1, 69O1, 70V1

general
68E2, 70B4, 70H1

57A1 Anderson, O. L., H. Christensen, and P. Andreatch
TECHNIQUE FOR CONNECTING ELECTRICAL LEADS TO SEMICONDUCTORS
J. Appl. Phys., vol. 28, p. 923, Aug. 1957.
FABRICATION-bond: TC; wire: Ag, Al, Au, Cu; substrate: Ge, Si
Procedure
Schedule
Variables
Test: visual inspection
DESCRIPTIVE

57A2 Anderson, O. L.
ADHESION OF SOLIDS: PRINCIPLES AND APPLICATIONS
Bell Lab. Rec., vol. 35, pp. 441-445, Nov. 1957.
FABRICATION-bond: TC; wire: Ag, Al, Au, Cu, Pb, Pt, Sn; substrate: Ge, Si
Theory: TC
Evaluation: bond (adhesion)
DESCRIPTIVE

58C1 Christensen, H.
ELECTRICAL CONTACT WITH THERMO-COMPRESSION BONDS
Bell Lab. Rec., vol. 36, pp. 127-130, April 1958.
FABRICATION-bond: TC; wire: Ag, Al, Au; substrate: Ge, Si
Procedure
Variables
Test: pull
DESCRIPTIVE

59A1 Antonevich, J. N.
ULTRASONIC WELDING EQUIPMENT
IRE Intern. Conv. Record, vol. 7, pt. 6, pp. 204-212, 1959.
FABRICATION-bond: US
Theory: US
Schedule
Variables
Apparatus: design
Test: bond monitor; pull
DESCRIPTIVE

59J1 Jones, J. B., N. Maropis, J. G. Thomas, and D. Bancroft
FUNDAMENTALS OF ULTRASONIC WELDING-PHASE I
Final Rpt. (Dec. 1, 1957 to Dec. 1, 1958), Contract No. NOas 58-108c, May 1959. AD 235508 [summarized in 61J1].
FABRICATION-bond: US
Theory: US
TEST-bond: US
Description: bond monitor
EXPERIMENTAL

59R1 Renaut, P.
APPARATUS FOR THE DETERMINATION OF THE EXISTENCE OR NON-EXISTENCE AND THE QUALITY OF A BONDING BETWEEN TWO PARTS OR MEMBERS
U.S. Patent 2,903,886; Sept. 15, 1959.
TEST
Description: ultrasonic probe
PATENT

59W1 Weare, N. E., J. N. Antonevich, R. E. Monroe, and D. C. Martin
RESEARCH AND DEVELOPMENT OF PROCEDURES FOR JOINING OF SIMILAR AND DISSIMILAR HEAT-RESISTING ALLOYS BY ULTRASONIC WELDING
Rpt. (July 1957 to June 1958), Contract No. AF 33(616)-5342, Feb. 1959. AD 208323 [summarized in 60W1].
FABRICATION-bond: US
Theory
Schedule
Variables
Apparatus: design
Tool: design
Bonding Surface: contamination; mechanical characteristics; preparation; topography
Test: bond monitor; metallurgical exam; pull
DEGRADATION-bond: US
Stress: process
Part: bond
Mechanism: fatigue; hardening
Test: metallurgical exam; pull
EXPERIMENTAL

60J1 Jones, J. B., N. Maropis, J. G. Thomas, and D. Bancroft
FUNDAMENTALS OF ULTRASONIC WELDING-PHASE II
Final Rpt. (Dec. 1, 1958 to Feb. 1, 1960), Contract No. NOas 59-6070-c, Dec. 1960. AD 257514.
FABRICATION-bond: US
Theory
Procedure
Schedule
Variables
Apparatus: description
Test: metallurgical exam; visual inspection
TEST-bond: US
Description: bond monitor
EXPERIMENTAL

60J2 Jones, J. B., W. C. Elmore and C. F. De Prisco
METHOD AND APPARATUS EMPLOYING VIBRATORY ENERGY FOR BONDING METALS
U.S. Patent 2,946,119; July 26, 1960.
FABRICATION-bond: US
Theory
Evaluation: US
Procedure
Variables
Apparatus: design
Test: metallurgical exam
PATENT

60W1 Weare, N. E., J. N. Antonevich, and R. E. Monroe
FUNDAMENTAL STUDIES OF ULTRASONIC WELDING
Welding J., vol. 39 (supplement), pp. 331S-341S, Aug. 1960. [summary of 59W1]
FABRICATION-bond: US
Theory: US
Schedule
Variables
Apparatus: design
Tool: design
Bonding Surface: contamination; mechanical characteristics; preparation; topography
Test: metallurgical exam, pull
DEGRADATION-bond: US
Stress: process
Part: bond
Mechaniam: hardening; fatigue
Test: metallurgical exam, pull
EXPERIMENTAL

61A1 Anderson, O. L. and H. Christensen
THERMO-COMPRESSION BONDING OF METAL TO SEMICONDUCTORS, AND THE LIKE
U.S. Patent 3,006,067; Oct. 31, 1961.
FABRICATION-bond: TC; wire: Ag, Al, Au, Au/Cu, Cu, Sn/Cu; substrate: Ge, Si
Theory
Procedure
Variables
Test: pull; visual inspection
PATENT

61A2 Ayre, R. S.
TRANSIENT RESPONSE TO STEP AND PULSE FUNCTIONS
Shock and Vibration Handbook, Volume 1 Basic Theory and Measurements
C. M. Harris and C. E. Crede, Eds., McGraw-Hill Book Co., Inc., New York, 1961, pp. 8-1 to 8-54.
TEST
Application: mechanical shock
THEORETICAL

61B1 Bernstein, L.
GOLD ALLOYING TO GERMANIUM, SILICON AND ALUMINUM-SILICON EUTECTIC SURFACES PART 2
Semicond. Prod., vol. 4, pp. 35-39, Aug. 1961.
DEGRADATION
Stress: thermal
Part: bond
Mechanism: intermetallics
EXPERIMENTAL

61D1 De Prisco, C. F.
METHOD AND APPARATUS FOR BONDING METALS
U.S. Patent 3,002,270; Oct. 3, 1961.
FABRICATION-bond: US
Evaluation: apparatus
Apparatus: adjustment
Test: shear
PATENT

61G1 Goetzberger, A.
INVESTIGATION OF CRYSTAL IMPERFECTIONS BY MEANS OF AVALANCHE BREAKDOWN PATTERNS OF VERY THIN DIFFUSED JUNCTIONS IN SILICON
International Conf. on Semiconductor Physics, Prague, 1960, Academic Press, New York, 1961, pp. 808-811.
DEGRADATION-bond: TC; wire: Au; substrate: Si
Stress: process
Part: substrate
EXPERIMENTAL

61J1 Jones, J. B., N. Maropis, J. G. Thomas, and D. Bancroft
PHENOMENOLOGICAL CONSIDERATIONS IN ULTRASONIC WELDING
Welding J., vol. 40 (supplement), pp. 289S-305S July 1961. [summary of 59J1]
FABRICATION-bond: US
Theory
Evaluation: US; metal system
Schedule
Variables
Test: bond monitor; bond temperature; metallurgical exam; photoelastic stress analysis; radiotracer
TEST-bond: US
Description: bond monitor
EXPERIMENTAL

62J1 Jones, J. B.
VIBRATORY WELDING PROCESS AND APPARATUS
U.S. Patent 3,056,192; Oct. 2, 1962.
TEST-bond: US
Description: bond monitor
PATENT

62M1 Matsuura, E., K. Matsui, and R. R. Hasiguti
TECHNIQUE FOR OHMIC CONNECTING LEADS TO SILICON
J. Appl. Phys., vol. 33, pp. 1610-1611, April 1962.
FABRICATION-bond: TC; wire: Ag, Au, Cu; film: Al, Bi, Ga, In, Sb; substrate: Ge, Si
Procedure
DESCRIPTIVE

62P1 Peterson, J. M., H. L. McKaig, and C. F. De Prisco
ULTRASONIC WELDING IN ELECTRONIC DEVICES
IRE Intern. Conv. Record, vol. 10, pt. 6, pp. 3-12, 1962.
FABRICATION-bond: US
Theory
Evaluation: US
Apparatus: description
DESCRIPTIVE

63L1 Longo, T. A. and B. Selikson
ALUMINUM WIRE BONDING OF SILICON TRANSISTORS
Semicond. Prod., vol. 6, pp. 27-31, Nov. 1963.
DEGRADATION-bond: TC; wire: Al, Au, Ag; film: Al, Au; substrate: Si, FeNiCo
Stress: process; thermal
Part: bond
Mechanism: intermetallics
ANALYTIC

63M1 McKinnon, M. C. and R. F. Hoeckelman
MECHANICAL AND ELECTRICAL PROPERTIES OF THERMOCOMPRESSION BONDS
IEEE Intern. Conv. Record, vol. 11, pt. 6, pp. 93-103, March 1963.
FABRICATION-bond: TC, wire: Al, Au, Cu, Pt, Ti, Zr; film: Al, Au/Al, Au/Cr, NiCr, Ta, Ti; substrate: Si
Theory
Evaluation: bond (adhesion)
Schedule
Variables
Apparatus: design
Test: pull; resistance; visual inspection
EXPERIMENTAL

63P1 Phillips, L. S.
THERMOCOMPRESSION BONDING TO THIN FILM MICROCIRCUITS
Brit. Commun. Electron., vol. 10, pp. 456-458, June 1963.
FABRICATION-bond: TC; wire: Au; film: Al/Cr, Au/Cr; substrate: ceramic, glass
Evaluation: TC; bond (adherence)
Schedule
Variables
Bonding Surface: preparation; topography
Test: pull; resistance; temperature cycle; thermal shock; visual inspection
DESCRIPTIVE

63W1 Weiler, P. M., Ed.
PRODUCTION ENGINEERING MEASURE 2N914 AND 2N995
Final Rpt. (May 1, 1962-Oct. 31, 1963), Contact No. DA-36-039-SC-86726, Oct. 1963. AD 429 920
FABRICATION-bond: TC, US; wire: Ag, Al, Au, Pl; film: Ag, Ag/Al; Ag/Cr, Ag/Cr-Al, Al, Au, Au/Ag/Cr-Al, Au/Pl
Evaluation: TC; US; metal system (TC); tool (TC,US); wire (US)
Schedule: US
Variables: US
Apparatus: adjustment (TC); description (US); design (TC, US)
Tool: design (TC, US)
Wire: mechanical characteristics
Test: centrifuge, mechanical shock, pull, thermal shock, vibration (variable frequency)
TEST
Description: centrifuge; mechanical shock; pull; thermal shock; vibration (variable frequency)
DESCRIPTIVE

64A1 Antle, W. K.
FRICTION TECHNIQUE FOR OPTIMUM THERMOCOMPRESSION BONDS
IEEE Trnas. Component Parts, vol. CP-10, pp. 25-29, Dec. 1964
FABRICATION-bond: TC; wire: Ag, Al, Au; substrate: Si
Theory
Schedule
Variables
Test: shear
EXPERIMENTAL

64C1 Cohn, A.
GOLD BONDING WIRES
Semicond. Prod. Solid State Technol., vol. 7, pp. 18-20, July 1964.
FABRICATION-wire: Au, Au/Ni, Au/Pt, Au/W
Wire: care; mechanical characteristics
DESCRIPTIVE

64C2 Clunie, D. M. and N. H. Rock
THE LASER FEEDBACK INTERFEROMETER
J. Sci. Instruments, vol. 41, pp. 489-492, Aug. 1964.
TEST-bond: US
Application: bond monitor
EXPERIMENTAL

64D1 Davidson, K. W.
RELIABILITY IMPROVEMENT PROCESS EVALUATION
Proc. Conf. on Reliability of Semiconductor Devices and Integrated Circuits, vol. 1, sect. 14, pp. 14.1-14.34, June 1964. AD 645221
FABRICATION-bond: TC; wire: Al; film: Al, Au
Evaluation: bond (stitch)
TEST-bond: TC; wire: Al
Evaluation: pull (nondestructive)
DESCRIPTIVE

64D2 De Prisco, C. F. and W. M. Barfield
METHOD AND MEANS FOR OPERATING A GENERATING MEANS COUPLED THROUGH A TRANSDUCER TO A VIBRATORY ENERGY WORK PERFORMING DEVICE
U.S. Patent 3,158,928; Dec. 1, 1964.
FABRICATION-bond: US
Apparatus: adjustment
PATENT

64H1 Hill, P.
UNIFORM METAL EVAPORATION
Proc. Conf. on Reliability of Semiconductor Devices and Integrated Circuits, vol. 2, sect. 27, pp. 27.1-27.10, June 1964. AD 645222
FABRICATION-bond: TC; wire: Au; film: Al
Bonding Surface: film thickness; preparation
EXPERIMENTAL

64H2 Howell, J. R. and J. W. Slemmons
EVALUATION OF THERMOCOMPRESSION BONDING PROCESSES
Presented to 9th Welded Electric Packaging Association Symposium, Santa Monica, California, Feb. 27, 1964; Autonetics Report No. T4-240/3110, March 1964. (13)
FABRICATION-bond: TC; wire: Au; film: Al, Pt; substrate: Si
Procedure
Schedule
Variables
Control: temperature
Tool: design
Bonding Surface: contamination; topography
Test: pull
TEST-bond: TC
Evaluation: visual inspection
REVIEW

64J1 Johnson, W. G.
LEAD BONDING MACHINE
U.S. Patent 3,125,906; March 24, 1964.
FABRICATION-bond: TC
Apparatus: design
PATENT

64M1 Myers, D. K.
SMALL BALL BONDING
Proc. Conf. on Reliability of Semiconductor Devices and Integrated Circuits, vol. 2, sect. 28, pp. 28.1-28.6, June 1964. AD 645222
FABRICATION-bond: TC; wire: Au; film: Al
Evaluation: bond (ball); tool
Procedure
Apparatus: design
Test: centrifuge; mechanical shock; thermal shock; vibration (variable frequency)
DESCRIPTIVE

64P1 Partridge, J., L. D. Hanley and E. C. Hall
PROGRESS REPORT ON ATTAINABLE RELIABILITY OF INTEGRATED CIRCUITS FOR SYSTEMS APPLICATION
Symp. on Microelectronics and Large Systems, Washington, D. C., cosponsored by ONR and UNIVAC, Nov. 1964. (12)
DEGRADATION-bond: TC; wire: Au; film: al
Stress: process; test (centrifuge)
Part: wire; bond
Mechanism: intermetallics
DESCRIPTIVE

64S1 Selikson, B., and T. A. Longo
A STUDY OF PURPLE PLAGUE AND ITS ROLE IN INTEGRATED CIRCUITS
Proc. IEEE, vol. 52, pp. 1638-1641, Dec. 1964.
DEGRADATION-bond: TC; wire: Al, Au; film: Al, Au; substrate: FeNiCo, Si
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: pull
FABRICATION-wire: Al, Au; film: Ag/Cr, Al, Au, Cr/Al, Pl, Pt
Evaluation: metal system
DESCRIPTIVE

64U1 Univac
FINAL REPORT FOR INTEGRATED CIRCUIT STUDY
Contract No. NObsr 89341, Aug. 1964. AD 605432
DEGRADATION-bond: TC; wire: Al, Au; film: Al, Au
Stress: process; test (centrifuge, mechanical shock, thermal shock); thermal
Part: wire; bond; metallization
Mechanism: intermetallics
Failure Rates
EXPERIMENTAL

64W1 Worlton, D. C. and R. A. Walker
METHOD AND DEVICE FOR CONTROLLING ULTRASONIC WELDING APPARATUS
U.S. Patent 3,153,850; Oct. 27, 1964.
TEST-bond: US
Description: bond monitor
PATENT

65B1 Baker, D. and I. E. Bryan
AN IMPROVED FORM OF THERMOCOMPRESSION BOND
Brit. J. Appl. Phys., vol. 16, pp. 865-871, June 1965. [similar to 66B4]
FABRICATION-bond: TC; wire: Al, Au; film: Al, Au; substrate: FeNiCo
Evaluation: bond (ball, wedge); tool; wire
Schedule: TC
Tool: design
Bonding Surface: contamination
Test: centrifuge, pull, pull (nondestructive)
TEST-bond: TC
Description: pull (nondestructive)
Correlation: centrifuge; pull
DESCRIPTIVE

65C1 Cohen, J.
PLATINUM-SILICON THERMO-COMPRESSION BONDS
Solid State Electron., vol. 8, p. 79, Jan. 1965.
FABRICATION-bond: TC; wire: Pt; substrate: Si
Procedure
DESCRIPTIVE

65C2 Cummings, D. G.
IDENTIFICATION OF THERMAL COMPRESSION BOND FAILURES
IEEE WESCON Convention Record, vol. 9, Session 16B.1, pp. 1-3, July 1965. [2]
TEST-bond: TC; wire: Au; film: Al
Precaution: resistance
DESCRIPTIVE

65C3 Colteryahn, L. E. and D. D. Shaffer
CHARACTERIZATION OF FAILURE MODES IN GOLD-ALUMINUM THERMOCOMPRESSION BONDS
IEEE WESCON Convention Record, vol. 9, Session 16B.2, pp. 1-8, July 1965. [2]
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: metallurgical exam; visual inspection
DESCRIPTIVE

65C4 Colteryahn, L. E. and J. F. Kersey
FAILURE MECHANISMS AND KINETICS OF INTERMETALLIC FORMATION
IEEE WESCON Convention Record, vol. 9, Session 16B.3, pp. 1-10, July 1965. [2]
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: metallurgical exam; pull
EXPERIMENTAL

65C5 Cunningham, J. A.
EXPANDED CONTACTS AND INTERCONNEXIONS TO MONOLITHIC SILICON INTEGRATED CIRCUITS
Solid State Electron, vol. 8, pp. 735-745, April 1965.
FABRICATION-bond: TC; wire: Au; film: Al, Au, Au/Ag, Au/Co, Au/Cr, Au/Mo, Au/Ni; substrate: Si
Evaluation: metal system; metallization
Bonding Surface: film thickness
Test: pull
DEGRADATION-bond: TC; wire: Al, Au; film: Al, Au, Au/Mo
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: centrifuge; pull; temperature cycle; vibration (fatigue)
ANALYTIC

65D1 Daniels, H. P. C.
ULTRASONIC WELDING
Ultrasonics, vol. 3, pp. 190-196, Oct.-Dec. 1965
FABRICATION-bond: US; wire: Al, Au; substrate: Ge, glass, Si
Theory
Variables
Apparatus: design
Tool: design
Bonding Surface; topography
REVIEW

65H1 Howell, J. R.
INFLUENCE OF BONDING VARIABLES ON AU/AL TC BOND FAILURE
Proc. Second Physics of Failure Colloquim (CQAP), pp. 71-79, June 4, 1965, presented on March 29, 1965 at North American Aviation, Inc., Autonetics, Anaheim, California 92803, [similar to 65H2] (13)
FABRICATION-bond: TC; wire: Au; film: Al; substrate: glass
Variables
Control: temperature
Bonding Surface: film thickness; preparation
Test: pull
DEGRADATION-bond: TC; wire: Au; film: Al; substrate: glass

65H1 (cont.)

Stress: thermal
Part: wire; bond
Mechanism: intermetallics
Test: metallurgical exam; pull
EXPERIMENTAL

65H2 Howell, J. R. and J. W. Kanz
TIME-TEMPERATURE EFFECTS ON GOLD-ALUMINUM THERMOCOMPRESSION BONDS
IEEE WESCON Convention Record, vol. 9, Session 16B.4, pp. 1-19, July 1965. [2]
FABRICATION-bond: TC; wire: Au, film: Al; substrate: glass
Variables
Control: temperature
Bonding Surface: film thickness; preparation
Test: pull; metallurgical exam
DEGRADATION-bond: TC; wire: Au; film: Al; substrate: glass
Stress: thermal
Part: wire; bond
Mechanism: intermetallics
Test: metallurgical exam; pull; resistance
EXPERIMENTAL

65H3 Hakim, E. B. and B. Reich
U.S. ARMY ADVANCEMENT IN TRANSISTOR RELIABILITY THROUGH MANUFACTURING PROCESS IMPROVEMENTS
IEEE Trans. Reliability, vol. R-14, pp. 94-99, Oct. 1965. [see p. 98]
TEST
Evaluation: thermal shock
DESCRIPTIVE

65J1 Jones, J. B., G. W. Fable, A. L. Jamieson, E. F. Nippes, N. E. Promisel, F. N. Rhines, and R. K. Sager
ULTRASONIC WELDING
Welding Handbook, A. L. Phillips, Ed., American Welding Society, New York, 1965, Chapt. 49, pp. 1-48. [8]
FABRICATION-bond: US
Theory
Procedure
Schedule
Variables
Apparatus: design
Test: bond monitor; metallurgical exam; pull
REVIEW

65K1 Kramer, I. R.
EFFECT OF SURFACES ON MECHANICAL BEHAVIOR OF METALS
Proc. 3rd Symp. on Fundamental Phenomena in the Materials Sciences, Boston, Mass.; vol. 3, pp. 171-193, Jan. 1965.
FABRICATION
Wire: contamination; mechanical characteristics; topography
DEGRADATION
Part: wire
Mechanism: fatigue
ANALYTIC

65M1 Maki, C. E., F. W. Hagert, H. J. Avil, L. Kirvida, M. N. Asmus, W. T. Sackett, Jr., C. R. Seashore
DETECTION OF ELECTRICAL FAULTS BY R. F. TECHNIQUES
Mater. Eval., vol. 23, pp. 285-291, June 1965.
TEST
Description: noise
EXPERIMENTAL

65N1 Neppiras, E. A.
ULTRASONIC WELDING OF METALS
Ultrasonics, vol. 3. pp. 128-135, July-Sept. 1965.
FABRICATION-bond: US
Theory
Procedure
Variables
Apparatus: design
DESCRIPTIVE

65R1 Ruggiero, E. M.
ALUMINUM BONDING IS KEY TO 40-WATT MICROCIRCUITS
Electronics, vol. 38, pp. 98-104, Aug. 23, 1965.
FABRICATION-bond: TC; wire: Al, Au; film: Al, Au
Evaluation: bond (ball, stitch, wedge); wire
Procedure
Test: centrifuge; mechanical shock; vibration (variable frequency)
DEGRADATION-bond: TC; wire: Al, Au; film: Al, Au
Stress: thermal
Part: bond
Mechanism: intermetallics
DESCRIPTIVE

65R2 Ruggiero, E. M.
GOLD-ALUMINUM ADHESION AND REACTION ON SEMICONDUCTOR SURFACES
Proc. IEEE Annual Microelectronics Symp., pp. 6B-1 to 6B-4, May 1965. [2] (14)
DEGRADATION-bond: TC; wire: Au; film: Al; substrate: alumina, BN, glass, Si
Stress: process; thermal
Part: bond
Mechanism: intermetallics

65R2 (cont.)

FABRICATION-film: Al; substrate: alumina, BN, glass, Si
Evaluation: metal system; wire
Bonding Surface: preparation
ANALYTIC

65S1 Slemmons, J. W. and J. R. Howell
BETTER BONDING METHODS INPROVE HYBRID CIRCUITS
Electronics, vol. 38, pp. 86-92, March 22, 1965.
FABRICATION-bond: TC; wire: Au; film: Al, Au/NiCr, Cu/NiCr; substrate: alumina, Si
Procedure
Control: temperature
Test: pull
DESCRIPTIVE

65S2 Soltau, R.
FAILURE MODES AND MECHANISMS IN MICRO-ELECTRONIC DEVICES
Seminar on Reliability in Space Vehicles, Los Angeles, Calif., April 2, 1965. (15)
DEGRADATION-bond: TC; wire: Au; film: Al, Au; substrate: Si
Stress: process; test (centrifuge); thermal
Part: wire; bond; metallization; substrate
Mechanism: contamination; corrosion; intermetallics; thermal mismatch
Test: centrifuge; resistance
DESCRIPTIVE

65S3 Szasz, P. R.
BIND-BEAK WIRE BONDING INSTRUMENT FOR THERMOCOMPRESSIVELY SECURING LEADS TO SEMICONDUCTOR DEVICES
U.S. Patent 3,216,640; Nov. 9, 1965.
FABRICATION-bond: TC
Apparatus: design
Tool: design
PATENT

65W1 Wasson, R. D.
THERMOCOMPRESSION BOND TESTER
Proc. IEEE, vol. 53, pp. 1736-1737, Nov. 1965.
TEST
Description: pull
DESCRIPTIVE

66A1 Antle, W. K.
DETERMINING THERMOCOMPRESSION BONDING PARAMETERS BY A FRICTION TECHNIQUE
Trans. Met. Soc. AIME, vol. 236, pp. 392-396, March 1966. [similar to 64A1]
FABRICATION-bond: TC; wire: Ag, Al, Au; film: Al, Au, Ni; substrate: Si
Theory
Schedule
Variables
Test: shear
EXPERIMENTAL

66A2 Angelucci, T. L. and F. W. Kulicke, Jr.
NAIL HEAD BONDING APPARATUS FOR THERMO-COMPRESSIVELY SECURING LEAD WIRE TO SEMI-CONDUCTOR DEVICES
U.S. Patent 3,250,452; May 10, 1966.
FABRICATION-bond: TC
Procedure
Apparatus: design
PATENT

66B1 Bagrowski, J., S. G. Konsowski, Jr., and G. D. Spencer
INTERCONNECTION OF MONOLITHIC INTEGRATED CIRCUITS THROUGH THE USE OF ADVANCED MATERIALS AND TECHNIQUES
IEEE Trans. Pts. Materials Packaging, vol. PMP-2, pp. 90-98, Dec. 1966.
FABRICATION-bond: TC, US
Evaluation: TC, US
Variables: TC, US
DESCRIPTIVE

66B2 Browning, G. V.
FAILURE MECHANISMS IN MICROCIRCUITS
Proc. Second Int. Symp. on Microelectronics, pp. 485-516, Munich, Germany, Oct. 1966. (13)
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: process
Part: wire; bond
Mechanism: intermetallics
Failure Rates
DESCRIPTIVE

66B3 Blech, I. A. and H. Sello
SOME NEW ASPECTS OF GOLD-ALUMINUM BONDS
J. Electrochem. Soc., vol. 113, pp. 1052-1054, Oct. 1966.
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: metallurgical exam; resistance
FABRICATION-bond: TC; wire: Au; film: Al
Bonding Surface: film thickness
ANALYTIC

66B4 Baker, D. and R. Jones
NEW DEVELOPMENTS IN THERMOCOMPRESSION BONDING
Microelectronics and Reliability, vol. 5, pp. 229-234, Aug. 1966. [similar to 65B1]
FABRICATION-bond: TC; wire: Al, Au; film: Al, Au; substrate: Al, FeNiCo, Si
Theory
Evaluation: bond (ball, wedge); tool
Tool: design
Bonding Surface: contamination
Test: pull, pull (nondestructive)
DEGRADATION-bond: TC; wire: Al; film: Au; substrate: FeNiCo
Stress: thermal
Part: wire; bond
Mechanism: intermetallics
Test: pull
TEST-bond: TC; wire: Al
Description: pull (nondestructive)
DESCRIPTIVE

66B5 Browning, G. V., L. E. Colteryahn and D. G. Cummings
FAILURE MECHANISMS ASSOCIATED WITH THERMOCOMPRESSION BONDS IN INTEGRATED CIRCUITS
Physics of Failure in Electronics, vol. 4, RADC Series in Reliability, M. E. Goldberg and J. Vaccaro, Eds., 1966, pp. 428-446. AD 637529
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: process; thermal
Part: bond
Mechanism: intermetallics
Test: metallurgical exam; resistance
DESCRIPTIVE

66B6 Bikerman, J. J.
SOLID TO SOLID ADHESION
Symposium on Fundamental Phenomena in the Materials Sciences, 2nd, Boston, 1964. Surface phenomena. L. J. Bonis and H. H. Hausner, Ed. "Fundamental Phenomena in the Materials Sciences, vol. 2", Plenum Press, New York, 1966, pp. 165-174.
FABRICATION-bond: TC, US
Theory
DESCRIPTIVE

66B7 Brandewie, G. V., P. H. Eisenberg, and R. A. Meyer
INVESTIGATION OF SURFACE FAILURE MECHANISMS IN SEMICONDUCTOR DEVICE BY ENVELOPE AMBIENT STUDIES
Physics of Failure in Electronics, vol. 4, M. E. Goldberg and J. Vaccaro, Eds., RADC Series in Reliability, 1966, pp. 493-521. AD 637529. [see pp. 510-516]
DEGRADATION-film: Al
Stress: moisture
Part: metallization
Mechanism: corrosion
EXPERIMENTAL

66C1 Conti, R. J.
THERMOCOMPRESSION JOINING TECHNIQUES FOR ELECTRONIC DEVICES AND INTERCONNECTS
Metals Eng. Quart., vol. 6, pp. 29-35, Feb. 1966.
FABRICATION-bond: TC; wire: Ag, Au, Au/Cu, Cu/Ni; substrate: alumina, glass
Evaluation: TC
Schedule
Variables
Control: temperature
Tool: design
Wire: size
Bonding Surface: contamination
Test: pull; thermal shock
DESCRIPTIVE

66C2 Clews, K. J. and J. G. Young
METALLURGICAL EVALUATION OF MICROCIRCUIT INTERCONNEXIONS MADE BY THE PARALLEL-GAP PROCESS
Microelectronics and Reliability, vol. 5, pp. 207-208, Aug. 1966.
FABRICATION
Evaluation: bond
Test: metallurgical exam
DESCRIPTIVE

66E1 Eimbinder, J.
LINEAR INTEGRATED CIRCUITS
EEE, vol. 14, pp. 76-86, Nov. 1966.
FABRICATION-bond: TC, US
Evaluation: TC; US; bond (ball, stitch, wedge)
DESCRIPTIVE

66G1 Go, H. T., N. J. McAfee and H. C. Jones
MICROELECTRONICS RELIABILITY FROM A SYSTEM MANUFACTURER'S POINT OF VIEW
Second Int. Symp. on Microelectronics; Munich, Germany, Oct. 1966. (16)
DEGRADATION
Stress: process
Part: wire; bond
Mechanism: contamination; intermetallics
Test: centrifuge; thermal cycle; vibration (variable frequency)
DESCRIPTIVE

66G2 Gianelle, W. H.
ANALYSIS OF SEVEN SEMICONDUCTOR METALLURGY SYSTEMS USED ON SILICON PLANAR TRANSISTORS
Physics of Failure in Electronics, vol. 4, M. E. Goldberg and J. Vaccaro, Eds., RADC Series in Reliability, 1966, pp. 46-57. AD 637529
FABRICATION-bond: TC; wire: Ag, Al, Au; film: Ag, Ag/Cr, Al, Au, Au/Mo
Evaluation: bond (ball, wedge); metal system; wire
Bonding Surface: film thickness
Test: pull; resistance
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: thermal
Part: wire; bond
Mechanism: grain growth; intermetallics
Test: pull; resistance
ANALYTIC

66H1 Hammond, V. J.
THIN-FILM PREPARATION IN RELATION TO MICROBONDING
Microelectronics and Reliability, vol. 5, pp. 213-217, Aug. 1966.
FABRICATION-bond: TC, US; film: Al, Al/Cr, Au, Au/Cr; substrate: ceramic, glass
Evaluation: metallization
Bonding Surface: preparation
DESCRIPTIVE

66I1 IEC
BASIC ENVIROMENTAL TESTING PROCEDURES FOR ELECTRONIC COMPONENTS AND ELECTRONIC EQUIPMENT PART 2: TESTS—TEST F: VIBRATION
IEC Recommendation, publication 68-2-6 (1966) and supplements 68-2-6A, 68-2-6B and 68-2-6C; 1966-1969. [3]
TEST
Description: vibration (variable frequency, fatigue
STANDARD

66K1 Khorouzan, M. and L. Thomas
CONTAMINATION OF ALUMINUM BONDS IN INTEGRATED CIRCUITS
Trans. Met. Soc. AIME, vol. 236, pp. 397-405, March 1966.
DEGRADATION-bond: US; wire: Al; film: Al; substrate: FeNiCo
Stress: process; test (thermal cycle); thermal
Part: wire; bond
Mechanism: anneal; contamination; grain growth
Test: pull
ANALYTIC

66K2 Koedam, M.
DETERMINATION OF SMALL DIMENSIONS BY DIFFRACTION OF A LASER BEAM
Philips Tech. Rev., vol. 27, pp. 208-212, Nov. 2, 1966.
FABRICATION
Wire: size
DESCRIPTIVE

66K3 Köllner, H.
METHOD AND DEVICE FOR BONDING A CONTACT WIRE TO A SEMICONDUCTOR MEMBER
U.S. Patent 3,289,452; Dec. 6, 1966.
FABRICATION-bond: TC
Apparatus: design
PATENT

66L1 Larson, R. B.
MICROJOINING PROCESSES FOR ELECTRONIC PACKAGING PART 3
Assembly Engineering, vol. 9, pp. 30-33, Nov. 1966. (17)
FABRICATION-bond: TC; wire: Au
Evaluation: bond (ball, stitch, wedge); temperature control
Procedure
Variables
Control: temperature
DESCRIPTIVE

66L2 Landis, D.
CATASTROPHIC FAILURES IN SEMICONDUCTOR DEVICES EXPOSED TO PULSED RADIATION
IEEE Trans. Nucl. Sci., vol. NS-13, pp. 591-600, June 1966.
DEGRADATION-bond: TC; wire: Au
Stress: radiation
Part: bond
ANALYTIC

66L3 Langenecker, B.
EFFECTS OF ULTRASOUND ON DEFORMATION CHARACTERISTICS OF METALS
IEEE Trans. Sonics Ultrason., vol. SU-13, pp. 1-8, March 1966.
FABRICATION-bond: US
Wire: mechanical characteristics
DEGRADATION-bond: US
Stress: process
Part: wire
Mechanism: hardening
REVIEW

66L4 Lombardi, J., L. McDonough, H. Padden
HIGH RELIABILITY SCREENING OF SEMICONDUCTOR AND INTEGRATED CIRCUIT DEVICES
Final Rpt.,Contract NAS 5-9639, Sept. 1966. N67-16772
TEST
Description: centrifuge; temperature cycle; vibration (monitored, variable frequency); visual inspection; x-ray
Evaluation: centrifuge; temperature cycle; vibration (monitored, variable frequency); visual inspection; x-ray
DESCRIPTIVE

66M1 Mann, R. M.
BAD WELD DETECTOR USES INTEGRATED CIRCUITS
EDN, vol. 11, pp. 108-112, July 1966.
TEST
Description: resistance
DESCRIPTIVE

66O1 Oswald, K. B., Jr.
FRACTURE OF SILICON AND GERMANIUM INDUCED BY PULSED ELECTRON IRRADIATION
IEEE Trans. Nucl. Sci., vol. NS-13, pp. 63-69, Dec. 1966.
DEGRADATION
Stress: radiation
Part: substrate
Mechanism: spallation
EXPERIMENTAL

66P1 Partridge, J., E. C. Hall, and L. D. Hanley
THE APPLICATION OF FAILURE ANALYSIS IN PROCURING AND SCREENING OF INTEGRATED CIRCUITS
Physics of Failure in Electronics, vol. 4, M. E. Goldberg and J. Vaccaro, Eds., RADC Series in Reliability, 1966, pp. 95-139. AD 637529
TEST
Description: centrifuge; vibration (variable frequency); mechanical shock; Mil-Std-750; temperature cycle; visual inspection
Screening Procedures
DESCRIPTIVE

66R1 Riben, A. R., and S. L. Sherman
MICROBONDS FOR HYBRID MICROCIRCUITS PROGRESS REPORT
Rpt. 8 (Nov. 1, 1965-Jan. 31, 1966), Contract No. DA 36-039 AMC-03742 (E), May 20, 1966. AD 633723 [summarized in 67L1]
FABRICATION-bond: US; wire: Al, film: Au/Cr; substrate: alumina, beryllia, sapphire
Evaluation: US
Schedule
Wire: mechanical characteristics
Bonding Surface: film thickness; topography
Test: pull; resistance
DEGRADATION-bond: US; wire: Al; film: Au/Cr; substrate; alumina, beryllia, sapphire
Stress: thermal
Part: metallization
Test: pull, resistance
TEST-bond: US; wire: Al; film: Au/Cr; substrate: alumina, beryllia, sapphire
Correlation: pull; resistance
EXPERIMENTAL

66W1 Wagner, R.
SEMICONDUCTOR DEVICES WITH SILVER-GOLD LEAD WIRES ATTACHED TO ALUMINUM CONTACTS
U.S. Patent 3,271,635, Sept. 6, 1966.
FABRICATION: wire: Au, Au/Ag; film: Al
Evaluation: metal system; wire
Test: pull
DEGRADATION
Mechanism: intermetallics
PATENT

67A1 Arleth, J. M. and R. D. Demenus
NEW TEST FOR THERMOCOMPRESSION MICROBONDS
Electron. Prod., vol. 9, pp. 92, 94, May 1967.
TEST-bond: TC; wire: Au; film: Al, Au
Description: shear
DEGRADATION-bond: TC; wire: Au; film: Al, Au
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: shear
DESCRIPTIVE

67A2 Avedissian, M. K.
THERMOCOMPRESSION BONDING APPARATUS
U.S. Patent 3,313,464, April 11, 1967.
FABRICATION-bond: TC
Procedure
Apparatus: design
PATENT

67A3 Anstead, R. J.
FAILURE ANALYSIS USING A SCANNING ELECTRON MICROSCOPE
Proc. 6th Annual Reliability Physics Symposium, Los Angeles, Calif. pp. 127-137, Nov. 1967. [2]
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al
Stress: process
Part: wire; bond
Mechanism: intermetallics
Test: visual inspection (SEM)
DESCRIPTIVE

67B1 Bobo, S. N.
MICROELECTRIC WELDING — AN APPROACH TO IMPROVED RELIABILITY
Proc. SAE Electronic Packaging Conf. New York, N. Y., pp. 6-12, Feb. 1967.
TEST
Description: IR Monitor
DESCRIPTIVE

67B2 Beadles, R. L.
INTEGRATED SILICON DEVICE TECHNOLOGY VOLUME XIV
Rpt. (Jan. 1966-March 1967), Contract AF 33 (615)-3306, May 1967. AD 654630. [see pp. 23-48]
FABRICATION-bond: TC, US; wire: Al, Au; film: Al, Al/Cr, Au, Au/Cr
Theory: TC, US
Evaluation: US, TC; bond (ball, stitch, wedge)
Procedure: TC, US
Schedule: TC
Variables: TC
Apparatus: description (US)
Tool: design (TC)
Wire: care
DEGRADATION
Mechanism: intermetallics
REVIEW

67B3 Blech, I. A., and H. Sello
THE FAILURE OF THIN ALUMINUM CURRENT-CARRYING STRIPS ON OXIDIZED SILICON
Physics of Failure in Electronics, vol. 5, T. S. Shilliday and J. Vaccaro, Eds., RADC Series in Reliability, 1967, pp. 496-505. AD 655397
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: electrical; thermal
Part: bond
Mechanism: electromigration; intermetallics
DESCRIPTIVE

67B4 Bayer, R. G. and T. S. Burke
APPLICATION OF THE ULTRASONIC RESONANCE TECHNIQUE TO INSPECTION OF MINIATURE SOLDERED AND WELDED JUNCTIONS
Mater. Eval., vol. 25, pp. 20-24, Jan. 1967.
TEST
Description: US probe
DESCRIPTIVE

67C1 Cunningham, J. A. and J. G. Hayser
SEMICONDUCTOR RELIABILITY: FOCUS ON THE CONTACTS
EE, vol. 26, pp. 74-79, Jan. 1967.
FABRICATION-bond: TC; wire: Al, Au; film: Al, Au/Mo, Au/Mo/Pt
Evaluation: metallization; bond (ball, wedge)
Bonding Surface: metal system; preparation
DEGRADATION-bond: TC; wire: Al, Au; film: Al, Au/Mo, Au/Mo/Pt
Stress: thermal
Part: bond
Mechanism: corrosion; intermetallics
DESCRIPTIVE

67C2 Cline, J. E. and S. Schwartz
ELECTRON MICROPROBE TECHNIQUES FOR FAILURE ANALYSIS OF SILICON PLANAR DEVICES
Proc. 6th Annual Reliability Physics Symposium, Los Angeles, Calif. pp. 193-200, Nov. 1967. [2]
DEGRADATION
Stress: process
Part: bond
Mechanism: contamination
Test: electron microprobe
DESCRIPTIVE

67C3 Chen, G. K. C.
ON THE PHYSICS OF PURPLE PLAGUE FORMATION, AND THE OBSERVATION OF PURPLE PLAGUE IN ULTRASONICALLY JOINED GOLD-ALUMINUM BOND
IEEE Trans. Pts. Material Packaging, vol. PMP-3, pp. 149-153, Dec. 1967.
DEGRADATION-bond: US; wire: Au; film: Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: pull; resistance
TEST-bond: US; wire: Au; film: Al
Correlation: pull; resistance
ANALYTIC

67C4 Cunningham, J. A.
THE PLAGUES IN SEMICONDUCTOR CONTACTS
EE, vol. 26, p. 39, April 1967.
DEGRADATION
Mechanism: intermetallics
REVIEW

67G1 Gill, W. L. and W. Workman
RELIABILITY SCREENING PROCEDURES FOR INTEGRATED CIRCUITS
Physics of Failure in Electronics, vol. 5, RADC Series in Reliability, T. S. Shilliday and J. Vaccaro, Eds., 1967, pp. 101-141. AD 655397
DEGRADATION-bond: TC; wire: Au; film: Au/Mo
Stress: process; test (centrifuge, thermal shock); thermal
Part: wire; bond; metallization; substrate
Mechanism: contamination
Test: centrifuge; shear; visual inspection
Failure Rates
TEST-bond: TC; wire: Au; film: Au/Mo

67G1 (cont.)

Evaluation: centrifuge; shear; visual inspection; x-ray
Screening Procedures
FABRICATION
Evaluation: package
DESCRIPTIVE

67G2 Graham, R. A. and R. E. Hutchison
THERMOELASTIC STRESS PULSES RESULTING FROM PULSED ELECTRON BEAMS
Appl. Phys. Lett., vol. 11, pp. 69-72, July 15, 1967.
TEST
Application: mechanical shock (radiation-induced)
ANALYTIC

67H1 Higbie, T. E.
THERMOCOMPRESSION BONDING OF GOLD WIRE FOR MICROELECTRONIC CIRCUITS
Report No. NAFI-TR-1108, Oct. 1967.
AD 671879
FABRICATION-bond: TC; wire: Au; film: Al, Au
Procedure
Schedule
Variables
Apparatus: adjustment
Test: pull
TEST-bond: TC; wire: Au; film: Au
Description: pull
DESCRIPTIVE

67H2 Haigler, E. D.
ULTRASONIC SCISSORS BONDING INSTRUMENT
U.S. Patent 3,314,582; April 18, 1967.
FABRICATION-bond: US
Apparatus: design
PATENT

67I1 IEC
BASIC ENVIROMENTAL TESTING PROCEDURES FOR ELECTRONIC COMPONENTS AND ELECTRONIC EQUIPMENT PART 2: TESTS — TEST EA: SHOCK
IEC Recommendation, publication 68-2-27 and supplement 68-2-27A; 1967-1968. [3]
TEST
Description: mechanical shock
STANDARD

67J1 Jones, J. B.
ULTRASONIC WELDING
Proc. CIRP Int. Conf. on Mfg. Technol., sponsored by ASTME, pp. 1387-1409, Sept. 1967. (18)
FABRICATION-bond: US
Theory
Schedule
Variables
Apparatus: design
Test: bond monitor, metallurgical exam
REVIEW

67K1 Koshinz, E. F.
THERMOCOMPRESSION BONDING — AN OVERVIEW
Proc. 1967 Welding Congress, pp. 86-94, Stuttgart, Germany, 1967. [In German] (19)
FABRICATION-bond: TC; wire: Al, Au; film: Ag/Cr, Al, Au, Au/Mo/Pt
Evaluation: bond (ball, wedge); metal system; temperature control
Procedure
Variables
Test: centrifuge; pull
DEGRADATION-bond: TC; wire: Au; film: Al
Mechanism: intermetallics
REVIEW

67K2 Keen, R. S., L. R. Loewenstern and G. L. Schnable
MECHANISMS OF CONTACT FAILURES IN SEMICONDUCTOR DEVICES
Proc. 6th Annual Reliability Physics Symp. Los Angeles, Calif., pp. 216-233, Nov. 1967. [2]
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: resistance
REVIEW

67L1 Lane, W. V.
MATERIALS FOR CONDUCTIVE ELEMENTS PART II — CONNECTIONS TO THIN FILMS
IEEE Intern. Conv. Record, vol. 15, pt. 7, pp. 129-145, 1967. [summary of 66R1, 67R2]
FABRICATION-bond: US; wire: Al; film: Al, Au/Cr; substrate: alumina, beryllia, glass, sapphire, Si; silica (96%); application: hybrid devices
Evaluation: US; wire bond
Schedule
Apparatus: description
Bonding Surface: film thickness; preparation; topography
Test: pull; visual inspection
DEGRADATION: bond: US; wire: Al; film: Al, Au/Cr; substrate: alumina, beryllia, glass, sapphire, Si; silica (96%); application: hybrid devices
Stress: process; thermal
Part: bond; metallization; wire
Mechanism: intermetallics
Test: pull; resistance
EXPERIMENTAL

67P1 Parker, C. D.
INTEGRATED SILICON DEVICE TECHNOLOGY VOLUME XV RELIABILITY
Rpt. (March 1966-March 1967), Contract No. AF 33(615)-8306, May 1967. AD 655082 [see pp. 35-65]
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al, Au, Au/Mo; substrate: FeNiCo, Si
Stress: process; thermal
Part: bond
Mechanism: contamination; intermetallics
Failure Rates
TEST
Screening Procedures
FABRICATION-bond: TC, US; wire: Al, Au; film: Ag, Ag/Cr, Al, Au, Au/Mo; substrate: Si
Evaluation: metal systems, metallization, wire
Procedure
REVIEW

67P2 Pruden, D. H. and D. Schoenthaler
METHODS OF BONDING ELECTRICAL CONDUCTORS TO ELECTRICAL COMPONENTS
U.S. Patent 3,302,277; Feb. 7, 1967.
TEST-bond: US
Description: bond monitor
PATENT

67R1 Riben, A. R. and S. L. Sherman
MICROBONDS FOR HYBRID MICROCIRCUITS
Physics of Failure in Electronics, vol. 5, RADC Series in Reliability, T. S. Shilliday and J. Vaccaro, Eds., 1967, pp. 534-556. AD 655397. [summary of 66R1, 67R2]
FABRICATION-bond: US; wire: Al; film: Al, Au/Cr; substrate: alumina, beryllia, silica (96%); application: hybrids
Evaluation: US
Schedule
Variables
Tool: design; wear
Wire: mechanical characteristics
Bonding Surface: film thickness; topography
DEGRADATION-bond: US; wire: Al; film: Al, Au/Cr
Stress: process; thermal
Part: bond; metallization
Mechanism: intermetallics
Test: pull; resistance
TEST-bond: US; wire: Al; film: Al, Au/Cr; substrate: alumina, beryllia, sapphire; silica (96%)
Correlation: pull; resistance
EXPERIMENTAL

67R2 Riben, A. R. and S. L. Sherman
MICROBONDS FOR HYBRID MICROCIRCUITS
Final Rpt. (Feb. 1, 1964-April 30, 1966) Contract Number DA 36-039 AMC-03742(E), Jan. 1967. AD 647464
FABRICATION-bond: US; wire: Al (pure), Al; film: Al, Au/Cr; substrate: alumina, sapphire, Si, silica (96%)
Evaluation: metal system
Procedure
Schedule
Apparatus: description
Rigidity: apparatus
Wire: mechanical characteristics
Bonding Surface: film thickness; preparation; topography
Test: pull; resistance; thermal shock; visual inspection
DEGRADATION-bond: US; wire: Al, Al (pure); film: Al, Au/Cr; substrate: alumina, sapphire, Si, silica (96%)
Stress: process; test (thermal shock); thermal
Part: wire; bond; metallization
Mechanism: intermetallics
Test: pull; resistance
TEST-bond: US; wire: Al, Al (pure); film: Al, Au/Cr; substrate: alumina, sapphire, Si, silica (96%)
Evaluation: pull; resistance
Correlation: pull; resistance
EXPERIMENTAL

67R3 Reber, R. L.
STEPPED BONDING WEDGE
U.S. Patent 3,347,442; Oct. 17, 1967.
FABRICATION
Tool: design
PATENT

67R4 Rasimenoks, P., T. L. Angelucci, and F. W. Kulicke, Jr.
THERMOCOMPRESSION WIRE BONDING APPARATUS WITH SCISSORS CUT-OFF
Patent 3,307,763; March 7, 1967.
FABRICATION-bond: TC
Apparatus: design
PATENT

67S1 Schnable, G. L. and R. S. Keen
METALLIZATION AND BONDS — A REVIEW OF FAILURE MECHANISMS
Proc. 6th Annual Reliability Physics Symp., Los Angeles, Calif. pp. 170-192, Nov. 1967. [2]
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al, Au, Au/Mo
Stress: process; thermal; test (centrifuge)
Part: wire; bond
Mechanism: intermetallics
Failure Rates
FABRICATION-bond: TC, US; wire: Al, Au; film: Al, Au, Au/Mo
Evaluation: TC; US
Apparatus: design (US)
Tool: design (TC, US)
REVIEW

67S2 Scarbrough, R. J. D. and J. Auchterlonie
THE ISOLATION OF A FAILURE MODE IN SILICON PLANAR TRANSISTORS CAUSED BY ORGANIC RESIDUES ASSOCIATED WITH ALUMINUM WIRE
Microelectronics and Reliability, vol. 6, pp. 319-321, Nov. 1967.
DEGRADATION-wire: Al
Stress: thermal
Part: device
Mechanism: contamination
Test: electrical parameter
ANALYTIC

67S3 Schile, R. D., and G. A. Rosica
SIMPLE TESTER FOR THE RAPID DETERMINATION OF THE TENSILE STRENGTH OF FINE FILAMENTS
Rev. Sci. Instr., vol. 38, pp. 1103-1104, Aug. 1967.
TEST
Application: pull
DESCRIPTIVE

67S4 Schumacher, D. H.
MEASURING MICROBOND INTEGRITY WITH AN INFRARED MICRORADIOMETER
Soc. for Nondestructive Testing, Inc., Fall Conf. ; Cleveland, Ohio, Oct. 1967 (20)
TEST-bond: TC; wire: Au/Cu; film: Au; substrate: ceramic
Description: IR Monitor
Evaluation: IR Monitor
ANALYTIC

67S5 Selikson, B.
FAILURE MECHANISM INTEGRATED CIRCUIT INTERCONNECT SYSTEMS
Proc. 6th Annual Reliability Physics Symposium, Los Angeles, Calif. pp. 201-208, Nov. 1967. [2]
DEGRADATION-bond: TC; wire: Al, Au; film: Ag/Cr; Al, Au/Mo, Au/Mo/Al, Au/Pt/Ti, Cr/Al
Stress: process; thermal
Part: wire: bond
Mechanism: anneal, intermetallics
Test: pull
FABRICATION-bond: TC; wire: Al, Au; film: Ag/Cr, Al, Au/Mo, Au/Mo/Al, Au/Pt/Ti, Cr/Al
Evaluation: metal system
REVIEW

67T1 Tiffany, P.
VIBRATORY WELDING TIP AND METHOD OF WELDING
U.S. Patent 3,357,090; Dec. 12, 1967.
FABRICATION-bond: US; wire: Au
Procedure
Tool: design
PATENT

67V1 van Lancker, M.
METALLURGY OF ALLUMINUM ALLOYS
John Wiley and Sons, Inc., New York 1967.
FABRICATION-wire: Al, Al (pure), Al/Mg
Wire: mechanical characteristics
REVIEW

68A1 Adams, A. H. and J. H. Anderson, Jr.
MEANS FOR GRIPPING FINE WIRES DURING MECHANICAL TESTS
Rev. Sci. Instr., vol. 39, p. 1768, Nov. 1968.
TEST
Application: pull
DESCRIPTIVE

68A2 Avedissian, M. K. and J. S. Manowczak
SEQUENTIAL WIRE AND ARTICLE BONDING METHODS
U.S. Patent 3,397,451; Aug. 20, 1968.
FABRICATION-bond: TC
Procedure
PATENT

68A3 Anderson, J. H., Jr. and W. P. Cox
AGING EFFECTS IN AU-AL AND AL-AL BONDS USED IN MICROELECTRONICS
Proc. 7th Annual Reliability and Maintainability Conf., pp. 533-536, San Francisco, Calif., July 1968. [7], (21)
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al
Stress: thermal
Part: wire; bond
Mechanism: anneal, intermetallics
Test: pull; resistance
FABRICATION-bond: TC; wire: Au; film: Al
Bonding Surface: film thickness
EXPERIMENTAL

68B1 Berry, R. W., P. M. Hall, and M. T. Harris
THIN FILM TECHNOLOGY
Van Nostrand Reinhold Co., Princeton, New Jersey, 1968, pp. 604-632.
FABRICATION-bond: TC, US
Theory: TC, US
Procedure: TC, US
Schedule: TC
Apparatus: design (US)
Control: temperature (TC, US)
Tool: design (TC)
Wire: size (TC)

68B1 (cont.)

Test: pull
TEST
Description: centrifuge; IR monitor; metallurgical exam; pull
Evaluation: noise; resistance
REVIEW

68D1 Dummer, G. W. A, and J. M. Robertson, Eds.
ELECTRONIC CONNECTION TECHNIQUES AND EQUIPMENT 1968-1969
Pergamon Press, New York, 1968.
FABRICATION-bond: TC, US
Apparatus: description
DESCRIPTIVE

68D2 Department of Defense
TEST METHODS AND PROCEDURES FOR MICROELECTRONICS
Military Standard 883, May 1, 1968; Notice 1, May 20, 1968; Notice 2, Nov. 20, 1969. [1]
TEST-bond: TC, US
Description: air blast; centrifuge; mechanical shock, Mil-Std-883; pull; resistance, shear; temperature cycle; thermal shock; vibration (fatigue, monitored, variable frequency); visual inspection; x-ray
Screening Procedures
STANDARD

68E1 Electronic Design
TEST YOUR IC IQ
Electronic Design, vol. 15, p. 84, July 18, 1968.
TEST
Precaution: resistance
DESCRIPTIVE

68E2 Electronic Design
TEST YOUR IC IQ
Electronic Design, vol. 2, p. 108, Jan. 18, 1968.
DEGRADATION
Failure Rates
REVIEW

68F1 Floyd, H. L., Jr.
A TECHNIQUE FOR DETERMINING TRANSISTOR SPALL THRESHOLDS
Sandia Corp. Rpt. No. SC-M-68-186A, April 1968. [22]
TEST-bond: US, TC
Description: mechanical shock (radiation-induced)
Evaluation: mechanical shock; mechanical shock (radiation-induced)
DEGRADATION-bond: TC, US; wire: Al, Au
Stress: test (mechanical shock (radiation-induced))
Part: bond
Mechanism: spallation
THEORETICAL

68G1 Gaffney, J.
INTERNAL LEAD FATIGUE THROUGH THERMAL EXPANSION IN SEMICONDUCTOR DEVICES
IEEE Trans. Electron Devices, vol. ED-15, p. 617, Aug. 1968.
DEGRADATION-bond: TC; wire: Al, Au; film: Al
Stress: thermal
Part: wire
Mechanism: fatigue
FABRICATION-bond: TC; wire: Al; film: Al
Wire: mechanical characteristics
DESCRIPTIVE

68G2 Gaffney, J., D. Bottaro and C. D. Root
INTERNAL LEAD FATIGUE IN SEMICONDUCTOR DEVICES THROUGH THERMAL EXPANSION
Presentation abstracts 7th Annual Reliability Physics Symp., Washington, D. C., p. 28, Dec. 1968. [2]
DEGRADATION-bond: TC; wire: Al; film: Al
Stress: thermal
Part: wire
Mechanism: fatigue
EXPERIMENTAL

68H1 Harris, D. H.
MEASURING THE ACCURACY OF HUMAN INSPECTION
Mater. Res. Std., vol. 8, pp. 8-12, Dec. 1968.
TEST
Application: visual inspection
DESCRIPTIVE

68H2 Holmes, P. J., and I. C. Jennings
FAILURE ANALYSIS OF PLANAR TRANSISTORS USED IN THE UK3 SATELLITE PROGRAMME
Microelectronics and Reliability, vol. 7, pp. 37-44, Feb. 1968.
DEGRADATION-bond: TC; wire: Au; film: Al, Au
Stress: process
Part: wire; bond
Mechanism: contamination; intermetallics; thermal mismatch
Failure Rates
DESCRIPTIVE

68H3 Hill, W. H., and G. D. Wrench
RECENT ADVANCES IN PULSE-HEATED WIRE BONDING FOR HYBRID MICROELECTRONICS
Proc. NEPCON, June 1968. Also Hughes Welding Note — Bulletin 109. [4] (23)
FABRICATION-bond: TC, US; wire: Al, Au; film: Al, Au, Cr; substrate: alumina, glass, Si; application: hybrid devices
Evaluation: TC; US; temperature control; tool (TC); wire (TC)
Apparatus: description (TC)
Control: temperature (TC)
Tool: design (TC); wear (TC)
DESCRIPTIVE

68H4 Howard, R. E.
HOW TO USE IC RELIABILITY SCREENING TECHNIQUES
Eval. Eng., vol. 7, pp. 22-26, Nov.-Dec. 1968.
TEST
Evaluation: centrifuge; mechanical shock; pull; temperature cycle; thermal shock; visual inspection; x-ray
DESCRIPTIVE

68H5 Helda, R. W. and W. E. LaPoint
METHOD OF BONDING FILAMENTARY MATERIAL
U.S. Patent 3,400,448; Sept. 10, 1968.
FABRICATION-bond: TC
Procedure
Apparatus: design
PATENT

68I1 IEC
BASIC ENVIROMENTAL TESTING PROCEDURES FOR ELECTRONIC COMPONENTS AND ELECTRONIC EQUIPMENT PART 2: TESTS — TEST GA: ACCELERATION, STEADY STATE
IEC RECOMMENDATION, PUBLICATION 68-2-7, 1968. [3]
TEST
Description: centrifuge
STANDARD

68J1 Johnson, C. A.
HOT GAS THERMO-COMPRESSION BONDING
U.S. Patent 3,409,977; Nov. 12, 1968.
FABRICATION-bond: TC
Control: temperature
PATENT

68K1 Koshinz, E. F.
SEMICONDUCTOR: WIRE BONDING AND FACE BONDING CONSIDERATIONS AND COMPARISONS
Proc. SAE Microelectronic Packaging Conf., Palo Alto, Calif., pp. 94-100, Nov. 1968. (19)
FABRICATION-bond: TC, US; wire: Al, Au; film: Ag/Cr, Al, Au, Au/Cr/Al, Au/Mo/Pt
Evaluation: TC, US
Procedure: TC, US
Variables: TC, US
REVIEW

68L1 Lawhorne, S., and J. N. Ramsey
SIMPLIFIED X-RAY EXAMINATION OF SOLID STATE DEVICES
Solid State Technol., vol. 11, pp. 37-39, Nov. 1968.
TEST-wire: Au
Description: x-ray
DEGRADATION-wire: Au; application: plastic devic
Stress: process
Part: wire
Test: x-ray
DESCRIPTIVE

68M1 McCormick, J. E.
ON THE RELIABILITY OF MICROCONNECTIONS
Electron. Packag. Prod., vol. 8, pp. 187-189, June 1968.
DEGRADATION-bond: TC, US; wire: Al, Au
Failure Rates
FABRICATION-bond: TC, US
Evaluation: TC; US
DESCRIPTIVE

68M2 Muncheryan, H. M.
HOW TO USE FAILURE ANALYSIS TO IMPROVE SEMICONDUCTOR RELIABILITY
EE, vol. 27, pp. 49-54, May 1968.
DEGRADATION-bond: TC, wire: Au; film: Al, Au
Stress: process
Part: bond; metallization; substrate
Mechanism: contamination; intermetallics
FABRICATION-bond: TC, US; wire: Al, Au; film: Al, Au/Cr, Au/Cu/Ti, Au/Mo, Au/Ni, Au/Pt/Ti, Pt/Ti
Evaluation: metal system
DESCRIPTIVE

68M3 McHale, P. and H. Fenster
INCREASED YIELDS IN HYBRID THICK FILM CIRCUITS BY INDIRECT ACTIVE DEVICE ATTACHMENT
IEEE Microelectronics Symp., St. Louis, Missouri, pp. D7-1 to D7-6, June 1968. [2] (24)
FABRICATION-bond: TC; wire: Au; film: Al; application: hybrid devices
Evaluation: bond (ball, stitch)
Control: temperature
DESCRIPTIVE

68P1 Poston, M. H.
TIME-TEMPERATURE EFFECTS ON WIRE BONDS
IEEE Microelectronics Symp., St. Louis, Missouri, pp. 1-21, June 1968. [2], (25)
FABRICATION-bond: TC; wire: Au; film: Al
Variables
Control: force; temperature
DEGRADATION: TC; wire: Au; film: Al
Stress: process; thermal
Part: bond
Mechanism: anneal; grain growth; intermetallics
Test: pull; visual inspection
TEST-bond: TC; wire: Au; film: Al
Description: pull
DESCRIPTIVE

68R1 Rodrigues de Miranda, W. R.
VISUAL INSPECTION OF IC'S BOOSTS RELIABILITY AT LITTLE COST
Electronics, vol. 41, pp. 104-108, Aug. 19, 1968.
TEST-bond: TC, US; wire: Al, Au
Description: visual inspection
DESCRIPTIVE

68R2 Ruggiero, E. M.
ALUMINUM BONDING FOR HIGH-POWER IC'S
Microelectronic Packaging, George Sideris, Ed., McGraw-Hill, New York, 1968, chapt. 7.3, pp. 240-248.
FABRICATION-bond: TC; wire: Al, Au; film: Al, Au
Evaluation: bond (ball, stitch, wedge), wire
Procedure
Test: centrifuge, mechanical shock, vibration (variable frequency)
DEGRADATION: bond: TC; wire: Al, Au; film: Al, Au
Stress: thermal
Mechanism: intermetallics
Failure Rates
DESCRIPTIVE

68S1 Shockley, W. L. and R. W. Weedfall
ULTRASONIC BONDING
Microelectronic Packaging, George Sideris, Ed., McGraw-Hill, New York, 1968, chapt. 7.2, pp. 232-240. [see p. 239]
FABRICATION-bond: US; wire: Au, Au/Ga
Wire: care; mechanical characteristics
Bonding Surface: orientation
DESCRIPTIVE

68T1 Takei, W. J. and M. H. Francombe
MEASUREMENT OF DIFFUSION-INDUCED STRAINS AT METAL BOND INTERFACES
Solid State Electron., vol. 11, pp. 205-208, Feb. 1968.
DEGRADATION
Stress: thermal
Part: bond
Mechanism: intermetallics
EXPERIMENTAL

68T2 Tanaka, S. and K. Chiba
SEMICONDUCTOR DEVICE UTILIZING AN AUAL$_2$ LAYER AS A DIFFUSION BARRIER THAT PREVENTS 'PURPLE PLAGUE'
U.S. Patent 3,401,316; Sept. 10, 1968.
FABRICATION-bond: TC, US; wire: Au, Al; film: Ag/Al, $AuAl_2$, Al, Cr; substrate: Si
Evaluation: metal system; metallization
Bonding Surface: metal system, preparation
PATENT

68U1 Uthe, P. M.
THE WIRE
Uthe Technology, Inc. Technical Newsletter, vol. 1, Sept. 1968. [summarized in 69U1] (5)
FABRICATION-bond: US; wire: Al, Al/Mg, Au
Evaluation: wire
Schedule
Tool: design
Wire: mechanical characteristics
Test: pull; visual inspection
DEGRADATION-bond: US; wire: Al; film: Al
Stress: process
Part: substrate
DESCRIPTIVE

68U2 Uthe, P. M.
THE SOLID STATE WELD
Uthe Technology, Inc. Technical Newsletter, vol. 1, May 1968. [summarized in 69U1] (5)
FABRICATION-bond: US
Theory
DESCRIPTIVE

68U3 Uthe, P. M.
THE FRICTION OF NON-LUBRICATED METALS
Uthe Technology, Inc. Technical Newsletter, vol. 1, June 1968. [summarized in 69U1] (5)
FABRICATION-bond: US
Theory
DESCRIPTIVE

68U4 Uthe, P. M.
WELDING
Uthe Technology, Inc. Technical Newsletter, vol. 1, July 1968. [summarized in 69U1] (5)
FABRICATION-bond: US

68U4 (cont.)

Theory
Schedule
Control: force; power; time
DESCRIPTIVE

68U5 Uthe. P. M.
A SIMPLE WIRE BONDER
Uthe Technology, Inc. Technical Newsletter, vol. 1, Aug. 1968. [summarized in 69U1] (5)
FABRICATION-bond: US
Apparatus: adjustment; design
Rigidity: apparatus; terminal
DESCRIPTIVE

69A1 Ang, C. Y., P. H. Eisenberg and H. C. Mattraw
PHYSICS OF CONTROL OF ELECTRONIC DEVICES
Proc. 1969 Annual Symp. on Reliability, Chicago, Ill., pp. 73-85, Jan. 1969. [see pp. 76, 82] (13)
TEST-bond: TC; wire: Au
Correlation: pull; pull (nondestructive)
DESCRIPTIVE

69A2 Anderson, J. H., Jr. and W. P. Cox
FAILURE MODES IN GOLD-ALUMINUM THERMOCOMPRESSION BONDS
IEEE Trans. Reliability, vol. R-18, pp. 206-207, Nov. 1969.
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: thermal
Part: bond; metallization
Mechanism: intermetallics
FABRICATION-bond: TC; wire: Au; film: Al
Bonding Surface: film thickness
EXPERIMENTAL

69A3 Antler, M.
WHAT DO GOLD PLATING SPECS REALLY MEAN?
Products Finishing, vol. 34, pp. 56-66, Oct. 1969.
FABRICATION-film: Au
Bonding Surface: contamination; film thickness; mechanical characteristics; preparation; topography
DESCRIPTIVE

69B1 Bell, J. L.
UPGRADING OF MICROELECTRONIC TEST PROCEDURES FOR MILITARY HI-REL ACHIEVEMENT
Trans. 23rd Annual Technical Conf., pp. 767-770, Los Angeles, Calif., sponsored by American Society for Quality Control, Ann Arbor, Mich., May 1969.
TEST
Evaluation: temperature cycle; thermal shock
DESCRIPTIVE

69B2 Binelli, W. D., and R. H. Soltau
DEVELOPMENT OF QUALIFICATION TEST PROGRAM FOR MICROELECTRONIC DEVICES,
Final Rpt. (Nov. 1, 1968 to July 3, 1969), Contract No. NAS1-8714, Sept. 1969. N70-11544
TEST
Description: centrifuge, mechanical shock; thermal shock
FABRICATION-bond: US; wire: Al; film: Al, Au
Evaluation: wire bond
Test: centrifuge; mechanical shock; thermal shock
DESCRIPTIVE

69B3 Budd, J. B.
DIE AND WIRE BONDING CAPABILITIES OF REPRESENTATIVE THICK-FILM CONDUCTORS
Solid-State Technol. vol. 12, pp. 59-63, June 1969.
FABRICATION-bond: TC, US; wire: Al, Au; film: Au/Mo/Mn; thick film: Ag, Ag/Pd, Au, Au/Pd, Au/Pd/Pt, Au/Pt, Pd/Ag
Evaluation: wire bond; metallization
Variables
Bonding Surface: preparation
Test: pull
DEGRADATION-bond: TC; wire: Au; thick film: Ag/Pd, Au
Stress: thermal
Test: pull
ANALYTIC

69B4 Browning, G. V.
MONOLITHIC INTEGRATED CIRCUIT FAILURE MECHANISMS
Nat. Electron. Conf. Seminar, *Designing with Monolithic Integrated Circuits,* Nat. Electron, Conf., Chicago, Ill., pp. 1-22, Dec. 1969. (26)
DEGRADATION-bond: TC; wire: Al, Au; film: Al, Au/Mo
Stress: thermal
Part: bond
Mechanism: intermetallics
Failure Rates
REVIEW

69B5 Bullis, W. M., Ed.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
NBS Technical Note 488, Quarterly Rpt. (Jan. 1 to March 31, 1969), July 1969. [see pp. 21-25] [30] (29)

69B5 (cont.)

TEST-wire: Al, Au
Application: pull
FABRICATION-bond: US; wire: Al; film: Al
Evaluation: wire (ribbon)
DEGRADATION-bond: US; wire: Al; film: Al
Stress: thermal
Part: wire
Mechanism: anneal
Test: pull
DESCRIPTIVE

69B6 Bullis, W. M., Ed.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
NBS Technical Note 495, Quarterly Rpt. (April 1-June 30, 1969), Sept. 1969. [see pp. 24-31] [30] (29)
FABRICATION-bond: US; wire: Al; film: Al
Evaluation: bond (ball); wire (ribbon)
Apparatus: adjustment
Tool: oscillation
TEST-bond: US; wire: Al; film: Al
Description: bond monitor
DESCRIPTIVE

69B7 Bellin, J. L. S., A. E. Brown, A. S. Hamamoto, and G. C. Knollman
PIEZOELECTRIC MONITOR OF MICROELECTRONIC WIRE BONDS
Lockheed Rpt. LMSC B-62-69-9, June 1969. (21)
TEST-bond: US; wire: Al; film: Al
Description: bond monitor
Correlation: bond monitor, pull, visual inspection
EXPERIMENTAL

69B8 Brinton, J.
MIL STD 883 — A REAL TEST CASE
Electronics, vol. 42, pp. 131-136, Aug. 18, 1969.
TEST
Application: Mil-Std-883
DESCRIPTIVE

69C1 Circuits Manufacturing
A PACKAGING TECHNIQUE IS NOT A BONDING METHOD . . . WIRE-LEADS, FLIP-CHIPS, ULTRASONICS, WHAT'S IT ALL ABOUT?
Circuits Mfg., vol. 9, pp. 8-16, Dec. 1969.
FABRICATION
Evaluation: TC; US; wire bond; bond (ball, stitch, wedge)
DESCRIPTIVE

69C2 Cline, J. E., J. M. Morris, and S. Schwartz
SCANNING ELECTRON MIRROR MICROSCOPY AND SCANNING ELECTRON MICROSCOPY OF INTEGRATED CIRCUITS
IEEE Trans. Electron Devices, vol. ED-16, pp. 371-375, April 1969.
FABRICATION
Test: visual inspection (SEM)
DESCRIPTIVE

69D1 Dudderar, T. D.
THE EFFECT OF GRIP STRESSES ON THE OCCURRENCE OF FAILURE IN TENSION TESTS OF WIRE
Mater. Res. Std., vol. 9, pp. 26-30, Oct. 1969.
TEST
Application: pull
THEORETICAL

69D2 Demer, L. J. and L. H. Fentnor
LAMB WAVE TECHNIQUES IN NONDESTRUCTIVE TESTING
Int. J. Nondestructive Testing, vol. 1, pp. 251-283, Oct. 1969.
TEST
Application: US probe
FABRICATION
Wire: mechanical characteristic
Test: US probe
ANALYTIC

69D3 Department of Defense
MILITARY SPECIFICATION MICROCIRCUITS GENERAL SPECIFICATION FOR —
Mil-M-38510, Nov. 20, 1969. [1]
TEST
Application: Mil-Std-883
Screening Procedures
STANDARD

69G1 Gurland, J.
MICROSTRUCTURAL ASPECTS OF THE STRENGTH AND HARDNESS OF CEMENTED TUNGSTEN CARBIDE
Contract No. SD-86, Dec. 1969.
AD 699187
FABRICATION
Tool: design
DESCRIPTIVE

69G2 Grable, R. C. and H. E. Patzer
WIRE BONDING APPARATUS FOR MICROELECTRONIC COMPONENTS
U.S. Patent 3,430,835; March 4, 1969.
FABRICATION-bond: TC; wire: Au
Procedure
PATENT

69H1 Heinen, K. G. and G. B. Larrabee
THE DETERMINATION OF RESIDUAL PHOTORESIST ON SILICON USING RADIOTRACER IODINE-131
Solid State Technol., vol. 12, pp. 44-47, April 1969.
FABRICATION
Bonding Surface: contamination
Test: radiotracer
DESCRIPTIVE

69K1 Kashiwabara, M., S. Nakayama and M. Suzuki
SETTING AND EVALUATION OF ULTRASONIC BONDING FOR AL WIRE
Rev. Elec. Commun. Lab., vol. 17, pp. 1014-1021, Sept. 1969.
TEST-bond: US; wire: Al; film: Al
Description: pull
Evaluation: visual inspection
Correlation: pull; visual inspection
FABRICATION-bond: US; wire: Al; film: Al
Procedure
Bonding Surface: film thickness
ANALYSIS

69K2 Krieg, R. D. and W. B. Murfin
STRUCTURAL CONSIDERATIONS IN ELECTRONIC MICROCIRCUIT LEAD WIRES
March 1969. PB 183544.
TEST
Application: mechanical shock; temperature cycle; thermal shock; vibration
THEORETICAL

69K3 Kashiwabara, M. and S. Hattori
FORMATION OF AL-AU INTERMETALLIC COMPOUNDS AND RESISTANCE INCREASE FOR ULTRASONIC AL WIRE BONDING
Rev. Elec. Commun. Lab., vol. 17, pp. 1001-1013, Sept. 1969.
DEGRADATION-bond: US; wire: Al; film: Au; substrate: FeNiCo
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: metallurgical exam; resistance
FABRICATION: bond: US; wire: Al; film: Au; substrate: FeNiCo
Procedure
Bonding Surface-film thickness
EXPERIMENTAL

69K4 Knollman, G. C., A. S. Hamamoto, and J. L. S. Bellin
REPORTS ON ULTRASONIC SCREENING OF TRANSISTORS AND INTEGRATED CIRCUITS
Lockheed Rpt. LMSC B-62-69-8, June 1969. (21)
TEST-bond: TC, US; wire: Al, Au; film: Al, Au
Description: US stress
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al, Au
Stress: test (US stress)
Part: bond, wire
Failure Rates
EXPERIMENTAL

69L1 Lauffenburger, H. A. and T. R. Myers
SUMMARY AND INTERPRETATION OF RELIABILITY DATA ON VARIOUS MICROCIRCUIT BONDING TECHNIQUES
Proc. Holm Seminar on Electrical Contact Phenomena, pp. 61-68, Nov. 1969. [6]
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al, Au
Stress: process; thermal
Mechanism: anneal; contamination; intermetallics
Test: pull; shear
Failure Rates
TEST
Screening Procedures
REVIEW

69L2 Laub, J. L. and M. N. Mansour
WIRE CLAMP
U.S. Patent 3,430,834; March 4, 1969.
FABRICATION-bond: US
Apparatus: design
PATENT

69O1 O'Connell, E. P.
AN INTRODUCTION TO MIL-STD-883 TEST METHODS AND PROCEDURES FOR MICROELECTRONICS
Proc. 8th Reliability and Maintainability Conf., Denver, Colorado, pp. 530-542, July 1969. [10] (27)
TEST
Description: centrifuge; Mil-Std-883; pull; temperature cycle; visual inspection
Evaluation: centrifuge; visual inspection
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al, Au
Stress: thermal
Mechanism: anneal, intermetallics
Test: pull
Failure Rates
REVIEW

69O2 Ono, K., M. Nishihata and S. Kobayashi
FINE ALUMINUM TRANSISTOR LEAD WIRES
Rev. Elec. Commun. Lab., vol. 17, pp. 974-988, Sept. 1969.
FABRICATION-bond: TC, US; wire: Al, Al (pure); film: Al, Au

6902 (cont.)

Wire: electrical characteristics; fabrication; mechanical characteristics; topography
Test: pull
DEGRADATION-bond: TC, US; wire: Al; film: Al, Au
Stress: thermal
Part: wire
Mechanism: anneal; grain growth
Test: pull
EXPERIMENTAL

69P1 Plough, C., D. Davis, and H. Lawler
HIGH RELIABILITY ALUMINUM WIRE BONDING
Proc. Electronic Components Conf., Washington, D. C., pp. 157-165, April-May 1969. [2] (28)
FABRICATION-bond: US; wire: Al, Au; film: Al, Au
Theory
Schedule
Variables
Apparatus: adjustment
Tool: design
Rigidity: apparatus; terminal
Bonding Surface: contamination; mechanical characteristics; topography
Test: pull, visual inspection
TEST-bond: US; wire: Al; film: Al, Au
Evaluation: air blast; thermal shock; visual inspection
Correlation: mechanical shock (radiation-induced); pull; visual inspection
DEGRADATION-bond: US; wire: Al, Al/Mg
Stress: thermal
Part: wire; device
Mechanism: anneal, contamination
Test: electrical parameters; pull
DESCRIPTIVE

69R1 Ruth, S. B.
TORTURE TESTS IMPROVE EQUIPMENT RELIABILITY
The Electronic Engineer, vol. 28, pp. 80-87, June 1969.
TEST
Description: centrifuge; mechanical shock; thermal shock; vibration
DESCRIPTIVE

69S1 Slemmons, J. W.
THE MICROWORLD OF JOINING TECHNOLOGY
American Welding Society 50th Annual Meeting and Welding Exposition; Philadelphia, Pa., April-May, 1969. [8] (13)
FABRICATION-bond: TC, US; wire: Al, Au, film: Al, Au
Theory: TC, US
Evaluation: US
Procedure: TC, US
Test: pull
TEST-bond: TC; wire: Au
Description: pull; pull (nondestructive); visual inspection (SEM); x-ray
DEGRADATION: bond: TC; wire: Au; film: Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: visual inspection (SEM)
REVIEW

69S2 Schnable, G. L. and R. S. Keen
ALUMINUM METALLIZATION ADVANTAGES AND LIMITATIONS FOR INTEGRATED CIRCUIT APPLICATIONS
Proc. IEEE, vol. 57, pp. 1570-1580, Sept. 1969.
FABRICATION-bond: TC, US; wire: Al, Au; film: Al, Au/Cr, Au/Mo
Evaluation: metallization
REVIEW

69S3 Selikson, B.
VOID FORMATION FAILURE MECHANISMS IN INTEGRATED CIRCUITS
Proc. IEEE, vol. 57, pp. 1594-1598, Sept. 1969.
DEGRADATION-wire: Al, Au; film: Al, Au
Stress: thermal
Part: bond
Mechanism: intermetallics
FABRICATION-wire: Au; film: Au/Ag/Cr, Au/Mo, Au/Ti/Al, Au/Pt/Ti/Pt, Cr/Al
Evaluation: metal system
REVIEW

69S4 Shurtleff, W. O.
RELIABILITY HANDBOOK FOR SILICON MONOLITHIC MICROCIRCUITS VOLUME 2 — FAILURE MECHANISMS OF MONOLITHIC MICROCIRCUITS
Contract NAS 8-20639, April 1969. N69-23226. [see pp. 2-IV-2 to 2-IV-6]
TEST
Description: centrifuge; mechanical shock, temperature cycle; thermal shock; vibration (variable frequency, fatigue)
Evaluation: vibration (variable frequency); visual inspection
DESCRIPTIVE

69S5 Speer, R. D.
CHIP BONDING: PROMISES AND PERILS
Electronic Design, vol. 17, pp. 61-79, Oct. 25, 1969.
FABRICATION-bond: TC, US
Evaluation: wire bond
REVIEW

69T1 Tamburrine, A. L. and V. C. Kapfer
FAILURE MECHANISMS IN PLASTIC ENCAPSULATED MICROCIRCUITS
Contract No. AF-5519, May 1969.
AD 689224
DEGRADATION-bond: TC; wire: Au; film: Ag, Al, Au, Ni; application: plastic devices
Stress: moisture; test (thermal shock); thermal
Part: wire; bond
Mechanism: corrosion; thermal mismatch
ANALYTIC

69T2 Tarowsky, N.
HOW TO ASSEMBLE HYBRID MICROWAVE IC's
Microwaves, vol. 8, pp. 52-62, Aug. 1969.
FABRICATION-bond: TC, US; application: hybrids
Evaluation: TC; US
DESCRIPTIVE

69U1 Uthe, P. M.
VARIABLES AFFECTING WELD QUALITY IN ULTRASONIC ALUMINUM WIRE BONDING
Solid State Technol., vol. 12, pp. 72-76, Aug. 1969.
FABRICATION-bond: US; wire: Al, Al/Mg, Au; film: Al, Au
Theory
Evaluation: wire
Schedule
Apparatus: adjustment; description; design
Tool: adjustment
Rigidity: apparatus; package
Wire: mechanical characteristics
Test: pull, visual inspection
Trouble Shooting
DEGRADATION-bond: US; wire: Al, substrate: Si
Stress: process
Part: substrate
DESCRIPTIVE

69U2 Uthe, P. M., Jr., L. G. Wright, and R. E. Greenan
ULTRASONIC FREQUENCY POWER SUPPLY
U.S. Patent 3,445,750; May 20, 1969.
FABRICATION-bond: US
Apparatus: design
PATENT

70A1 Adams, M. A.
AN INVESTIGATION OF THE STRENGTH OF ALUMINUM WIRE USED IN INTEGRATED CIRCUITS
NASA Tech. Brief 70-10275, Aug. 1970. [9]
TEST-bond: TC, US; wire: Al, Au; film: Al, Au
Description: pull
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al, Au
Stress: test (pull); thermal
Part: wire
Mechanism: anneal; grain growth
Test: visual inspection (SEM)
DESCRIPTIVE

70A2 Anderson, Jr., J. H., T. G. Maple, and W. P. Cox
AGING EFFECTS IN GOLD THERMOCOMPRESSION BONDS TO COMPLEX METALLIZATIONS
IEEE Trans. Reliability, vol. R-19, pp. 32-34, Feb. 1970.
DEGRADATION-bond: TC; wire: Au; film: Al, Au/Mo/Al, Au/Ti/Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: pull; resistance
FABRICATION-bond: TC; wire: Au; film: Al, Au/Mo/Al; Au/Ti/Al
Evaluation: metal system
Bonding Surface: preparation
EXPERIMENTAL

70A3 ASTM
STANDARD SPECIFICATION FOR GOLD WIRE FOR SEMICONDUCTOR LEAD-BONDING (ASTM DESIGNATION: F72-69)
1970 Annual Book of ASTM Standards, part 8, 1970. [11]
FABRICATION-wire: Au
Wire: care; contamination; mechanical characteristics; size
STANDARD

70A4 ASTM
STANDARD METHODS OF TESTING FINE ROUND AND FLAT WIRE FOR ELECTRON DEVICE AND LAMPS (ASTM DESIGNATION: F219-67)
1970 Annual Book of ASTM Standards, part 8, 1970. [11]
FABRICATION
Wire: mechanical characteristics, size
STANDARD

70A5 ASTM
STANDARD METHOD FOR MEASURING DIAMETER OF FINE WIRE BY WEIGHING (ASTM DESIGNATION: F205-63)
1970 Annual Book of ASTM Standards, part 8, 1970. [11]
FABRICATION
Wire: size
STANDARD

70A6 ASTM
STANDARD METHODS OF TENSION TESTING OF METALLIC MATERIALS (ASTM DESIGNATION: E8-69)
1970 Annual Book of ASTM Standards, part 31, 1970. [11]
Test
Application: pull
STANDARD

70A7 ASTM
STANDARD METHOD OF TEST FOR RESISTIVITY OF ELECTRICAL CONDUCTOR MATERIALS (ASTM DESIGNATION: B193-65)
1970 Annual Book of ASTM Standards, part 8, 1970. [11]
FABRICATION
Wire: electrical characteristics
STANDARD

70B1 Bevington, J. R., J. P. Cook, and D. R. Little
PLASTIC IC RELIABILITY EVALUATION AND ANALYSIS
8th Annual Proc. Reliability Physics, IEEE Catalog No. 70C59-PHY, pp. 73-80, 1970. [abbreviated version of 71B3] [2]
TEST-bond: TC; wire: Au; film: Au, Ag; application: plastic devices
Evaluation: thermal shock
DEGRADATION-bond: TC; wire: Au; film: Au; application: plastic devices
Stress: test (thermal shock)
Part: bond; wire
Mechanism: thermal mismatch
EXPERIMENTAL

70B2 Bullis, W. M., Ed.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
NBS Technical Note 520, Quarterly Rpt. (July 1-Sept. 30, 1969), March 1970. [see pp. 32-43] [30] (29)
FABRICATION-bond: US; wire: Al; film: Al
Apparatus: design
Tool: adjustment; design; oscillation
Rigidity: apparatus
Test: interferometry
DEGRADATION-bond: US; wire: Al; film: Al
Stress: thermal
Part: wire
Mechanism: anneal
Test: pull
TEST-bond: US; wire: Al; film: Al
Description: resistance
EXPERIMENTAL

70B3 Bullis, W. M., Ed.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
NBS Technical Note 527, Quarterly Rpt. (Oct. 1-Dec. 31, 1969), May 1970. [see pp. 31-47] [30] (29)
FABRICATION-bond: US; wire: Al; film: Al
Theory
Apparatus: adjustment
Tool: adjustment; oscillation
Rigidity: apparatus
Wire: contamination; mechanical characteristics
Bonding Surface: preparation
Test: pull
EXPERIMENTAL

70B4 Brauer, J. B., V. C. Kapfer, and A. L. Tamburrino
CAN PLASTIC ENCAPSULATED MICROCIRCUITS PROVIDE RELIABILITY WITH ECONOMY?
8th Annual Proc. Reliability Physics, IEEE Catalog. No. 70C59-PHY, pp. 61-72, 1970. [2] (27)
DEGRADATION-application: plastic devices
Stress: moisture, process, test (temperature cycle)
Part: metallization, wire
Mechanism: corrosion; fatigue; thermal mismatch
Test: resistance, x-ray
Failure Rates: general
DESCRIPTIVE

70B5 Bradfield, G.
ULTRASONIC TRANSDUCERS — 1. INTRODUCTION TO ULTRASONIC TRANSDUCERS, PART A
Ultrasonics, vol. 8, pp. 112-123, April 1970.
FABRICATION-bond: US
Apparatus: design
REVIEW

70B6 Bradfield, G.
ULTRASONIC TRANSDUCERS — 1. INTRODUCTION TO ULTRASONIC TRANSDUCERS, PART B
Ultrasonics, vol. 8, pp. 177-189, July 1970.
FABRICATION-bond: US
Apparatus: design
REVIEW

70B7 Bullis, W. M. and A. J. Baroody, Jr., Eds.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
NBS Technical Note 555, Quarterly Rpt. (Jan. 1 to March 31, 1970), Sept. 1970. [see pp. 27-36] [30] (29)

70B7 (cont.)

TEST
Description: centrifuge; pull; US stress
Application: bond monitor
FABRICATION-bond: US
Tool: design
Rigidity: apparatus
Test: pull; visual inspection (SEM)
DESCRIPTIVE

70B8 Bullis, W. M. and A. J. Baroody, Jr., Eds.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
NBS Technical Note 560, Quarterly Rpt. (April 1 to June 30, 1970), Nov. 1970. [see pp. 29-38] [30] (29)
FABRICATION-bond: US
Theory: US
Schedule
Wire: mechanical characteristics
Rigidity: apparatus
Test: pull; visual inspection (SEM)
TEST
Evaluation: pull
Application: pull
DEGRADATION
Stress: process; test (pull)
Part: bond
Test: visual inspection (SEM)
DESCRIPTIVE

70C1 Cox. W. P., E. E. Anderson, and J. H. Anderson, Jr.
ULTRASONIC ALUMINUM WIRE BONDING FOR MICROELECTRONIC APPLICATIONS
Proc. 1970 Annual Symp. on Reliability, Los Angeles, Calif., vol. 3, pp. 228-236, Feb. 1970. (31)
FABRICATION-bond: US; wire: Al; film: Al
Evaluation: wire
Control: force, power, time
Test: pull; resistance; visual inspection
DEGRADATION-bond: US; wire: Al; film: Al
Stress: process, thermal
Part: wire; substrate
Mechanism: anneal
Test: pull, resistance; visual inspection
EXPERIMENTAL

70C2 Curran, L.
PLASTIC IC'S GET FOOT IN MILITARY DOOR
Electronics, vol. 43, pp. 127-130, May 11, 1970.
TEST-application: plastic devices
Description: Mil-Std-883
DESCRIPTIVE

70D1 Devaney, J. R.
APPLICATION OF SCANNING ELECTRON MICROSCOPY TO INTEGRATED CIRCUIT FAILURE
Solid State Technol., vol. 13, pp. 73-77, March 1970.
DEGRADATION-bond: TC; wire: Au; film: Al
Part: bond
Mechanism: contamination
Test: visual inspection (SEM)
DESCRIPTIVE

70D2 Davis, D.
FACTORS IN HIGH RELIABILITY WIRE BONDING
8th Annual Proc. Reliability Physics, IEEE Catalog No. 70C59-PHY, pp. 170-176, 1970. [similar to 69P1] [2] (28)
FABRICATION-bond: US; wire: Al; film: Al, Au
Schedule
Variables
Apparatus: adjustment, design
Tool: adjustment; design; oscillation
Rigidity: apparatus, terminal, package
Bonding Surface: contamination; thickness; topography
Test: pull; visual inspection
TEST-bond: US; wire: Al; film: Al, Au
Correlation: pull; mechanical shock (radiation induced); visual inspection
REVIEW

70D3 Department of Defense
MILITARY STANDARD — TEST METHODS FOR SEMICONDUCTOR DEVICES
Military Standard 750B, Feb. 27, 1970. [1]
TEST
Description: centrifuge; mechanical shock; thermal shock; vibration (fatigue, monitored, variable frequency)
STANDARD

70D4 Dicken, H. K.
SURVEYING CHIP INTERCONNECTION TECHNIQUES
Electron. Packag. Prod., vol. 10, sect. 1, pp. 34-45, Oct. 1970.
FABRICATION-bond: TC, US; wire: Al, Au; film: Al, Au
Evaluation: TC, US, wire bond
REVIEW

70H1 Hnatek, E. R.
PLASTIC IC'S ENTICE MILITARY
EDN, vol. 15, pp. 43-47, Nov. 15, 1970.
DEGRADATION-application: plastic devices
Stress: test (temperature cycle, thermal shock)
Failure Rates
DESCRIPTIVE

70H2 Haberer, J. R.
STRESS INDUCED INTERMITTENT FAILURES IN ENCAPSULATED MICROCIRCUITS
Report No. RADC-TR-70-213, pp. 1-49, Oct. 1970. AD 715984 [see also 71H2] [1] (27)
TEST-bond: TC; wire: Au; application: plastic devices
Description: resistance; temperature cycle
Evaluation: resistance; temperature cycle
DEGRADATION-bond: TC; wire: Au; application: plastic devices
Stress: moisture, test (temperature cycle)
Part: bond; metallization; wire
Mechanism: corrosion; thermal mismatch
EXPERIMENTAL

70M1 Miller, L. F.
A CRITIQUE OF CHIP-JOINING TECHNIQUES
Solid State Technol., vol. 13, pp. 50-62, April 1970.
FABRICATION
Evaluation: wire bond
REVIEW

70M2 Mann-Nachbar, P., and W. Nachbar
THERMAL SHOCK FOLLOWING RAPID UNIFORM HEATING OF SPHERES AND LONG CYLINDRICAL RODS
Rpt. (April-August, 1968), Contract No. F04701-69-C-0066, Feb. 1970. AD 702170
TEST
Application: mechanical shock (radiation-induced)
THEORETICAL

70P1 Pankratz, J. M. and D. R. Collins
A COMPARISON OF 1% MG-Al AND 1% SI-Al WIRE INTERCONNECTS
8th Annual Proc. Reliability Physics, IEEE Catalog No. 70C59-PHY, pp. 163-169, 1970. [also published in IEEE Trans. Reliability, vol. R-19, pp. 89-94, Aug. 1970] [2] (32)
FABRICATION-bond: US; wire: Al, Al/Mg
Evaluation: wire
Bonding Surface: topography
DEGRADATION-bond: US; wire: Al/Mg
Stress: thermal
Part: device
Mechanism: contamination
EXPERIMENTAL

70P2 Philofsky, E.
INTERMETALLIC FORMATION IN GOLD-ALUMINUM SYSTEMS
Solid State Electron., vol. 13, pp. 1391-1399, Oct. 1970. [also 8th Annual Proc. Reliability Physics Symp., pp. 177-185, 1970]
DEGRADATION-wire: Al, Al (pure), Au
Stress: thermal
Mechanism: intermetallics
Test: metallurgical exam; pull
TEST
Application: temperature cycle; thermal shock
EXPERIMENTAL

70R1 Rossiter, T. J.
AMBIENT EFFECTS ON GOLD-ALUMINUM BONDS
8th Annual Proc. Reliability Physics, IEEE Catalog No. 70C59-PHY, pp. 186-190, 1970. [2] (27)
DEGRADATION-bond: TC; wire: Au; film: Al
Stress: thermal
Part: bond
Mechanism: intermetallics
Test: pull; resistance
EXPERIMENTAL

70S1 Spectrum
HIGH-PRESSURE PROCESS MAKES WIRE BY SQUEEZING
Spectrum, vol. 7, pp. 21, Aug. 1970.
FABRICATION
Wire: fabrication
DESCRIPTIVE

70S2 Straub, R. J.
RELIABILITY OF HYBRID MICROCIRCUITS IN USE TODAY
Proc. Electronic Components Conf., May 1970. [2] (33)
TEST-application: hybrids
Evaluation: Mil-Std 883
Screening Procedures
DEGRADATION-bond: TC; application: hybrids
Failure Rates
DESCRIPTIVE

70V1 Villella, F. and M. F. Nowakowski
INVESTIGATION OF FATIGUE PROBLEM IN 1-MIL DIAMETER THERMOCOMPRESSION AND ULTRASONIC BONDING OF ALUMINUM WIRE
NASA Technical Memorandum, NASA TM X-64566, pp. 1-45, Nov. 30, 1970. N71-16494
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al
Stress: thermal
Part: wire
Mechanism: fatigue
Test: pull; visual inspection (SEM)
Failure Rates
TEST
Application: temperature cycle
EXPERIMENTAL

70W1 Wilson, A. D., B. D. Martin, and D. H. Strope
HOLOGRAPHIC INTERFEROMETRY APPLIED TO MOTION STUDIES OF ULTRASONIC BONDERS
IEEE Ultrasonics Symp., San Francisco, Calif., Oct. 21-23, 1970. [2] (34)
FABRICATION-bond: US
Apparatus: design
Tool: oscillation
Test: interferometry
DESCRIPTIVE

70W2 Wood, W. A.
FATIGUE CRACK INITIATION AS VIEWED BY SCANNING ELECTRON MICROSCOPY
Contract N-00014-67-A-0214-0011, Rpt., Jan. 1970. AD 704789
DEGRADATION
Stress: mechanical
Part: wire
Mechanism: fatigue
ANALYTIC

71B1 Bullis, W. M., Ed.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
NBS Technical Note 571, Quarterly Rpt. (July 1-Sept. 30, 1970), April 1971. [see pp. 23-32] [30] (29)
FABRICATION-bond: US; wire: Al; film: Al
Tool: design; oscillation
Rigidity: apparatus
TEST-bond: US; wire: Al; film: Al
Evaluation: pull
DEGRADATION-bond: US; wire: Al; film: Al
Stress: process
Part: wire
EXPERIMENTAL

71B2 Boylan, J. R.
THERMOCOMPRESSION BONDING
IEEE Intern. Conv. Digest, New York, Session 7C1, pp. 598-599, March 1971. [2]
FABRICATION-bond: TC, US; wire: Al, Au
Evaluation: TC, US; wire bond; temperature control
Procedure: TC
Tool: design (TC)
Rigidity: terminal
REVIEW

71B3 Bevington, J. R., J. P. Cook, D. R. Little, and L. V. Ingle
RELIABILITY EVALUATION OF PLASTIC INTEGRATED CIRCUITS
Rpt. (Jan. 9, 1969 to Sept. 9, 1970) Contract No. F30602-69-C-0154, pp. 1-154, Jan. 1971. AD 722043 [70B1 is abbreviated version] [1]
TEST-bond: TC; wire: Au; film: Ag, Au; application: plastic devices
Evaluation: thermal shock
DEGRADATION-bond: TC; wire: Au; film: Au; application: plastic devices
Stress: test (thermal shock)
Part: bond; wire
Mechanism: thermal mismatch
EXPERIMENTAL

71B4 Bullis, W. M., Ed.
METHODS OF MEASUREMENT FOR SEMICONDUCTOR MATERIALS, PROCESS CONTROL, AND DEVICES
Quarterly Rpt. (Oct. 1-Dec. 31, 1970) NBS Technical Note 592. [see pp. 34-45], [30] (29)
TEST-bond: US; wire: Al; film: Al
Description: bond monitor
Application: pull
FABRICATION-bond: US
Apparatus: adjustment (US); design (US)
Rigidity: apparatus
Wire: mechanical characteristics
DEGRADATION: bond: US; wire: Al; film: Al
Stress: process
Part: bond; wire
Mechanism: anneal
Test: pull
DESCRIPTIVE

71D1 Dushkes, S. Z.
A DESIGN OF ULTRASONIC BONDING TIPS
IBM J. Res. Develop., vol. 15, pp. 230-235, May 1971.
FABRICATION-bond: US; wire: Au/CuBeO; film: Au/Cu; substrate: epoxy
Tool: design; oscillation
Test: pull
EXPERIMENTAL

71G1 Glass, R. A., T. G. Maple, and R. D. Wales
INTERCONNECTION PROBLEM AREAS IN MICROCIRCUITS
IEEE Intern. Conv. Digest, New York, Session 5B, pp. 248-249, March 1971. [2]
FABRICATION-bond: US; wire: Al; film: Al, Au; substrate: Fe/Ni/Co
Tool: design
Bonding Surface: contamination; film thickness; metal system; preparation
Test: pull, visual inspection
DEGRADATION-bond: US
Stress: process
Part: wire
TEST-bond: US; wire: Al; film: Al
Correlation: pull, visual inspection
EXPERIMENTAL

71G2 Goldfarb, S.
WIRE BONDS ON THICK FILM CONDUCTORS
Proc. Electronic Components Conf., Washington, D. C., pp. 295-302, May 1971. [2] (36)
DEGRADATION-bond: US; wire: Al, Au; thick film: Au
Stress: thermal
Part: bond; wire
Test: pull; resistance
EXPERIMENTAL

71H1 Harman, G. G. and H. K. Kessler
APPLICATION OF CAPACITOR MICROPHONES AND MAGNETIC PICKUPS TO TUNING AND TROUBLE SHOOTING OF MICROELECTRONIC ULTRASONIC BONDING EQUIPMENT
NBS Tech. Note 573, pp. 1-22, May 1971. [30] (29)
FABRICATION-bond: US
Apparatus: adjustment
Tool: adjustment, oscillation
Trouble Shooting
DESCRIPTIVE

71H2 Haberer, J. R.
TECHNIQUES FOR DETECTING STRESS INDUCED INTERMITTENT FAILURES IN ENCAPSULATED DEVICES
IEEE Intern. Conv. Digest, New York, Session 7CJ, pp. 612-613, March 1971. [see also 70H2]
TEST-bond: TC; wire: Au; application: plastic devices
Description: resistance; temperature cycle
Evaluation: resistance; temperature cycle
DEGRADATION-bond: TC; wire: Au; application: plastic devices
Stress: moisture, test (temperature cycle)
Part: bond; metallization; wire
Mechanism: corrosion; thermal mismatch
EXPERIMENTAL

71H3 Hart, R. R.
A WIRE EXTENSOMETER FOR DETERMINING THE MECHANICAL PROPERTIES OF FINE WIRES
Mater. Res. Std., vol. 11, pp. 26-28, April 1971.
FABRICATION
Wire: mechanical characteristics
EXPERIMENTAL

71J1 Johannesen, F.
ULTRASONIC ALUMINUM WIRE BONDING
IEEE Intern. Conv. Digest, Session 7CI, pp. 600-601, March 1971.
FABRICATION-bond: US; wire: Al; film: Al, Au; substrate: Fe/Ni/Co
Variables
Apparatus: design
Tool: design, wear
Rigidity: apparatus, package
Bonding Surface: topography
REVIEW

71K1 Kalvelage, B. F.
A PNEUMATIC SHOCK TESTER FOR ELECTRON DEVICES
Solid State Technol., vol. 14, pp. 57-59, March 1971.
TEST
Description: mechanical shock
DESCRIPTIVE

71K2 King, C. M.
DYNAMIC SIMULATION OF AN ULTRASONIC WIRE BONDING TOOL
Raytheon Report ER71-4135, Contracts N0003070-C0055 and N0003071-C0061, Jan. 25, 1971. (35)
TEST
Application: bond monitor
THEORETICAL

71L1 Leyshon, W. E., and R. E. Warr
AN OVERVIEW OF HYBRID INTEGRATED CIRCUIT RELIABILITY PROBLEMS AND SOLUTIONS
IEEE Intern. Conv. Digest, New York, Session 7CJ, pp. 606-607, March 1971.
DEGRADATION-application: hybrid devices
Stress: moisture; test (temperature cycle)
Part: metallization, wire
Mechanism: contamination; corrosion; fatigue; intermetallics
Test: resistance
REVIEW

71M1 Matcovich, T. J.
INTERCONNECTIONS IN HYBRID CIRCUITS
IEEE Intern. Conv. Digest, New York, Session 5B, pp. 240-241, March 1971.
FABRICATION-bond: TC, US
Evaluation: wire bond
REVIEW

71N1 NASA
LINE CERTIFICATION REQUIREMENTS FOR MICROCIRCUITS
NHB 5300.4(3C), May 1971. [30]
TEST
Description: Mil-Std-883; pull; resistance; visual inspection; visual inspection (SEM)
Application: Mil-Std-883
Screening Procedures
STANDARD

71N2 NASA
TEST STANDARDS FOR MICROCIRCUITS
NHB 5300.4(3D), May 1971. [30]
TEST
Description: mechanical shock; pull; resistance
STANDARD

71P1 Philofsky, E.
DESIGN LIMITS WHEN USING GOLD-ALUMINUM BONDS
9th Annual Proc. Reliability Physics Symp., Las Vegas, IEEE Catalog No. 71-C-9-PHY, 1971. [2] (37)
FABRICATION-bond: TC, US; wire: Al, Au; film: Al, Au
Bonding Surface: film thickness
DEGRADATION-bond: TC, US; wire: Al, Au; film: Al, Au
Stress: test (temperature cycle); thermal
Part: bond; wire
Mechanism: fatigue; intermetallics
ANALYTIC

71P2 Philofsky, E., R. Bowman, and W. Miller
ALUMINUM ULTRASONIC JOINING IN SPIDER AND WIRE CONNECTIONS
Proc. Electronic Components Conf., Washington, D. C., pp. 289-294, May 1971. [2] (37)
FABRICATION-bond: US; wire: Al; film: Al
Theory: US
Evaluation: US
Bonding Surface: topography
REVIEW

71R1 Ravi, K. V. and E. Philofsky
THE STRUCTURE AND MECHANICAL PROPERTIES OF FINE DIAMETER ALUMINUM — 1 PCT SI WIRE
Metallurgical Transactions, vol. 2, pp. 711-717, March 1971.
FABRICATION-bond: TC, US; wire: Al
Evaluation: wire
Wire: mechanical characteristics
DEGRADATION-bond: TC, US; wire: Al
Stress: thermal
Part: wire
Mechanism: anneal; fatigue; grain growth
Test: pull
EXPERIMENTAL

71S1 Straub, R. J. and J. P. Farrell
THE EFFECTIVITY OF SCREENING HYBRID MICROCIRCUITS PER MIL-STD-883
Proc. Electronics Components Conf., Washignton, D. C., pp. 17-26, May 1971. [2] (38)
TEST-bond: TC; wire: Au; film: Al, Au; application: hybrid devices
Screening Procedures
DEGRADATION-bond: TC; wire: Au; film: Al, Au application: hybrid devices
Stress: test (centrifuge, mechanical shock, temperature cycle, thermal shock)
Part: bond, wire
EXPERIMENTAL

Appendix A. Organization of Bibliography

Each entry has been given an *identification code* which consists of a sequence of two digits, a letter, and another digit. The first two digits indicate the year of publication and the letter is the initial of the first author's surname. The last digit is used to distinguish those papers which would otherwise have the same code. No rule was used in the assignment of the last digit. The papers in the bibliography are arranged according to their codes. The codes are grouped first by year, then in alphabetical order by letter, and then in numerical order by the last digit.

Key words (or phrases) are listed beneath each reference in the bibliography to indicate the contents and approach of the paper. Three levels of key words are used to indicate the subject matter of the entries at three levels of detail. These levels and the key words assignments are discussed in Appendix D. A *Key Word Index* is provided and presented in two parts. The first part lists the key words in alphabetical order with the page number where the same key word may be found in the second part of the Index. This second part lists the key words by subject area. With each key word is a tabulation of literature citations (using their identification codes). In both parts of the Index, key words that may require additional definition are followed by clarifying notes, in brackets, except for those for the test methods. Brief descriptions of the test methods may be found in *Table 4*. Here, key words for the test methods are listed in alphabetical order with a brief description for each. The test methods listed are not necessarily restricted to testing wire bonds. However, the descriptive phrases are directed to the particular function described in the papers compiled.

Reading priority is suggested by giving prominence to those papers that are of such scope or relative importance in a particular area that they should be seen first. These papers are so indicated by underlining the identification code for the paper listed under the appropriate key word in the Key Word Index. They are also indicated by underlining the code of the citation and the appropriate key word(s) in the bibliography.

Some citations are followed by notes which refer to additional information intended to assist in obtaining the referenced work. This and other information related to *availability* is included in Appendix C.

A complete *Author Index* is also provided.

Appendix B. Sources for Bibliography and Abbreviations

The *sources* of the bibliography are listed in *Table 1*. Emphasis was placed on searching the report and journal literature from 1965 to 1970. Citations to much of the important earlier work were found in the articles published during this period. Another source of papers was a number of restricted bibliographies, containing references to unrestricted literature, and personal files.

The journal or conference *abbreviations* generally follow those of the *Chemical Abstracts*. In order to minimize any possible confusion, those journals abbreviated are listed in alphabetical order by their abbreviations in *Table 2*. Additional abbreviations are included which are used in citations to some conference meetings. Another purpose of this Table is to indicate those journals which have been scanned completely at least over the period from 1965 to 1970, inclusive. They are indicated by an asterisk in the left-hand margin.

Appendix C. Availability

Some entries in the bibliography have availability notices after the citation to assist in procurement.

The citations to reports available from the *National Technical Information Service (NTIS)*, Sills Building, 5285 Port Royal Road, Springfield, Virginia 22151, are followed by a number preceded by the letters AD or PB, or the letter N. This is the NTIS Acession number which should be used when ordering.

A number of other entries, generally to conference papers, have the citation followed by a number either in brackets or parentheses. The number refers to an address listed in *Table 3*. If the number is in brackets the address listed is one to which an order may be placed for the paper or the conference proceedings. If the number is in parentheses the address is that of the first author's place of work at the time the paper was published.

TABLE 1. SOURCES FOR BIBLIOGRAPHY

1. Bibliographic search by the Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314. A data bank and a report bibliographic search was performed in May, 1969 and updated in June, 1970. A two level search strategy was used: level one - 1. integrated circuits, 2. microelectronics; level two - 1. circuit interconnections, 2. bonding, 3. bonded joints, 4. ultrasonic welding.

2. Bibliographic search by the Reliability Analysis Center, IIT Research Institute, 10 West 35th Street, Chicago, Illinois 60616. Performed in June 1969.

3. U. S. Patent search. Performed May, 1969.

4. <u>Scientific and Technical Aerospace Reports</u> for the years 1965-1970. Subject categories were: electronics, electronic equipment, and physics.

5. <u>U. S. Government Research and Development Reports</u> for at least the period from 1969-1970. Earlier entries would be included in item 1. Subject fields were electronic and electrical engineering, methods and equipment, and physics.

6. Journals in Table 2 that are preceded by an asterisk. Issues of these journals published in the period from 1965 to 1970, inclusive, were examined.

TABLE 2. ABBREVIATIONS AND JOURNALS SEARCHED

AIME - American Institute of Mining, Metallurgical and Petroleum Engineers
ASME - American Society of Mechanical Engineers
ASTM - American Society for Testing and Materials
ASTME - American Society of Tool and Manufacturing Engineers
Appl. Phys. Lett. - Applied Physics Letters
*Bell Lab. Rec. - Bell Laboratories Record
*Bell System Technical Journal
Brit. Commun. Electron. - British Communication and Electronics
Brit. J. Appl. Phys. - British Journal of Applied Physics
Circuits Mfg. - Circuits Manufacturing
Conf. - Conference
*EDN - (formerly Electrical Design News)
*EE - (now, The Electronic Engineer; formerly, Electronic Industries)
*EEE
*Electron. Packag. Prod. - Electronic Packaging and Production
*Electron. Prod. - Electronic Products Magazine
*Electronic Design
*Electronic Engineer - The Electronic Engineer (formerly EE, formerly Electronic Industries)
*Electron. Lett. - Electronics Letters
*Electronics
*Electro-technol. - Electro-technology (New York)
Eval. Eng. - Evaluation Engineering
*IBM Journal of Research and Development
IEEE - Institute of Electrical and Electronics Engineers (formerly IRE)
IEEE Intern. Conv. Record - IEEE International Convention Record (formerly IRE . . .)
*IEEE Trans. Electron Devices -IEEE Transactions on Electron Devices (formerly IRE . . .)
*IEEE Trans. Nucl. Sci. - IEEE Transactions on Nuclear Science
*IEEE Trans. Pts. Materials Packaging - IEEE Transactions on Parts, Materials and Packaging
*IEEE Trans. Sonics Ultrason. - IEEE Transactions on Sonics and Ultrasonics
*Industrial Research
*International Journal of Nondestructive Testing
Int. - International
IEC - International Electrotechnical Commission
IRE - Institute of Radio Engineers
IRE Intern. Conv. Record - IRE International Convention Record
IRE Trans. Electron Devices - IRE Transactions on Electron Devices
J. Appl. Phys. - Journal of Applied Physics
*J. Electrochem. Soc. - Journal of the Electrochemical Society
J. Sci. Instrum. - Journal of Scientific Instruments
Mater. Eval. - Materials Evaluation
*Mater. Res. Std. - Materials Research and Standards
Metals Eng. Quart. - Metals Engineering Quarterly
*Microelectronics and Reliability
Nat. Electron. Conf. - National Electronics Conference
Mfg. - Manufacturing
NEPCON - National Electronic Packaging and Production Conference
Philips Tech. Rev. - Philips Technical Review
Proc. IEEE - Proceedings of the Institute of Electrical and Electronics Engineers
*Prod. Eng. - Product Engineering
*RCA Review
*Rev. Sci. Instr. - The Review of Scientific Instruments
Rev. Elec. Commun. Lab. - Review of the Electrical Communications Laboratory. Tokyo. (Denki Tsushin Kenkyujo)
SAE - Society of Automotive Engineers
Semicond. Prod. - Semiconductor Products
*Semicond. Prod. Solid State Technol. - Semiconductor Products and Solid State Technology
Soc. - Society
*Solid State Abstracts
*Solid State Electron. - Solid State Electonics
Solid State Technol. - Solid State Technology
Symp. - Symposium
Technol. - Technology
*Trans. Met. Soc. AIME - Transactions of the Metallurgical Society of the AIME
*Ultrasonics
Welding J. - Welding Journal
WESCON - Western Electric Show and Convention

*Journals searched completely for period 1965-1970.

TABLE 3. AVAILABILITY NOTES

[1] U. S. Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, Pennsylvania 19120.
[2] Publications Sales Department, The IEEE, 345 East 47th Street, New York, New York 10017.
[3] American National Standards Institute, Inc., 1430 Broadway, New York, New York 10018.
[4] Industrial and Scientific Conference Management, Inc., 222 West Adams Street, Chicago, Illinois 60606.
(5) Uthe Technology, Inc., 670 Almanor Ave., Sunnyvale, California 94086.
[6] Illinois Institute of Technology, Chicago, Illinois 60606.
[7] ASME Order Dept., 345 47th Street, New York, New York 10017.
[8] American Welding Society, 345 East 47th Street, New York, New York 10017.
[9] Technology Utilization Division, NASA, Code UT, Washington, D. C. 20546.
[10] Gordon and Breach, Science Publishers, Inc., New York, New York 10001.
[11] ASTM, 1916 Race Street, Philadelphia, Pennsylvania 19103.
(12) MIT Instrumentation Laboratories, Cambridge, Massachusetts 02142.
(13) North American Aviation/Autonetics, Anaheim, California 92803.
(14) Norden Division of United Aircraft Corp., Norwalk, Connecticut.
(15) Philco-Ford Corp., Microelectronics Div., Blue Bell, Pennsylvania 19422.
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(23) Hughes Aircraft Co., Welder Dept., Oceanside, California 92054.
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(37) Motorola Inc., Phoenix, Arizona 85008.
(38) Delco Electronics Division, General Motors Corp., Milwaukee, Wisconsin.

Three levels of key words are used in the bibliography to indicate the subject material in the works compiled, each successive level being less broad in scope. To help identify key words of different levels, all the letters are capitalized for first-level key words while only the first letter of the second-level key words is capitalized. The third-level key words are all in lower-case.

First-level key words are used to indicate general subject areas discussed; they are TEST, FABRICATION, and DEGRADATION. One or more of these key words may be used, depending on the contents of the work. The order of listing is meant to indicate the relative emphasis given each area if more than one is listed.

The *kind of wire bonds* involved in the discussions of a given subject is described by a series of *descriptors* arranged on the same line and following the first-level key word describing the subject area. The descriptions that may be used, depending on what is discussed, are: *bond, wire, film, thick film, substrate, and application.* They refer, respectively, to the bond involved; the wire material; the metallization film(s) on the bonding surface or the material on which the wire is bonded if no metallization film is used; the thick-film (>> 1 μm) conductive composition, if used; the substrate material under the conducting film; and the application or use of the wire bond in hybrid circuits or plastic devices. Following each of these descriptors are symbols or words to indicate the kinds of bonds, materials, and applications that are used or discussed. If the comments are of a general nature and no particular wire bond is mentioned in the entry then descriptors are not given.

If a *test method* is discussed in the context of testing or evaluating the wire bond then the first-level key word TEST is listed under the entry in the bibliography. As appropriate, one or more of the following *second-level* key words is listed below TEST: *Description, Evaluation, Correlation, Application, Precautions, and Screening Procedures;* in that order. The key words (third-level) for the test methods are arranged in alphabetical order after and on the same line with the appropriate second-level key words listed above. If the entry describes a test method in any detail, the key word for the method will follow Description; if it evaluates the methods the key word will follow Evaluation; if it presents correlation information with other methods for the same type of wire bond, then key words for these methods will follow Correlation. If the material in the entry is or may be applicable to a test method, its key word will follow Application, while if the material deals with precautions in the use of a method its key word will follow Precautions. Finally, if the material in the entry deals with procedures in which several tests are performed as a means of culling out weak wire bonds then Screening Procedures will be listed without an indication of the test methods involved.

If material in the entry deals with some aspect of the fabrication of wire bonds then the first-level key word FABRICATION is used. The *second-level* key words that have been selected are as follows: *Theory, Evaluation, Procedure, Schedule, Variables, Apparatus, Control, Tool, Rigidity, Wire, Bonding Surface, Test, and Trouble Shooting.* Without mentioning the third-level key words in any detail, the meaning and intent of the above listed second-level key words will now be indicated. The key word *Theory* relates to the theory of making a bond while *Evaluation* relates to the evaluation of such things as the type of bonding process, the type of bond, the metal systems used, etc. The key word *Procedure* refers to the procedures or steps in making a particular type of wire bond. The key word *Schedule* refers to the optimization of the fabrication processes and procedures for making wire bonds, while the key word *Variables* refers to the effects that specific variables have on the quality or strength of a wire bond. The key word *Apparatus* refers to the bonding machine and its accessories; *Control* refers to the importance of controlling specific parameters; *Tool* refers to the tool used to press against the wire while the bond is made; *Rigidity* refers, generally, to the importance of mechanical rigidity and positional control in the fabrication of the wire bond; *Wire* refers to the wire used; and *Bonding Surface* to the characteristics of the bonding surface pertinent to good bonding. If test methods are used to evaluate the fabrication procedures their key words are listed after *Test*. Finally, if the entry discusses hints or methods for locating and correcting deficiencies in the fabricating procedures, the key word *Trouble Shooting* will be used.

If material in the entry deals with some aspect of the degradation or failure of wire bonds then the first-level key word DEGRADATION is used. The *second-level* key words that have been selected are as follows: *Stress, Part, Mechanism, Test, and Failure Rates.* The third-level key words for the first three of these were selected to be more specific in terms of, respectively, (1) the kind of stress that produces a weakened wire bond as a result of the fabrication process or that results in degradation or failure of an already completed wire bond; (2) the part or component, primarily of the wire bond, that is or has been affected by the stress; and (3) the mechanism, if defined, that is involved in the degradation or failure. If a test method is used to detect or measure this degradation or failure then the key words of the test methods used will follow Test. If general reliability data, such as failure rates of specific kinds of wire bonds under specific conditions or stress, are included in the entry then the key word Failure Rates is used; third-level key words follow to indicate if the information pertains to thermocompression or ultrasonic wire-bonds, or if the kinds of wire bonds are not indicated.

The *first-level* key words used to indicate the approach or the type of the entry are ANALYTIC, DESCRIPTIVE, EXPERIMENTAL, and THEORETICAL; and PATENT, REVIEW, and STANDARD. Only one of these key words is used and it is listed last.

TABLE 4. TEST METHODS AND BRIEF DESCRIPTIONS

air blast
A jet of gas, usually air or nitrogen, is directed at the wire.

bond monitor
Some measure of the mechanical coupling between the tool, wire, and metal film is monitored during ultrasonic bonding.

centrifuge
A constant centrifugal force is applied to the device.

electrical parameter
A device performance test is used to determine device degradation caused in some way by the wire bond.

electron microprobe
An electron microprobe is used to identify contaminants in the wire bond.

IR monitor
The infrared radiation from a bond is used to obtain a measure of the thermal resistance of the bond interface and hence the area of contact and the quality of the bond of the wire to the bonding surface.

interferometry
The motion of ultrasonic bonding tools and velocity transformers in ultrasonic bonding machines is studied with use of interferometry.

mechanical shock
A large, short-duration deceleration is applied to the device.

mechanical shock (radiation-induced)
The absorption of a short pulse of high-energy electrons in a plate fastened to the base of the device header is used to generate thermally-induced stress waves which are used to stress the wire bond.

metallurgical exam
The structure and interface of wire bonds are examined metallurgically.

Mil-Std-750B
Military standard test methods for discrete devices.

Mil-Std-883
Military standard test methods for integrated circuits.

noise
Electrical noise measurements are used to detect abnormalities in the wire bond.

photoelastic stress analysis
Stress distributions in the vicinity of the bond are studied.

pull
The wire is pulled by a probe, usually hook-like, until some part of the wire bond ruptures.

pull (nondestructive)
The wire is pulled by a probe to a predetermined tensile stress.

radiotracer
Radiotracers are used to detect the distribution of contaminants and to study interfacial displacements.

resistance
The contact or bond-interface resistance is measured (directly or indirectly).

temperature cycle
The device is exposed alternately between two temperature extremes to test the ability of the wire bond to sustain the mechanical stresses that result from differences in the thermal coefficients-of-expansion of the constituent parts.

thermal shock
Same as temperature cycle except that the transfer time between temperature extremes is shorter.

US probe
Ultrasonic energy is used to test (probe) the mechanical quality of bonds.

US stress
Ultrasonic energy is used to stress wire bonds.

vibration (fatigue)
The device is vibrated at a fixed frequency for long periods of time at a relatively low maximum acceleration level.

vibration (monitored)
The electrical parameters of the device are monitored while it is being vibrated.

vibration (variable frequency)
The device is vibrated thru a frequency range at a relatively constant, maximum acceleration.

visual inspection
Wire bonds are examined under a microscope to determine if they conform to predetermined criteria of physical appearance, location, and orientation.

visual inspection (SEM)
The same as the visual inspection test except a scanning electron microscope (SEM) is used.

x-ray exam
X-rays are used to look for abnormalities in wire routing and orientation in encapsulated devices.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

More than 245 papers relevant to wire-bond type electrical interconnections used in microelectronic and low-power discrete and hybrid devices are listed together with key words. The bibliographic search concentrated on compiling papers which appeared in the period from 1965 to 1970, inclusive. The selection of papers was generally limited to those that were pertinent to wire-bonds where the wire diameter is less than about 50μm (2 mils) and where the wire is bonded by either thermocompressive or ultrasonic means. Two indexes are provided: (1) an Author Index and (2) a Key Word Index. The latter includes a tabulation of the literature citations.

Key words (cont.): (wire-bond); wire-bond.

17. KEY WORDS (Alphabetical order, separated by semicolons) Bibliography; degradation (wire-bond); discrete devices; electrical interconnection; fabrication (wire-bond); failure(wire-bond) hybrid circuits; integrated circuits; microelectronics; reliability; testing; (cont.)

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Optical Radiation Measurements:

Photometric Instrumentation and Research (1970 to 1971)

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Optical Radiation Measurements:

Photometric Instrumentation and Research (1970 to 1971)

Edward F. Zalewski, A. Russell Schaefer,

Kshitij Mohan, and Donald A. McSparron

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Institute for Materials Research
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Preface

This is the second issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series will consist primarily of reports of progress in or details of research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division and will appear about every six weeks.

The level of presentation in OPTICAL RADIATION MEASUREMENTS will be directed at a general technical audience. The equivalent of an undergraduate degree in engineering or physics plus familiarity with the basic concepts of radiometry and photometry [e.g., G. Bauer, Measurement of Optical Radiations (Focal Press, London, New York, 1965)] should be sufficient for understanding the vast majority of material in this series. Occasionally a more specialized background will be required such as for some of the electronic techniques required in this issue. Even in such instances, a careful reading of the assumptions, approximations and final conclusions should permit the non-specialist to understand the gist of the argument if not the details.

At times, certain commercial materials and equipment will be identified in this series in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

Any suggestions readers may have to improve the utility of this series are welcome.

Henry J. Kostkowski, Chief,
Optical Radiation Section
National Bureau of Standards

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Photometric Instrumentation and Research (1970 to 1971)

Edward F. Zalewski, A. Russell Schaefer,
Kshitij Mohan*, and Donald A. McSparron

This document was written primarily to serve two purposes. First, some of the basic instrumentation which has recently been developed for use in photometry at NBS is described. The design and application of photodetector amplifiers, lamp power circuitry, and mechanical instrumentation are discussed. Second, three photometric experiments are described: the stability testing of some flux lamps and intensity lamps and the determination of the dependence of relative intensity on orientation. These experiments and their conclusions have proven useful in pointing out areas which need further investigation and in planning the directions of future work.

Key words: Instrumentation; lamp orientation; lamp power circuitry; lamp stability; photodetector amplifier; photometry.

1. Introduction

A little over a year ago there was at NBS a merger of several related groups, including radiometry and photometry, into one managerial unit. This was done in order to bring the programs of these heretofore independent groups into concert. Before the merger there already was a move under way in the photometry group to expand the research program and modernize the instrumentation. This work continued, of course, and evolved into the research programs presently under way.

Because the instrumentation developed during this period is now used in several of the present programs, we have decided to describe it in a single document for ease of reference in future publications. In addition to a description of our instrumentation, we have described three of the experiments that were either completed or well under way at the time of the merger. The results of these experiments have proved useful to us in the planning of further research in photometry.

In keeping with the intention of this series on research in optical radiation measurement, we have tried to be as detailed as possible in the descriptions of our equipment and procedures. There is a danger that beyond a certain point additional details become trivia. It is difficult to determine where this point actually lies because it is a function of the background of the individual reader. We apologize in advance for those sections that the reader may find boring and welcome any comments or questions that may arise in those sections he or she finds obscure.

In the description of our instrumentation we discuss the current to voltage converters that were designed and built at NBS for the amplification of the photodetector output. The operation of a stable DC lamp power circuit is presented. And finally, we describe the various pieces of hardware we have constructed to support and align the lamps and to perform various photometric measurements.

Under the heading of photometric research we have included two different sets of measurements on lamp stability and one set on lamp characterization. The two experiments on lamp stability are a study of the drift of a specific type of lamp that may be used as a standard of geometrically total luminous flux and a study of the reproducibility of the output of a type of lamp that is currently used as a luminous intensity standard. The lamp characterization experiment deals with the orientational dependence of the output of three types of lamps that have been used as either luminous intensity or spectral irradiance standards.

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*National Bureau of Standards Research Associate from the Electrical Testing Laboratories.

2. Instrumentation

2.1 Photodetector Amplifier

Introduction:

One critical aspect of procedures for the measurement of light is the method used for measuring the rather small electrical currents produced by photosensitive detectors. Two of the most common types of these detectors, the selenium barrier-layer cell which has been used for many years in photometry at NBS, and the silicon photodiode now being employed in experiments here, are essentially current sources. It has been found that they must be operated into a very low impedance circuit in order to maintain a linear relationship between the illuminance incident on these detectors and the resultant current output. The device used to accomplish this task, besides having a very low input impedance, must be quite stable, must be linear over the range of currents encountered, and must have a low noise characteristic. In addition it must be sensitive enough to handle the currents involved, which typically range from a tenth to a hundred microamps.

In the past, two methods were used at NBS to fulfill the above requirements. These were essentially current balancing techniques which created an effective zero impedance across the photodetectors. One method, described by Barbrow [1][1], involves balancing the current from a photocell against that from a stable source supply. The other method shown in figure 1 balances the output current of two photocells to achieve a low impedance. Each photocell viewed a different source and a null was achieved by varying the distance between the comparison source and the receiver. These techniques are fairly simple and fulfill the requirements of low input impedance and high sensitivity. However, these circuits are somewhat cumbersome to use, the stability and linearity are open to question, and they are difficult to adapt to an automated data acquisition system.

A simple experiment to compare a commercially available DC current to voltage converter-amplifier with these earlier methods indicated that the signal-to-noise ratio and the stability of the current to voltage converter were at least as good as the current balance and the photocell balance circuits. Because of this one would expect a notable improvement in measurement capability by utilizing state-of-the-art operational amplifiers. It was therefore decided to design and construct a very stable, sensitive, low noise DC current to voltage converter using an operational amplifier with good stability and noise specifications.

Operational amplifier principles:

A few basic principles of operational amplifiers which make them suitable for the present application will now be discussed. For a detailed treatment and derivation of some of the following expressions, see e.g. Graeme et al. [2]. Operational amplifiers are simply high gain amplifiers, often having two differential input terminals and a single output. There are certain useful properties which a so-called perfect or ideal operational amplifier would possess. These are an infinite input impedance, Z_i; a zero output impedance, Z_0; instantaneous response time, implying infinite bandwidth; infinite internal or open loop gain, A; and output voltage V_0 such that

$$V_0 = A(V_2 - V_1) \tag{1}$$

where V_2 and V_1 are the two input voltages. The ways in which the device can be used depend largely on the type of feedback network employed. Figure 2 shows the basic configuration in which the operational amplifier (op amp) is used as a current amplifier, or more specifically, a current to voltage converter. In this diagram a typical real photocell of near infinite impedance is represented by an ideal negative current source i_s with infinite impedance coupled with a finite impedance R_s in parallel. The equivalent voltage source is shown in the insert for ease of analysis. In this case the positive polarity input is tied to common so that the voltage drop across the op amp inputs can be

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[1]Figures in brackets indicate the literature references at the end of this paper.

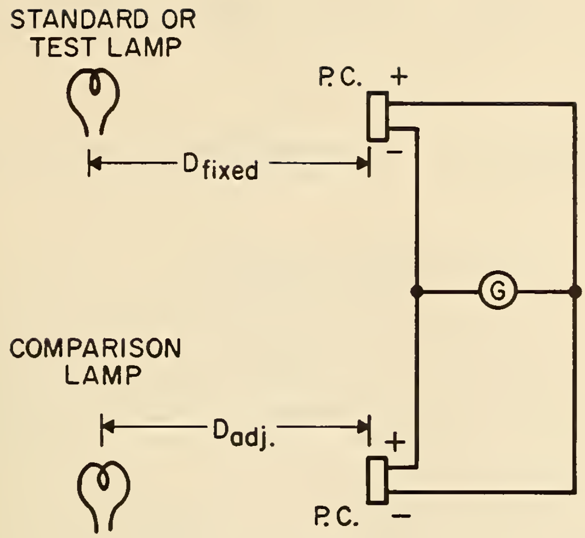

Figure 1. Balanced photocell circuit. This figure depicts a system in which the output of a comparison photocell (P.C.) is successively balanced against that of a photocell measuring the illuminance from a standard lamp and that from a test lamp. Values of D_{adj}, the adjustable distance between the comparison lamp and photocell, for the two balanced conditions yield the intensity of the test lamp:

$$I_T = \frac{I_s D_s^2}{D_T^2}$$

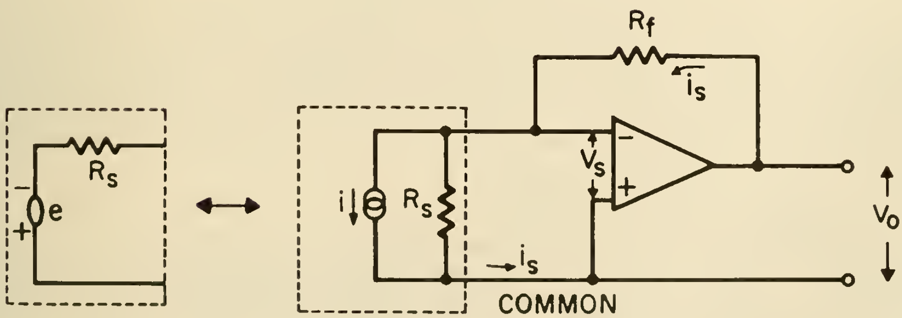

Figure 2. Basic current to voltage converter circuit. The dotted insert shows the equivalent voltage source.

represented by V_s. This is called an "inverting circuit", since the polarity of the amplified signal will be changed in polarity. The properties mentioned above now imply that

$$V_0 = -AV_s \text{ as } A \to \infty \tag{2}$$

and, since all the current i_s must flow through the feedback network because of infinite input impedance of the op amp,

$$i_s = \frac{e - V_s}{R_s} = \frac{V_s - V_0}{R_f} \tag{3}$$

From eqs. (2) and (3)

$$i_s = V_s \frac{1 + A}{R_f} \tag{4}$$

and thus the input impedance of this circuit is

$$Z_s = \frac{V_s}{i_s} = \frac{R_f}{1 + A} \tag{5}$$

Hence in the case of infinite or near infinite gain ($A \to \infty$) the impedance is quite low, practically zero. Equation (5) also implies V_s is approximately zero for finite signals i_s. Because of this well-known condition in which the signal input is practically at common potential (i.e. $V_s \simeq 0$, virtual ground) and because the circuit input impedance is very low, this is an excellent device for measuring current sources. Note also that $i_s = e/R_s = -V_o/R_f$ for $A \to \infty$ implies the current i_s is independent of the feedback resistor R_f. Changing R_f alters V_0, but has no effect on i_s. The closed loop gain of the circuit which can be expressed as the ratio of the output voltage to the equivalent source voltage gives a measure of the amplification of unwanted op amp noise voltage and offset voltage. From eqs. (3) and (4),

$$V_0/e = \frac{-A}{\left(R_s/R_f\right)(1+A) + 1} \quad . \tag{6}$$

If $R_s \simeq R_f$, then this ratio is approximately one, for large A, hence this circuit is often called a unity gain amplifier. Therefore, the voltage noise in this circuit is not very important unless R_f becomes greater than the photocell impedance. High frequency current noise can be a problem at these high impedances. To overcome this a small capacitor can be placed in parallel with R_f as a filter.

Current to voltage converter -- first version:

With this background let us proceed to the design of the first version of a current to voltage converter. This work was initiated by Dr. Bruce Steiner. The final design and construction was done by Mr. Louis Marzetta of the Electronic Instrumentation Section at NBS. The schematic diagram is shown in figure 3. The heart of this device is an Analog Devices Model 310 J varactor bridge operational amplifier. The most important characteristics which this op amp possesses for the present application are its stability (input offset voltage drift of ±30 μV/°C; ±100 μV/% power supply drift) and its low input noise characteristic (10 μV p-p voltage noise for 0.01 to 1 Hz and 10 μV rms voltage noise for 1 to 100 Hz; 10^{-15} A p-p current noise for 0.01 to 1 Hz and 2×10^{-15} A rms current noise for 1 to 100 Hz). Using the highest feedback resistor of 10 megohm and no filtering capacitance, which is the worst possible case, this means any current noise to be converted along with the signal is still a factor of 10^8 smaller than the signals encountered at this level (about 0.1 microamp). Hence current noise does not pose a problem. Furthermore, because of the unity gain configuration, voltage noise will only contribute about 10 μV noise on any given range: this is about 10^4 less than output voltages generally encountered

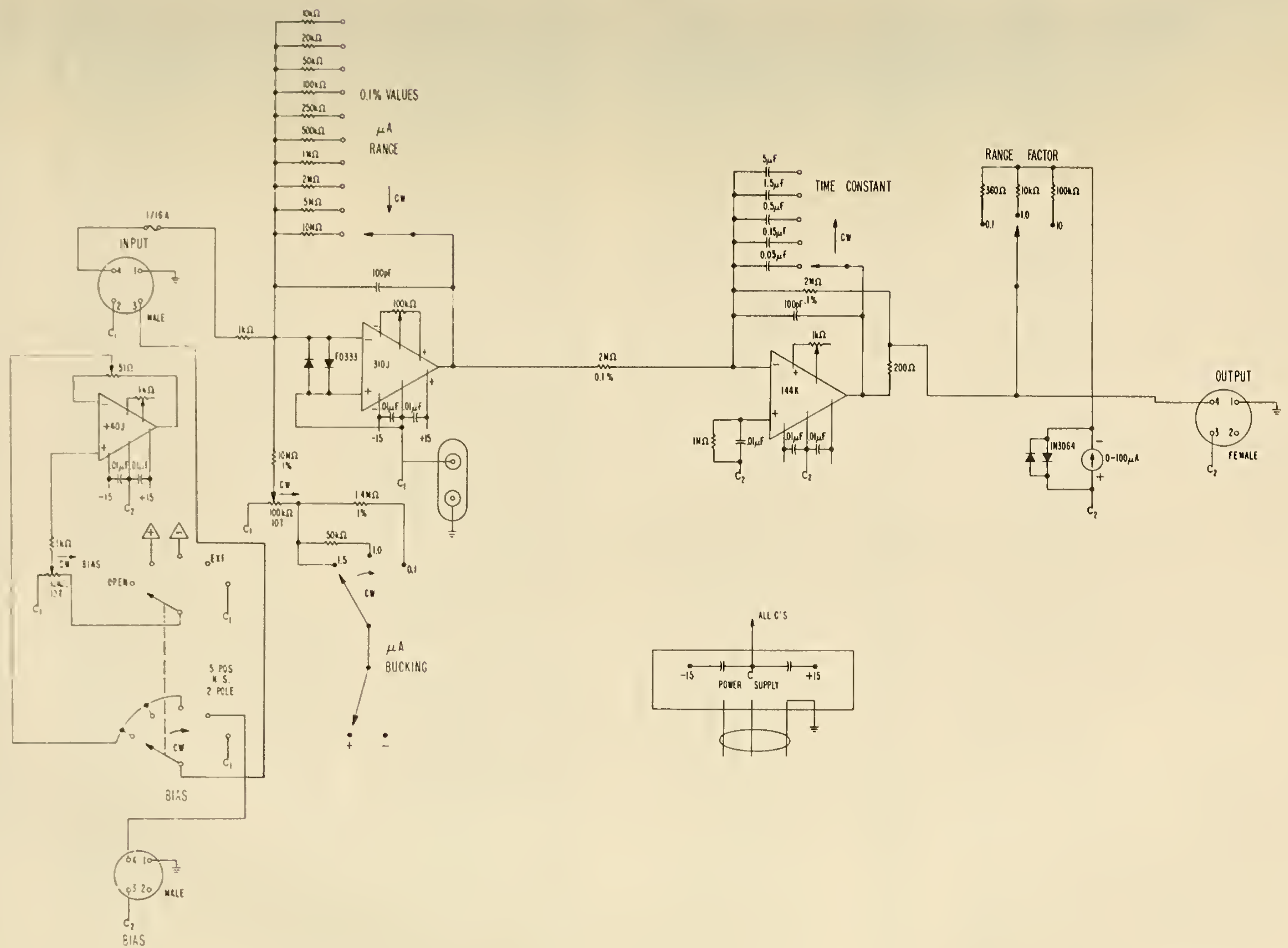

Figure 3. Current to voltage converter: first version. C_1 and C_2 are circuit commons connected at the power module common.

It is important to have very stable feedback resistors in the circuit. For this reason 0.1% tolerance, low temperature coefficient (50 ppm/°C) metal film resistors were chosen. These provide 0 - 10 volt output ranges for input currents from 0.1 to 100 microamps. Low leakage capacitors were used in all critical circuit locations because of the high sensitivity of the op amp and to maintain good accuracy in the transfer through it. A small capacitance is placed in parallel to limit the bandwidth enough to prevent misbehavior due to high frequency current noise.

The second stage Analog Devices Model 44 K op amp which also has a low noise voltage characteristic is used as a noninverting voltage follower which provides a well isolated low impedance voltage output. Its main purpose, however, is to provide the ability to select a given RC time constant filter independent of the feedback range selected. Five selectable capacitors in parallel with a two megohm resistor yield instrument time constants of 0.1, 0.3, 1, 3, and 10 sec. for averaging of noisy signals. An output voltage meter switchable to three ranges (0.1, 1.0, and 10 volts full scale) gives an indication of output, although in most cases data are recorded by reading the voltage output with a digital voltmeter.

Provision was made for bucking out a signal current of either positive or negative polarity. This is supplied by a divider circuit which introduces ±0 to 0.1, 0 to 1.0, or 0 to 1.5 microamps of current from the power supply into the signal input of the op amp.

An allowance was also made for voltage biasing a photodetector if desired. The voltage bias, which appears across the signal input leads, can be selected from the power supply internally, providing plus or minus 0 to 15 volts. Alternatively the bias can be switched to a rear panel input which allows the use of an external bias source. The Analog Devices Model 40J is used as a noninverting follower to allow good isolation and high input impedance for the voltage bias source, yet a very low impedance is maintained at the signal input leads for the photodetector current source. With the switching used one can connect the return signal lead to either a positive or negative internal bias, an externally applied bias, common potential, or an open circuit.

There are several more design features of this instrument that are not evident in the schematic diagram in figure 3. First, the power supply used was a modular unit constructed to power operational amplifier circuits with good stability and low noise. Second, to minimize any AC pickup from this supply, the entire unit and its AC power input cord are located in a separate compartment shielded from the rest of the instrument. Third, the common of the circuit has been left floating, with a terminal on the rear panel to allow a user the option of grounding the common. Finally, all inputs and outputs are on 4-pin plugs which follow this convention: Pin 1 - chassis ground, Pin 2 - common, Pin 3 - low or return signal lead, Pin 4 - high or input signal lead.

<u>Current to voltage converter checkout</u>:

After completion this unit was subjected to extensive usage and checkout procedures which will now be briefly described.

In order to get an approximate value of the voltage noise for this device, its input was open circuited to simulate the high impedance from a current source. The output was monitored with a five digit, dual-slope integrating digital voltmeter (IDVM) sampling with a 1/10 second gate, which had an average normal mode rejection ratio of about 10 db or less for the frequencies encountered (except for harmonics of 0.1 second where it is considerably greater). The voltage noise registered under these conditions for the maximum instrument bandwidth of 0 - 10 Hz was about 10 μV, independent of feedback range.

To determine an approximate level of stability, the input was again open circuited, and the output read with the IDVM. A constant signal input was generated simply by introducing a current through the bucking circuit. This served as a test of both the stability of the operational amplifier and that of its internal power supply. Output was read automatically every 20 minutes with a data acquisition system. The output was found to vary only a couple of parts per hundred thousand over a period of eighteen hours.

Linearity was checked using the following procedure. A picoammeter source was used to generate a current, and a Leeds and Northrup Model K-3 potentiometer was employed for measuring current and voltage. This was done in conjunction with a voltage divider (Leeds and Northrup volt box, Model 7592) used in the voltage measurements and a 10,000 ohm metal film resistor of excellent stability characteristics used for the current determinations. The procedure was to measure a set current from the picoammeter source with the potentiometer, then switch this current into the operational amplifier and record the voltage output with the potentiometer for each feedback resistor. The process was then repeated for another current. Three different ranges of input current were tested. They were: 0.1 to 1.0 μa in steps of 0.1 μa, 1.0 to 10.0 μa in steps of 1.0 μa, and 10.0 to 100.0 μa in steps of 10.0 μa.

Analysis of the linearity data was done by fitting a straight line to voltage out versus current in for each feedback resistor and for each of the three sets of current values, resulting in thirty curves. The results indicate the device is linear to within a few tenths of a percent for all currents encountered, and if one chooses the feedback resistor so that a signal of about one volt or more is put out (as is usually done in actual practice), then linearity is within a few hundredths of a percent. These linearity results are undoubtedly limited by the experiment, and not the op amp itself, since experiments elsewhere [3] have shown that operational amplifiers used in this way are linear even over a greater range and to a greater degree than indicated by the results of this experiment. This work was done primarily to ascertain that there were no malfunctions which might manifest themselves as a grossly nonlinear output response.

In summary, this current to voltage converter appeared to be quite satsifactory over the range of precision and accuracy required for intended laboratory use. However, it was found during actual use that in order to attain the low noise levels expected from the manufacturer's specification, it is necessary that the op amp common be grounded rather than floating. When this connection was made the noise decreased by a factor of ten.

<u>Current to voltage converter -- second version:</u>

As might be expected it became apparent that several improvements could be made on a second design of a current to voltage converter. First, it was thought desirable to be able to reverse the input with a switch to accommodate those photodetectors which had been wired with a reverse polarity. Second, it might be useful at times to have a greater bandwidth than 0 - 10 Hz. This could be provided by a switch that in one of its positions places no capacitance across the second stage op amp, thus allowing a much faster time response (of the order of several microseconds). Third, a more sophisticated filter, such as a three pole filter giving a higher filtering ratio with a smaller inherent time constant would be desirable. Fourth, it was found there were times when even more gain would be desirable: an additional feedback resistor of 30 megohm would give a maximum useful sensitivity of 0.1 volts output for 0.003 μa input. Also, a switch and resistor installed in the noninverting second stage feedback network would permit one to switch in a factor of ten voltage gain. This would result in a maximum sensitivity of 0.1 volts out for 0.3 nanoamps in. The final change desired would be to install an input socket to include the option of introducing a bucking current from an external source. This would allow use of a bucking current greater than that supplied by the internal bucking circuit.

A second current to voltage converter was constructed which incorporated the above mentioned modifications. The circuit diagram is shown in figure 4. Instead of the varactor bridge, however, an Analog Devices Model 42K FET operational amplifier was used because of its even lower input noise specification and smaller size. Testing proceeded in about the same manner as for the first device. The results are summarized below.

Noise and stability appear to be of about the same level as with the first model, with one exception. There was initially a slight degradation in voltage noise (to about 20 microvolts) when the time constant was set at zero. It was range independent. The test was done with the same IDVM as in the previous checkout. Linearity of this instrument within experimental limits was again found to be the same as that of the previous one. The extra feedback resistor was useful, but the optional gain of ten on the second stage, since it also amplifies the noise voltage by a factor of ten, has not been useful as yet. As with the previous instrument, it has been necessary to run the common at ground potential to reduce noise effects. There initially was a problem with the 42 K op amp. It became

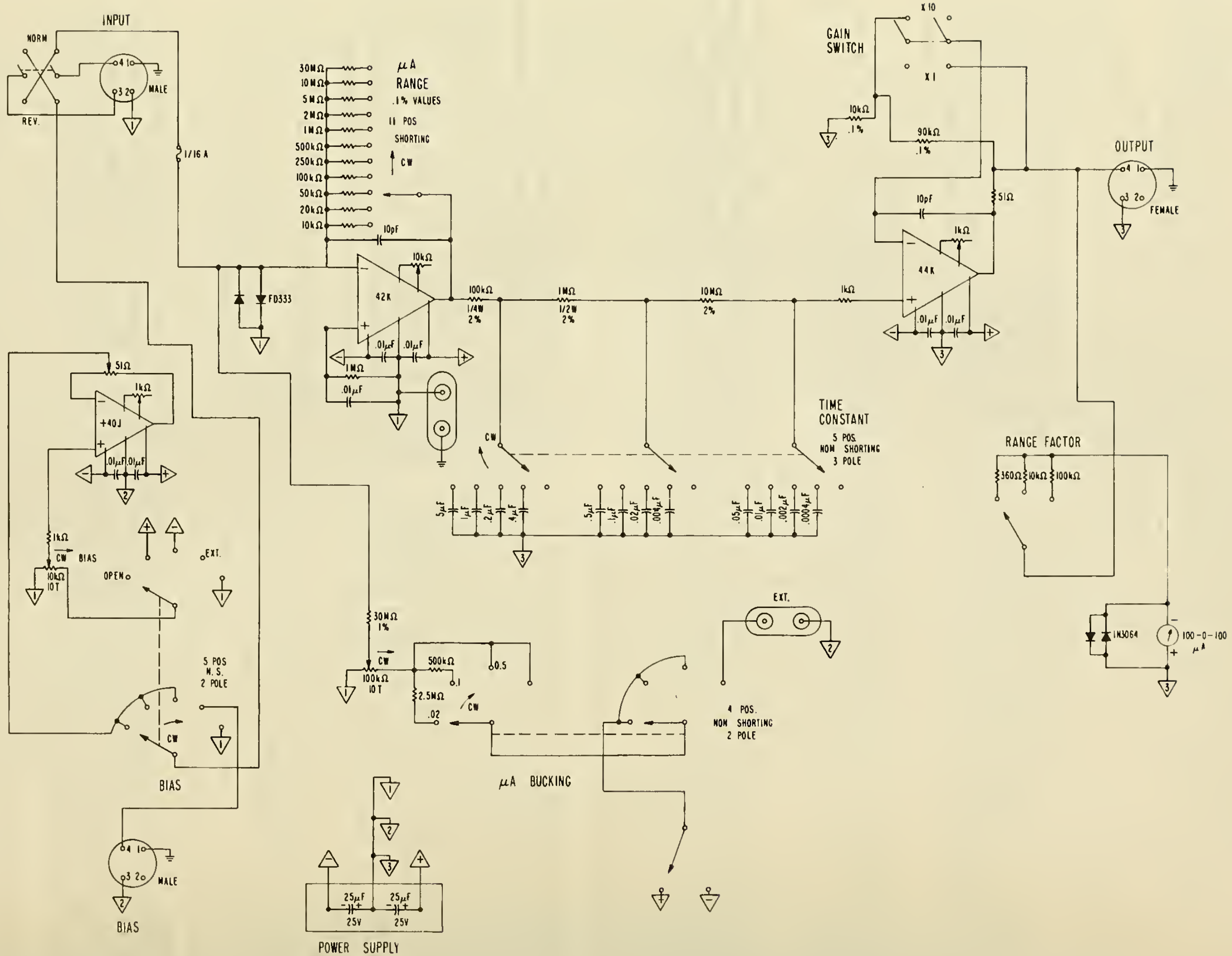

Figure 4. Current to voltage converter: second version. ①, ②, and ③ are circuit commons connected at the power module common.

unstable and put out maximum voltage with no signal on the input. This was thought to be due to the extremely high intrinsic impedance and sensitivity of the FET op amps. Initially the protective diodes for the 42 K op amp were mistakenly connected directly from the negative to the positive input leads. The problem was corrected by connecting the diodes directly to common instead of first to the positive input and by installing a different 42 K op amp. The new op amp seemed somewhat less susceptible to this anomaly and also exhibited a lower voltage noise level of less than 10 μV.

In conclusion, both of these instruments have performed very well in their intended usage. It is anticipated that similar instruments will be constructed for future use in photometric and radiometric applications at NBS.

2.2 Lamp Power Circuitry

Introduction:

In order to obtain a steady light output from a tungsten filament lamp for use in deriving standards for radiometry and photometry, a very stable source of electrical power must be provided for the lamp. It is known empirically that, for a typical gas filled tungsten lamp, the light flux is approximately proportional to the 3.4 power of the voltage and the 6.2 power of current [4]. Thus, if it is desired to hold the flux output to within 0.01% of a constant value, then the voltage must be held to within about 0.0029% and the current to within 0.0016%. These are fairly stringent requirements which must be met by the power supply and circuitry over the time of the measurement involved. In some cases this may be several hours. The following material discusses a type of supply and circuit which has been found applicable to the above mentioned requirements.

Lamp current and voltage measurements:

Figure 5 shows a schematic of the circuits which are typically used. If it is desirable to make measurements of the load voltage and current with a potentiometer, in order to assure maximum accuracy, then a voltage divider network or "volt box" and current measuring shunt must be employed. This divider has an impedance which is low enough (typically 750 ohms/volt) that a significant amount of current will be diverted through it from the load. Hence some judgement must be exercised in choosing the location of the current measuring shunt relative to the measurement of the voltage. If the parameter of greatest interest is the voltage across the load, then the position of the current measuring shunt should be as shown in part A of figure 5. Only the voltage divider appears across the load. This is in keeping with good measurement practice since the potentiometer can be at a low potential in this configuration, thus reducing the chance of measurement error due to stray leakage. The current actually measured through the shunt can then be corrected by calculating the amount of current diverted from the load by the voltage divider.

If, on the other hand, the load current is the parameter of greatest interest, then the current measuring shunt should be as shown in part B of figure 5. This will allow a true measure of the current passing through the load, and the voltage measured across the load and current shunt can be corrected by using the known resistance of the current measuring shunt. The inconvenience caused by having to correct for the presence of the voltage divider can be eliminated by using instead a high input impedance digital voltmeter. The impedance of a high accuracy digital voltmeter is typically 10^7 ohms or more; therefore, it will draw negligible current from the circuit.

Another decision to be considered is whether to regulate the voltage across the circuit or the current through it. There are certain advantages and disadvantages to each approach. The well regulated power supplies currently available monitor the voltage across a load impedance using remote error sensing leads. These sensing leads complete a feedback circuit that controls the current or voltage by supplying a small bucking or boosting output. Taking these facts into account, the easiest way to power the lamp circuit is to simply connect it to the supply power output with the remote sensing leads connected directly to this supply output (circuit input) as indicated in part A of figure 5. The error sensing leads were not connected directly across the load, as might at first seem appropriate, because they are active current carrying leads, and connecting them in such

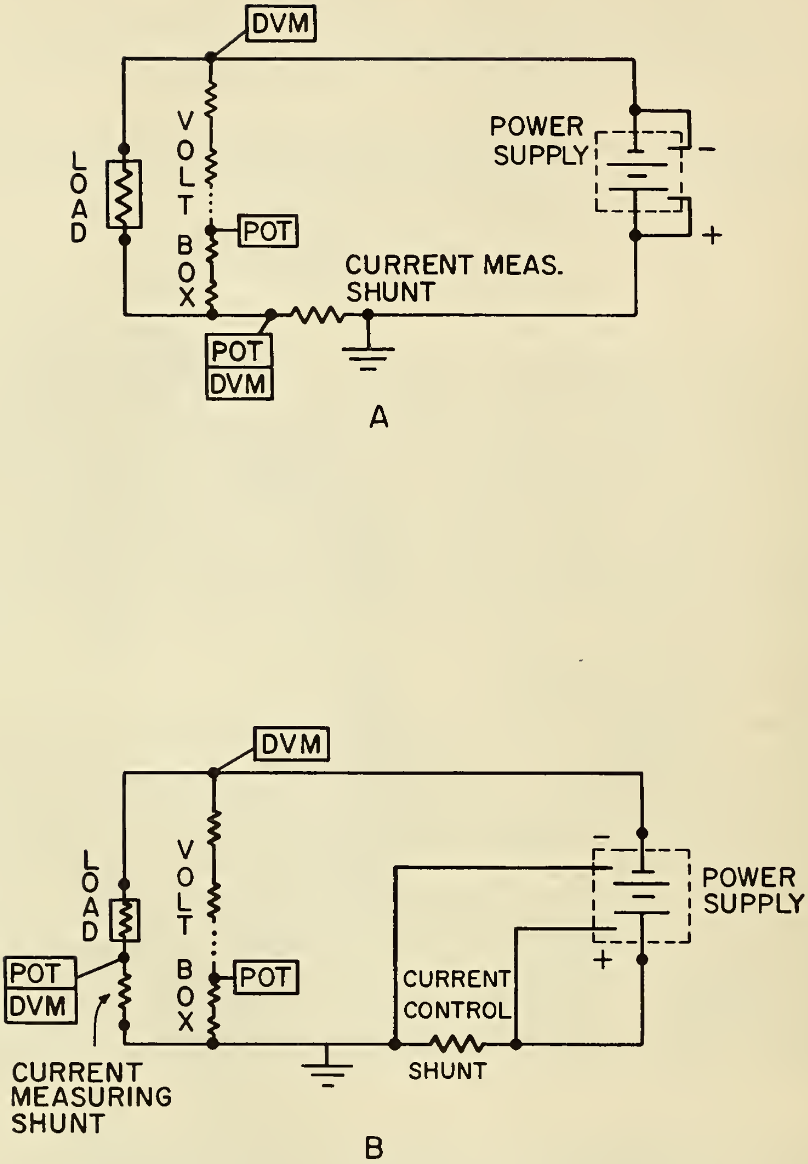

Figure 5. Lamp power circuits: A, voltage controlled; B, current controlled. The locations of the remote sensing leads from the power supply are indicated. The appropriate positions of the "high" lead of the digital voltmeter and potentiometer for the measurement of load parameters are indicated.

a way could conceivably cause errors in determining the actual voltage and current parameters of the load itself.

Because of several factors, for instance, shifting contact potentials at the load terminals due to lamp replacement or load resistance changes (e.g. that of a lamp filament) that are a function of time, it has often been found desirable to regulate the current through the load rather than the voltage across it. This is accomplished by sensing and controlling the voltage drop across a current control shunt which is shown in part B of figure 5. In this case the remote error sense leads are used to maintain a constant voltage across the control shunt. This results in a constant current being supplied to the circuit. More details of this method will be discussed later.

Basically, then, the lamp power circuit consists of a stable power source; a current controlling shunt used with the supply to regulate the current flowing in the circuit; another shunt used to measure the current flowing through the load; a relatively high impedance voltage divider across the load to allow potentiometric measurement of the load voltage; a potentiometer for precise continuous measurement of load voltage or current; and a digital voltmeter for digital measurement and output of these parameters. The location of the electrically "high" measuring leads of the potentiometer and digital voltmeter with respect to ground for measurement of various parameters is indicated in figure 5.

In addition to the above considerations, several more comments on this circuit are in order. First, the location of the system ground is significant. For stable high accuracy and precision measurements, it is desirable to have the potentiometer and peripheral devices properly guarded. Also one side of the potentiometer, voltage divider, and current shunts should be at ground potential to minimize stray leakage currents, as mentioned previously. This is accomplished by the configuration shown in figure 5.

Second, although the power supply used could be operated with both terminals above the ground potential, in the circuit in figure 5 one side is very near ground potential, since the current control shunt is normally only a fraction of an ohm. For the supplies presently used it is preferable to have the positive output rather than the negative one at ground potential, hence the polarity shown was adopted.

Third, the current shunts must be overrated so that they will not heat up and change resistance values at the current levels used. Low temperature coefficient shunts (<30 ppm/$^\circ$C) with a power rating at least ten times that actually required are desirable.

Fourth, a four terminal system with separate leads for voltage measurement should be used throughout the circuit.

Finally, the potentiometer, voltage divider, and digital voltmeter should be guarded and of reasonably high quality, capable of precisely measuring at least five significant digits.

Stable DC power supplies:

Using the apparatus described above with loads of a size typically encountered in our experimentation, the Kepco Series JQE power supplies were found for our purposes to give adequate regulation in both the current and voltage modes, and the Hewlett-Packard Harrison series performed similarly in the voltage mode. In order to maintain some versatility in the maximum voltage and current output capability, two supplies are used together in parallel for higher currents and in series for higher voltages. The output of this type of supply can be remotely programmed with a variable resistance. In order to run two of the supplies together in the manner referred to above it is preferable to program only one and have it control the other supply. This is often called the "master/slave" combination. Some difficulty was initially encountered in determining how best to run these supplies in the "master/slave" configuration in series and in the current regulating mode, but after some experimentation the arrangement shown in figure 6 was settled upon. The details of how these supplies operate can be found in the manufacturer's handbooks and operating manuals.

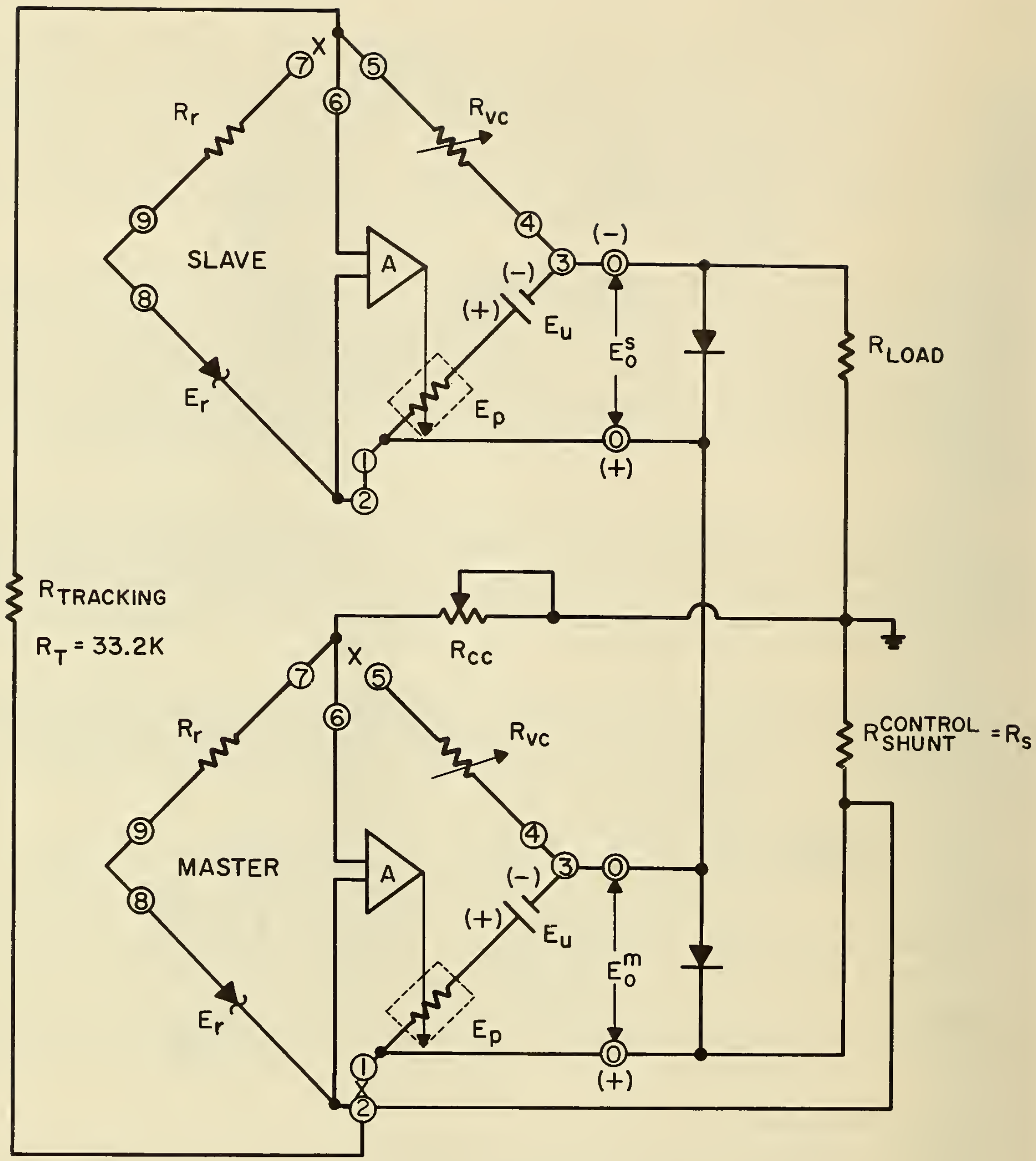

Figure 6. Lamp power supply circuit, master/slave, constant current, series configuration using Kepco JQE series power supplies. The bridge circuits are internal to the power supplies and the numbered circles represent the external connections on the instrument. (See the manufacturer's instruction manual for more information.)

For the Kepco power supplies used in our experiments, R_s, the current control shunt, was chosen such that at maximum current about an 0.5 volt drop occurs across it. The current control, R_{cc}, a 0-500 ohm potentiometer in our case, should be a high quality, low temperature coefficient device. The voltage output of the slave supply is equal to that of the master supply multiplied by the ratio of the slave supply voltage control resistor, R_{vc}, to the tracking resistance, R_t. Since R_{vc} is 60 KΩ, R_t was chosen about 30 KΩ, so that with the R_{vc} of the slave supply set at about the halfway position, both supplies contribute equal amounts of power. The power ratio can be altered at will by adjusting R_{vc}. It is apparent that R_t should also be a high quality resistor. Two diodes are placed across the individual supply outputs to protect them against possible transient reverse potentials. This provides a harmless bypass for any reverse current. Each diode, of course, must have a reverse breakdown voltage greater than the maximum voltage output of the power supply. The diodes should be able to carry the maximum short circuit current that the power supplies are capable of producing. It is advisable to use not only heavy power leads, but also heavy shielded sense and control leads to minimize stray noise pickup.

The supplies and circuit described have been used to regulate current through resistive loads typical of tungsten lamps at maximum supply voltage capability and approximately half maximum current capability. Under these conditions, the degree of regulation is about one part in 10^5 over a period of about fifteen hours. Performance appears to be degraded somewhat at higher current output levels. The system is capable of regulating in the voltage mode at all levels of output to the order of one part in 10^5 for periods of twelve hours. The circuit has proven to be stable, versatile, and convenient for automation, particularly when using the digital voltmeter. The potentiometer is useful to maintain a check on the digital voltmeter calibration and to provide simultaneous and continuous analog monitoring of any desired parameter in addition to the digital measurements of the voltmeter.

2.3 Mechanical Instrumentation

Optical bench enclosure and baffles:

Two Ealing Double Rail optical benches are presently in use in photometric research: one is 3m and the other is 5m long. Each optical bench is mounted on hardwood surfaced laboratory benches that have been bolted to the floor. The bench tops are covered with black suedine cloth (manufactured by Vertipile, Inc., type FF8-7184) and the cloth is held in place around the outside edge of the table by iron strips one inch wide.

Bolted to the table top at each corner is a channel-frame column (such as Unistrut or Globestrut) 40 inches high. These four columns support a channel-frame rectangle which spans the length and width of the table. This structure serves as a support for the baffles and for the materials which form a light-tight enclosure. The baffles are hung from wheel assemblies which roll inside the length of the channel. Black suedine covered aluminum sheets cover the top of the enclosure and several sets of black drapes about 30 inches wide cover the sides. The drapes are made of a double thickness of the black suedine material, back to back, with a sheet of black polyethylene between them. Strip magnets are sewn into the material around the edges of each drape to hold it closed against the iron strip along the table edge and against thin, suedine covered iron sheets about 8 inches wide hung in the spaces between the drapes.

By housing the optical bench with magnetically secured drapes, each section of the bench is made independently and rapidly accessible. In addition to being opaque, the drapery material is of very low reflectance in order to minimize scattered light. The baffles are made of aluminum sheet cut to fit within the channel-frame enclosure and covered on both sides with the suedine cloth. The cloth extends about one inch on the sides of each baffle to meet with the drapes which billow slightly. Several different size baffles are used and since the baffles clip onto the movable wheel assemblies they can be easily inserted, changed or moved to new positions.

Optical bench alignment:

The optical benches have been mounted on their respective table tops in a kinematic manner. The procedures used may be generally useful and will therefore be summarized for one (5m) of the benches.

The 5m bench has eleven supporting posts each having two leveling screws as shown in figure 7A. Each supporting post rests on an 8" × 1¼" × ¼" aluminum supporting plate. One of the leveling screws in each of the four supporting posts located at the ends and adjacent to the center of the bench has a conical tip. These tips rest in three Vee grooves and a round hole in their respective supporting plates as shown in figure 7B. The remaining leveling screws have round tips or bottoms and rest on flat portions of the supporting plates.

The optical bench was aligned relative to the optic axis defined by the beam from a one milliwatt He-Ne laser in the following manner. The laser was mounted on a channel-frame platform separate from the structure which encloses the optical bench. It was then aligned so that the beam would pass through the center of a baffle hung anywhere within the channel-frame enclosure; the track in which the wheel assemblies rolled having previously been made horizontal with the aid of a spirit level. The optic axis is approximately 15 inches above the optical bench rails.

The optical bench was then made level along both the long and short horizontal directions using a spirit level. Leveling was started at the center support posts and progressed out to the ends. This procedure had to be repeated several times to make the optical bench approximately level along its entire length. All the screws holding the optical bench together were then loosened and gradually retightened. The bench was allowed to rest in this new position overnight and releveled the next day.

The optical bench was then brought into position relative to the laser beam with the aid of two pointed rods mounted in carriers with fixed position stems. The height of the rods was adjusted so that the points were at the center of the laser beam. The optical bench was then positioned so that these two rods could be moved anywhere along the bench and still intersect the beam. The optical bench was then fixed in place by bolting the three supporting plates having grooves and the one having a hole to the table top. This alignment procedure resulted in no discernable twist along one half of the bench and 0.2° to 0.3° twisting between the support posts along the mating half[2]. The distance between the laser beam and the bench rails was constant to within 1 mm.

Lamp orientation mounts:

Three different lamp mounts, based on two different design principles, have been used for the rotational positioning of the lamps relative to the optic axis. In one design, rotation is accomplished by pivots that are colinear with the three axes of rotation; whereas in the other design two curved surfaces sliding against each other provide rotation.

In the first design category, the mount employed was originally used to position radiance standards. A sketch of this mount is shown in figure 8. It is very similar to a pair of gimbals with one-half of the circle cut away. Two pillars attached to the base support the outer pivots. This pair of pivots forms a horizontal axis to allow a pitch rotation; that is, a rotation about an axis perpendicular to the optic axis. The semicircular ring attached to these pivots is held almost horizontal by a section of a 7½-inch radius worm gear which extends down to engage a worm screw.

The semicircular ring has an inside diameter of 7 3/4 inches. It contains a third pivot which allows a rotation around the optic axis (roll rotation). The axis of this pivot is perpendicular to that of the first two. A platform 7 inches in diameter is attached 8.75 inches below this pivot by means of a vertical metal strip. The platform is fixed to the axis of a gear and worm assembly identical to the one used for pitch rotation.

The third rotation around the vertical axis (yaw rotation) is accomplished by a small turntable, Unislide Model A2504TS, mounted on the platform. The lamp socket is then mounted on this turntable and the height adjusted so that the three axes of rotation intersect at approximately the center of the lamp filament.

The relative pitch and roll angles could be read to a resolution of one minute of arc

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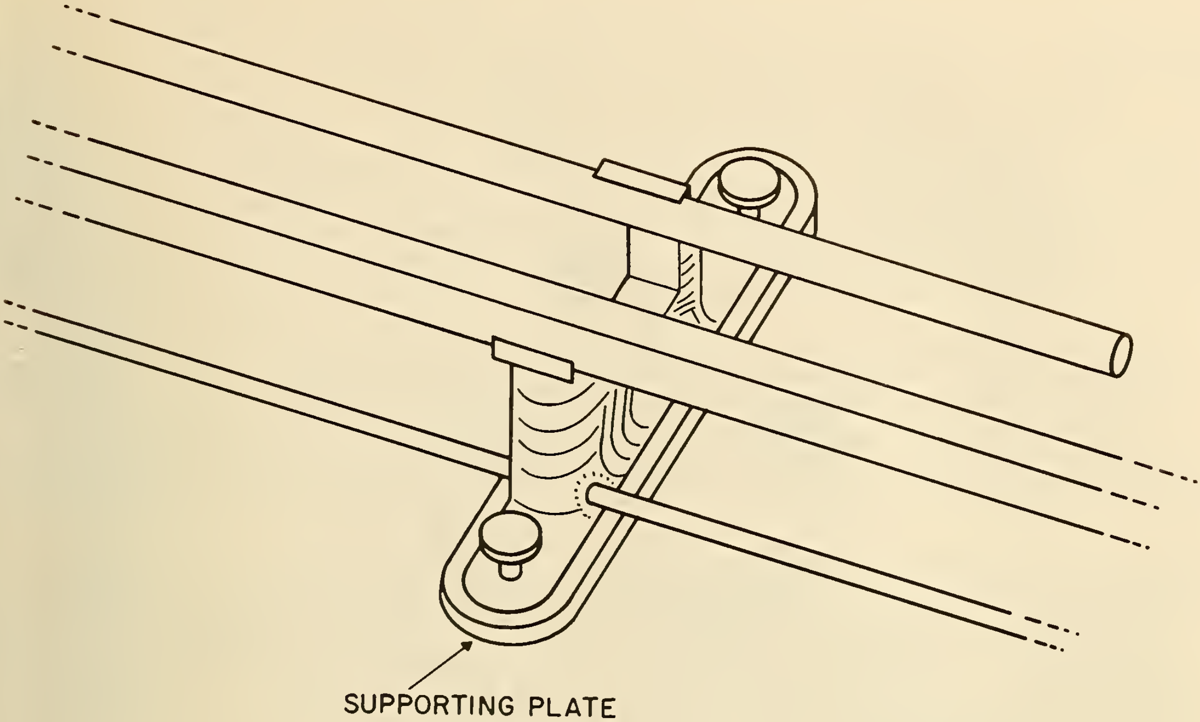
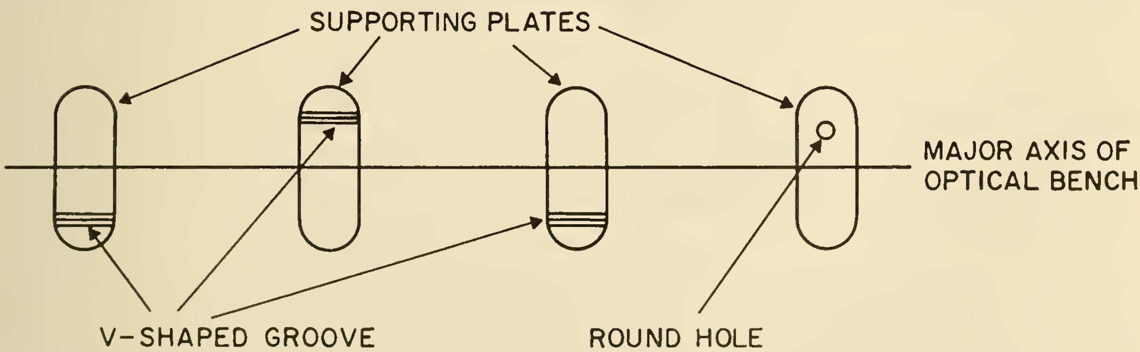
[2]The 5m bench was shipped in two sections.



A



B

Figure 7. Optical bench: A, optical bench support post with leveling screws on flat plate; B, schematic diagram of optical bench. Only the three plates with vee grooves and the one with a hole, all of which mate with the conical support screws, are shown. The flat plates with round tipped screws are not shown but are situated between these four supporting plates.

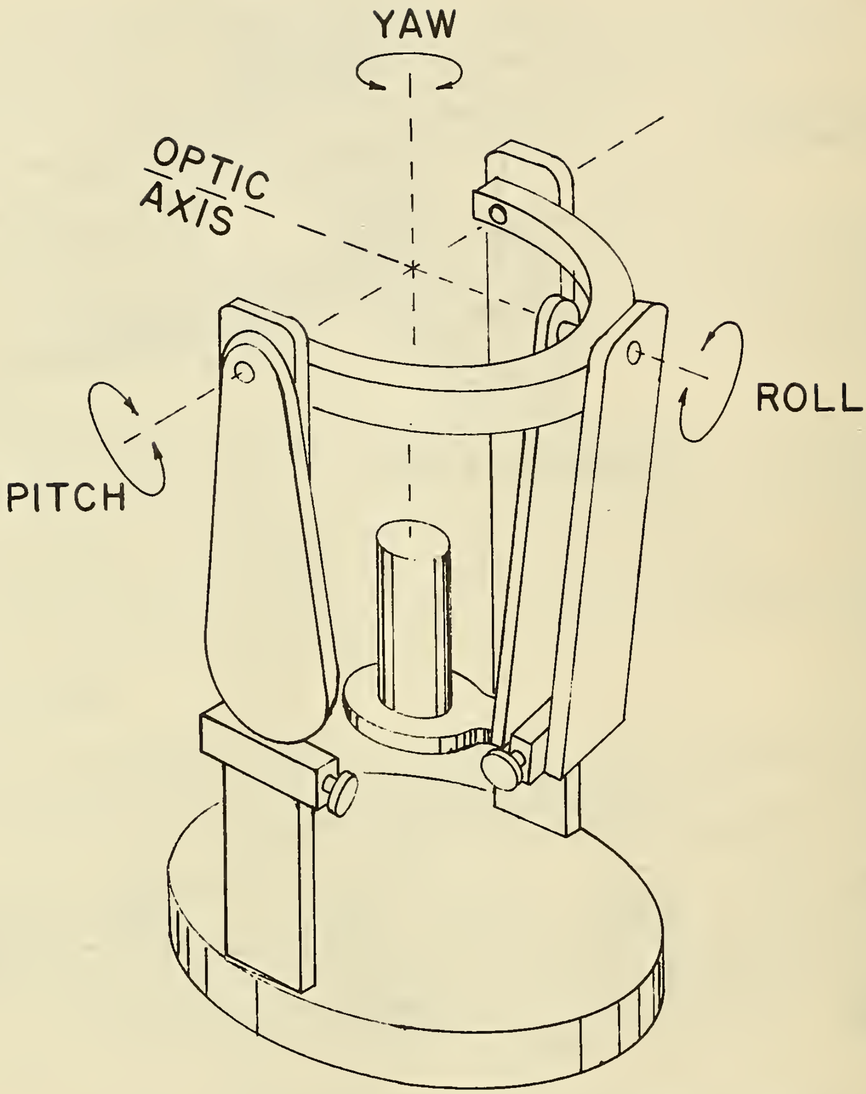


Figure 8. Radiance Lamp Mount.

from scales attached to the worm drives, and the yaw angle could be read to a resolution of six minutes of arc from a scale on the turntable. This mount performed well in reproducing the lamp orientation in pitch and roll; however, some care had to be taken in repositioning the yaw angle because of the lower resolution of this adjustment and the lightweight character of the turntable. This objection is, however, outweighed by the scattered light problem posed by the presence of the lamp mount structure around the sides and in back of the lamp. This is especially critical in an intensity or irradiance measurement since the entire lamp, and hence part of the lamp mount, is viewed by the detector. This mount has, however, proved quite useful in studying the variations in lamp intensity as a function of orientation and in other experiments where only relative measurements are needed. For convenience, this mount will be referred to as the "radiance lamp mount".

In order to eliminate the problem of scattered light from the lamp mount, two mounts based on the sliding surfaces principle were designed and constructed. One of the mounts consisted of a convex spherical section sliding in a mating concave spherical section, the other was a cylindrical section sliding within a mating section. The axis (or axes) of rotation is (are) then through the center of the cylinder (sphere). Since only a small section of the cylinder or sphere is used, there are no mechanical supports around the lamp to scatter light into the detector.

A cross sectional view of the sliding sphere mount is shown in figure 9. The radius of the spherical surface was 8 inches and the diameter of the section (platform) was 8 inches. Four thumbscrews (only one pair is illustrated) are mounted symmetrically on the outside block; that is, along two perpendicular lines. These screws pushed against the inside spherical surface along two directions parallel to the spherical tangents. This produced a rotation either around the optic axis (roll) or around an axis perpendicular to the optic axis (pitch). The screw lengths and positions chosen allowed about a 10° rotation in pitch and roll. The yaw rotation was accomplished by means of a small turntable as described in the previous mount. As in the previous mount the socket height was adjusted so that the center of the lamp filament was at the intersection of the three axes of rotation.

In order to read the pitch and yaw variations on this mount, a small mirror was affixed to the lamp socket and the beam from a one milliwatt He-Ne laser was reflected from it to a scale on the laboratory wall. The laser beam was approximately four inches below and parallel to the optic axis. With this device the relative rotations could easily be determined to a resolution of better than 0.1°. No measurements of roll variation were made with this mount and, therefore, no provisions were made for the measurement of roll angle. An optical lever similar to the one used to measure pitch and yaw could have been constructed for this purpose.

The main advantage in using a sliding sphere mount is the elimination of scattered light from the lamp mount itself. On the other hand, the main disadvantage is the difficulty encountered in making an adjustment. This is due to the many degrees of motion possible with a sphere. For example, in the adjustment of pitch,the yaw angle might change slightly because the motion was not firmly constrained to be only around the pitch axis.

This difficulty in maintaining alignment prompted the design of a third mount based on a cylinder sliding in a cylinder. The rotation is, of course, constrained to be around a unique axis and all orientation adjustments can be made below the lamp socket. The sliding cylinder mount has been adopted for use in the luminous intensity calibrations performed at NBS. However, since it was not used in any of the experiments described in this paper and since it is an obvious modification of the sliding sphere mount, further discussion of its construction will be omitted.

Lamp alignment:

The lamp mounts were aligned relative to the laser beam on the optic axis. That is, the roll axis was adjusted to be colinear with the optic axis and the pitch and yaw axes were adjusted to be at right angles to the laser beam: this set the zero position of all three rotations. In order to locate the axes perpendicular to the optic axis a pentaprism [5] was employed. The pitch and roll axes on the radiance lamp mount were located by means of small holes through the center of the pivots. In the cases where the pivot was not on the axis, a solid object was set on the lamp mount to intercept the beam. The

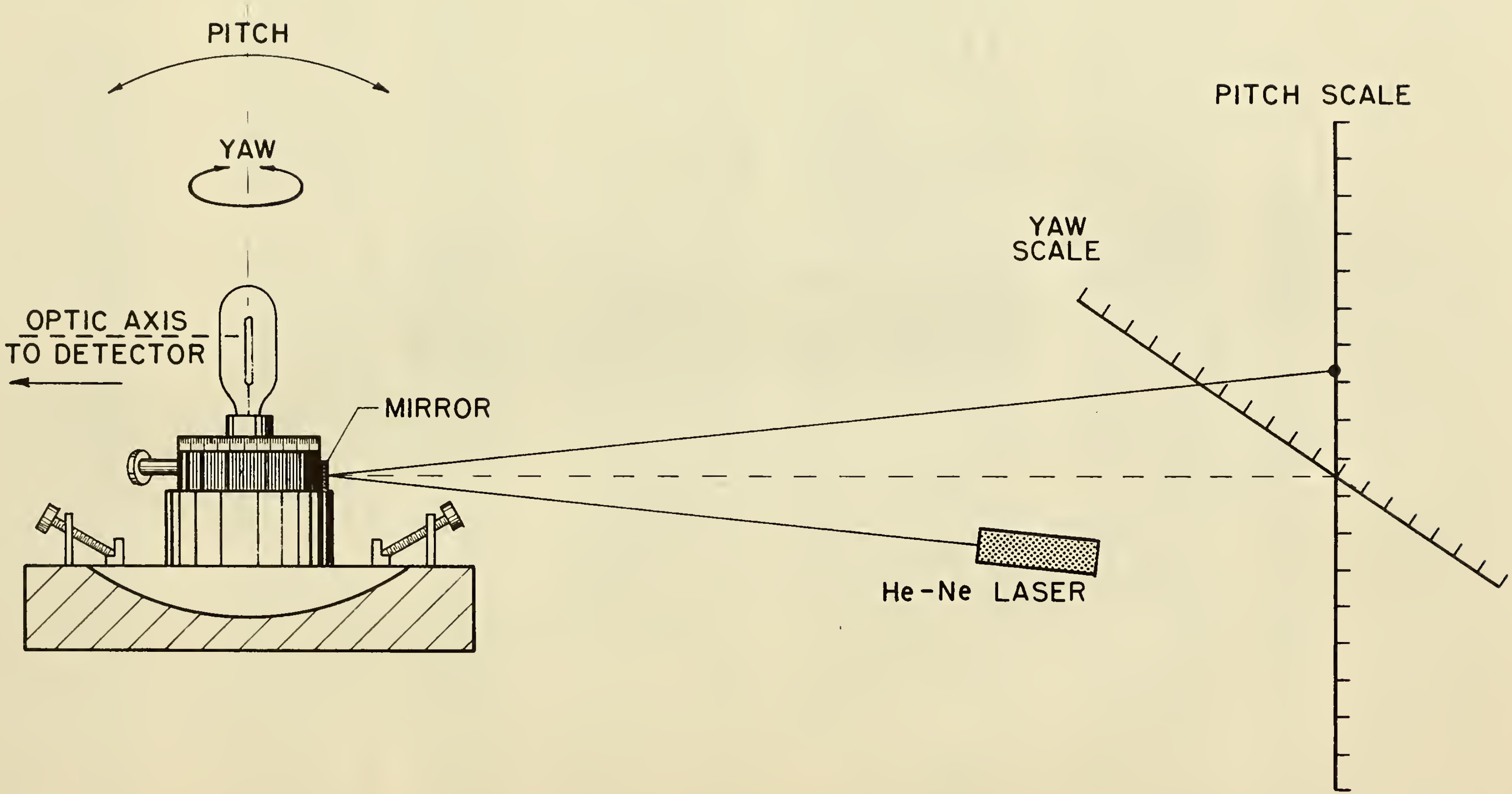


Figure 9. Sliding sphere mount.

object was then rotated about one of the rotation axes and the mount position adjusted until the laser spot appeared stationary.

As a slight digression it should be noted that in these several lamp mount designs the three axes of rotation are not all independently adjustable. For example, in the radiance lamp mount and in the sliding sphere mount, a variation of the pitch angle away from the zero position rotates both the roll and yaw axes away from their original orientation. Furthermore, in the radiance lamp mount rotation of the roll angle does not alter the direction of the pitch axis, whereas, in the sliding sphere mount it does. Therefore, at some higher level of accuracy it may not only be important to specify the lamp orientation relative to the optic axis but also the device on which the lamp was oriented in the process of calibration. Since the experiments described in this paper are only relative measurements and not absolute calibrations, the transferability of lamp orientation does not pose a problem at present.

After the lamp mount has been aligned relative to the optic axis, the detectors and the lamps themselves must be aligned to the same axis. In these experiments no attention was paid to the precise orientation of the detectors and only their position on or near the optic axis was noted. On the other hand, the effects of orientation on the lamp output was studied and in this case two methods were used to locate or reference the lamp orientation.

The first method has been employed in photometry for many years: it is a visual sighting technique which employs a plumb line, fiducial lines etched on the bulb and the filament supports within the bulb. The shadows of the filament supports and the plumb line projected on the laboratory wall were made coincident to set the zero of pitch alignment. (Note that this does not necessarily correspond to the zero of alignment for the lamp mount.) Next the lamp was rotated to bring the fiducial lines into alignment with the optic axis. This was done either by sighting through the bulb to the detector or by using the laser beam. This method is not compatible with frosted bulb lamps or with the radiance lamp mount.

The other method involves prealignment of the lamp socket before insertion of the lamp. In this case the lamp base must be of mechanically sound construction so that it can be reproducibly reinserted into the socket. The lamp base that satisfactorily fits this purpose is a medium bipost base. The pins are 1/4 inch in diameter, at least 3/4 inches long and are spaced 7/8 inches apart. As will be seen, a kinematically sound and compact socket can be constructed to reproducibly reposition lamps with these bases.

In this technique the socket is prealigned by using a pair of parallel 1/4 inch diameter rods which fit in place of the lamp. Fixed parallel to the rods is a mirror to reflect the laser beam onto the laboratory wall. This yields a measurement of the pitch and yaw orientation of the socket. Alternatively the socket can be positioned to coincide with the zero setting of the lamp mount. In addition, the use of a jig to align the socket allows a precise distance measurement to be made to the plane formed by the two rods rather than to an inaccessible point within the lamp bulb.

Lamp sockets:

The medium bipost socket used in all the experiments described in this paper consists of two silver plated 3/8 × 1 1/8 × 1 1/4 inch blocks mounted on a piece of transite. The lamp pins fit into holes in the blocks and are held by horizontally placed screws. Electrical connections are made directly to the block by means of separate screws. One of the metal blocks is mounted on the transite by means of a pivot to allow for bulb expansion. These sockets are manufactured by the Elastic Stop Nut Corporation, Model 1985-AL.

Because the lamp base pins are held against the walls of a cylinder, this socket reproducibly maintains the pitch and roll alignment of the lamp. However, the yaw alignment is not maintained since one of the blocks can rotate. The following socket was designed to eliminate this deficiency. Although it was not used in any of the experiments described in this paper, its design was prompted by the results of some of them. Therefore, a description of it is included here.

Two views of this socket are shown in figure 10. The lamp pins are held by spring

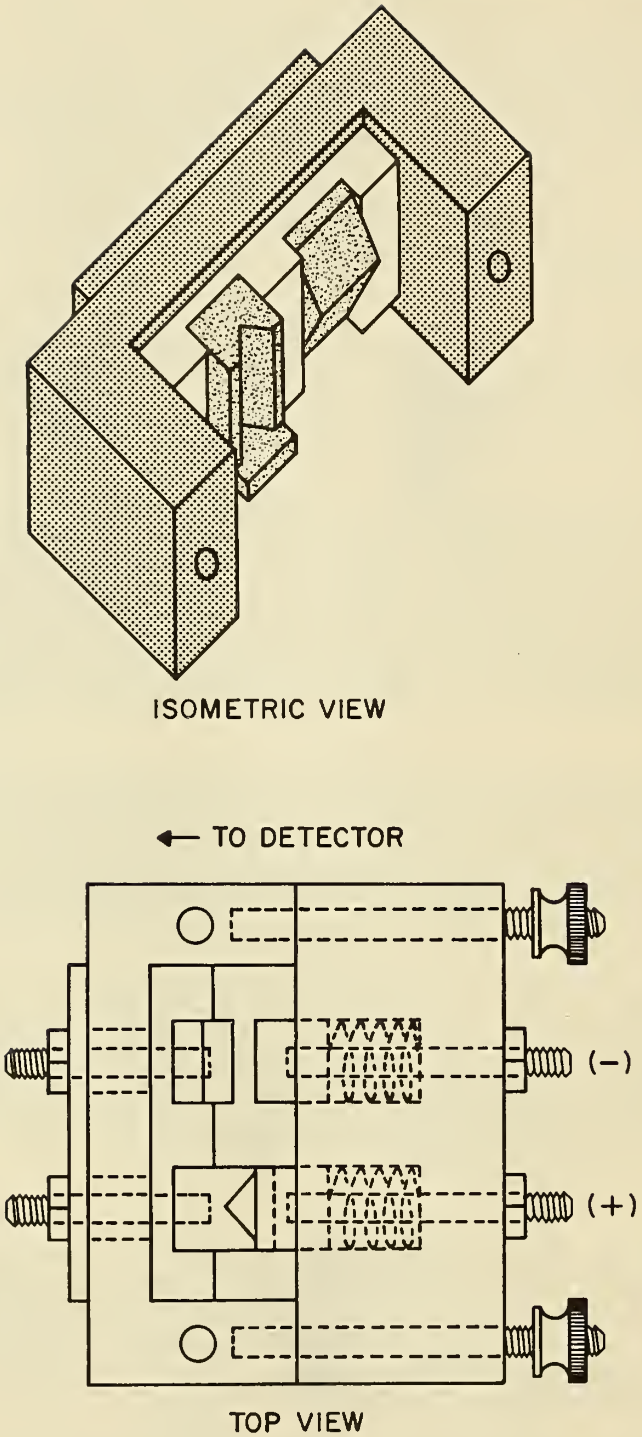


Figure 10. Kinematically designed lamp socket.

tension against two stainless steel blocks. One of the blocks has a Vee groove terminating in a flat plate. By holding one of the lamp pins against this groove and flat, the pitch, roll and lamp height can be maintained when the lamps are replaced in the socket: providing, of course, that the same pin is placed in the groove each time. The other stainless steel block is cut from hexagonal bar stock to form a roof shaped piece. When the socket is closed the pin is held against the "peak of the roof", thereby fixing the yaw rotation and still allowing the lamp base to expand.

The lamp pins are held by two gold-plated copper "pistons", and the pistons are held under tension by coiled springs inside the nylon block. The two outside screws shown protruding from the nylon block serve to close the socket. The remaining four screws hold the stainless steel blocks and the copper pistons in place and serve as electrical connections.

The convention that has been adopted in the use of this socket is depicted in the figure. That is, the Vee block is the positive electrode and the lamps are viewed by the detector from the side of the socket containing the Vee block. In this direction, that is, looking at the lamp from the detector position, the Vee block is on the right.

3. Experimentation

3.1 Flux Lamp Stability Tests

Introduction:

In the Fifth International Intercomparison of Photometric Units, lamps of a special type [6,7] were used to represent the various national laboratory units of luminous flux at a color temperature of 2788 K (IPTS-48). They were full wreath filament clear bulb, gas filled lamps. This intercomparison showed these lamps to be relatively stable. The present work was undertaken to evaluate further these lamps as possible standards of luminous flux.

The 200 watt lamps of this type are designed to operate at 95 volts and have a rated life of 1,000 hours at this voltage. For the International Intercomparison the lamps were seasoned for 120 hours at the voltage necessary for 2788 K operation (approximately 95 volts), and had their bases plated with a nickel cadmium alloy. For the present test 24 uncalibrated lamps were procured from GEC, England. These 24 lamps were received with unplated brass bases and had been seasoned for 20 hours at 95 volts. Subsequently several lamp bases were plated with either pure nickel, nickel cadmium, or silver. The measurements then consisted of reading the total luminous flux of the various lamps, set consecutively at current and at voltage, every 5 burning hours after an initial seasoning of 40 or 60 hours (including the 20 hours seasoning performed by the manufacturer).

Experimental techniques and equipment:

The lamps were seasoned on regulated AC: six lamps at 102 volts (approximately CIE source A) and 8 lamps at 95 volts. The luminous flux measurements were made after 10 minutes warm-up with the lamps operated on DC in a 2 meter integrating sphere by a substitution method. A blue glass filter (Corning 5900) was used to reduce the effects of non-uniformities in the sphere wall spectral reflectance. The photometer detector was a Weston selenium barrier-layer photocell equipped by the manufacturer with a filter [8] which modifies the spectral response to approximately match the CIE luminous efficiency function [9]. In order to reduce the errors due to self absorption of the lamps, a standard (NBS 8380) of the same type and manufacturer was used. This standard had been previously calibrated including absorption correction as part of the international comparison. The standard was run at the beginning and end of each set of measurements to check for drifts in the photometer.

During seasoning the test lamp voltages were set on a moving iron AC voltmeter (3/4% accuracy class). The 2 meter diameter integrating sphere was coated with Burch sphere paint. The detector was a hermetically sealed, viscor corrected Weston barrier layer cell (Model 856, YYLSV). The detector photocurrent was measured with a commercial operational amplifier. The lamp voltage and the current, and the operational amplifier output were read on a digital voltmeter (.003% accuracy).

Results:

The results of the experiment are shown in figures 11 and 12. For each of the test lamps the data is normalized to the first measured value of total luminous flux. In each case for the first reading only, the lamps were set at voltage and readings taken of the flux and current. Subsequently the lamps were set at both voltage and current, as indicated in the figures and flux measured for each setting. Lamps NBS 9135 and 9136 were not measured at current until 135 hours of burning. Lamps NBS 9138, 9139, 9140 and 9143 suffered a filament failure at 85, 75, 90 and 70 hours, respectively.

Conclusions:

The figures vividly demonstrate the superiority of setting lamps of this type by current rather than voltage. All of the lamps set at voltage showed a steady decrease in flux output. This decrease was typically at the rate of 1% per 40 hours of burning. In contrast the lamps set at current increased slightly or held constant within the precision of the measurements. Previous experience has shown this equipment to have an overall precision level of about 1/4%. As the figures indicate, this was about the precision level of the present experiment. Figure 12 indicates that the lamps should be seasoned for at least 50 hours before initial calibration.

In the limited time period covered by this test no particular effect due to base plating material was noted. In the long run, it would be expected that plating with materials such as nickel-cadmium would offer more corrosion resistance than plain brass.

The occasional out-of-pattern point present in most of the lamp curves is probably due to variation in the experimental technique, and no particular significance should be attached to these points. The distinct shift in the flux values at 170 hours for lamp NBS 9135 run at current is in a different category. The cause of this shift is not known at this time and is particularly hard to explain since the shift is not mirrored in the flux values measured at voltage. It is unlikely that the shift is due to changes in the sphere or electrical measuring setup since other lamps measured on the same run in the same apparatus do not show a corresponding pattern. Shifts of this kind emphasize the desirability of running more than a single standard at any given time.

The lamp failures noted above present a problem. Three out of the six lamps run at 102 volts failed. Although the lamps were designed to operate at 95 volts, the manufacturer states he knows of no reason why they could not be run at higher voltage with, of course, a corresponding reduction in life. He further states that this test is the only one he knows that has shown this effect. In each case the failure was one of filament breakage. It would appear that some critical parameter has been exceeded and hence high failure rates can be expected at this voltage. We have decided to use these lamps only at color temperatures of 2788 K or lower.

It should be noted, particularly since the manufacturer states our experience is unique, that these tests were conducted on a limited sample from a single production run and may not be indicative of the performance of similar lamps from other production lots.

3.2 Orientational Dependence of Relative Luminous Intensity

Introduction:

In the calibration of the intensity or irradiance from a lamp, it is obviously important that both the direction in which the lamp is viewed and the lamp orientation be specified. This is necessary simply because a lamp is a nonuniform source [10,11]. The magnitude of the nonuniformity and consequently the extent of the possible error in the calibration of the lamps used as standards at NBS has not been documented in sufficient detail. The study that will be reported here was, therefore, carried out in order to get a more detailed picture of this effect and to identify the cause.

The terms used in this paper to describe the three orientational degrees of freedom

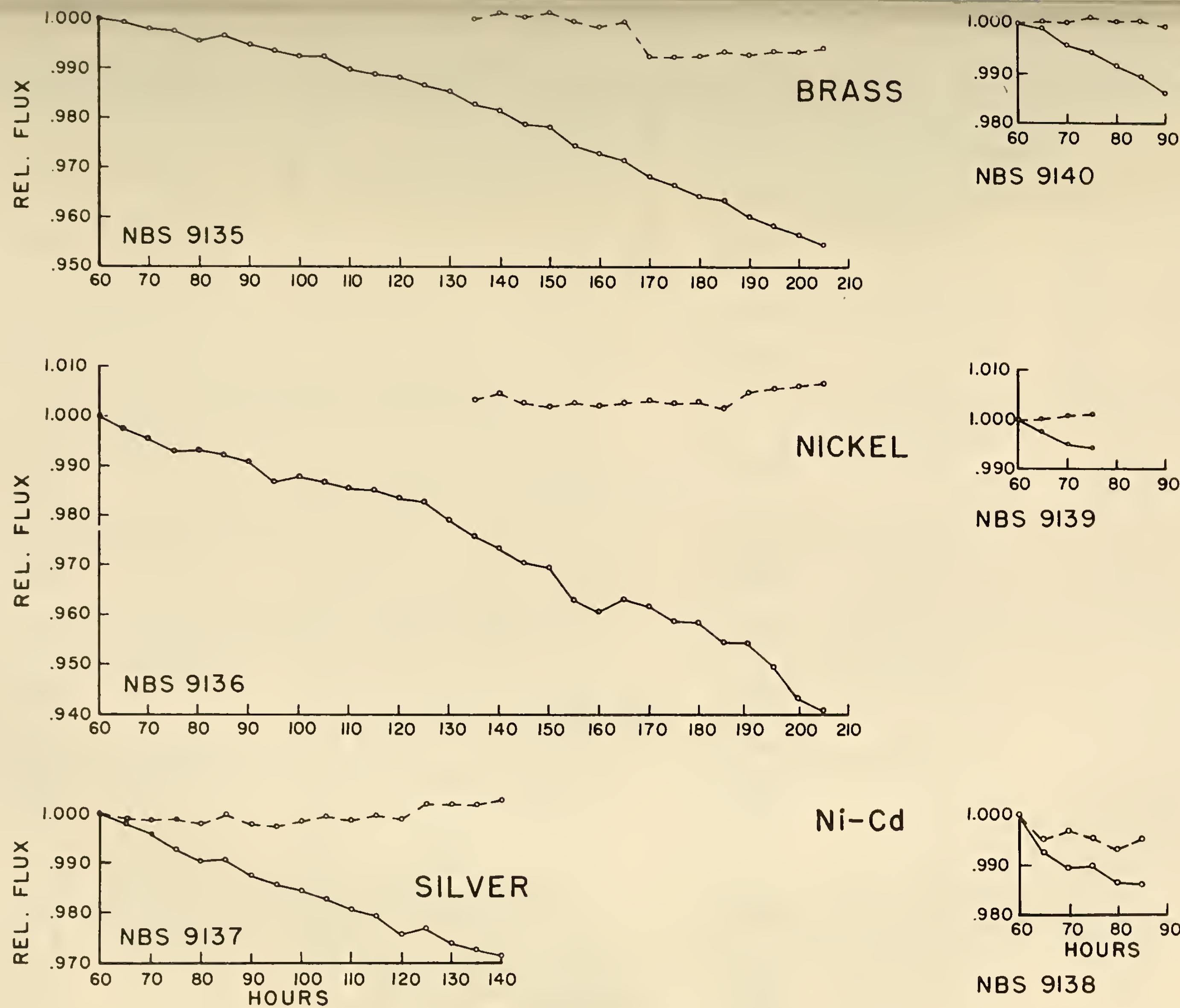


Figure 11. Total luminous flux output stability of 200 watt flux lamps run at 102 volts. In all cases, the lower curves indicate the flux readings made after setting the voltage. Where it occurs, the upper curves represent flux values read after setting the current. Elements indicate the lamp base plating material used.

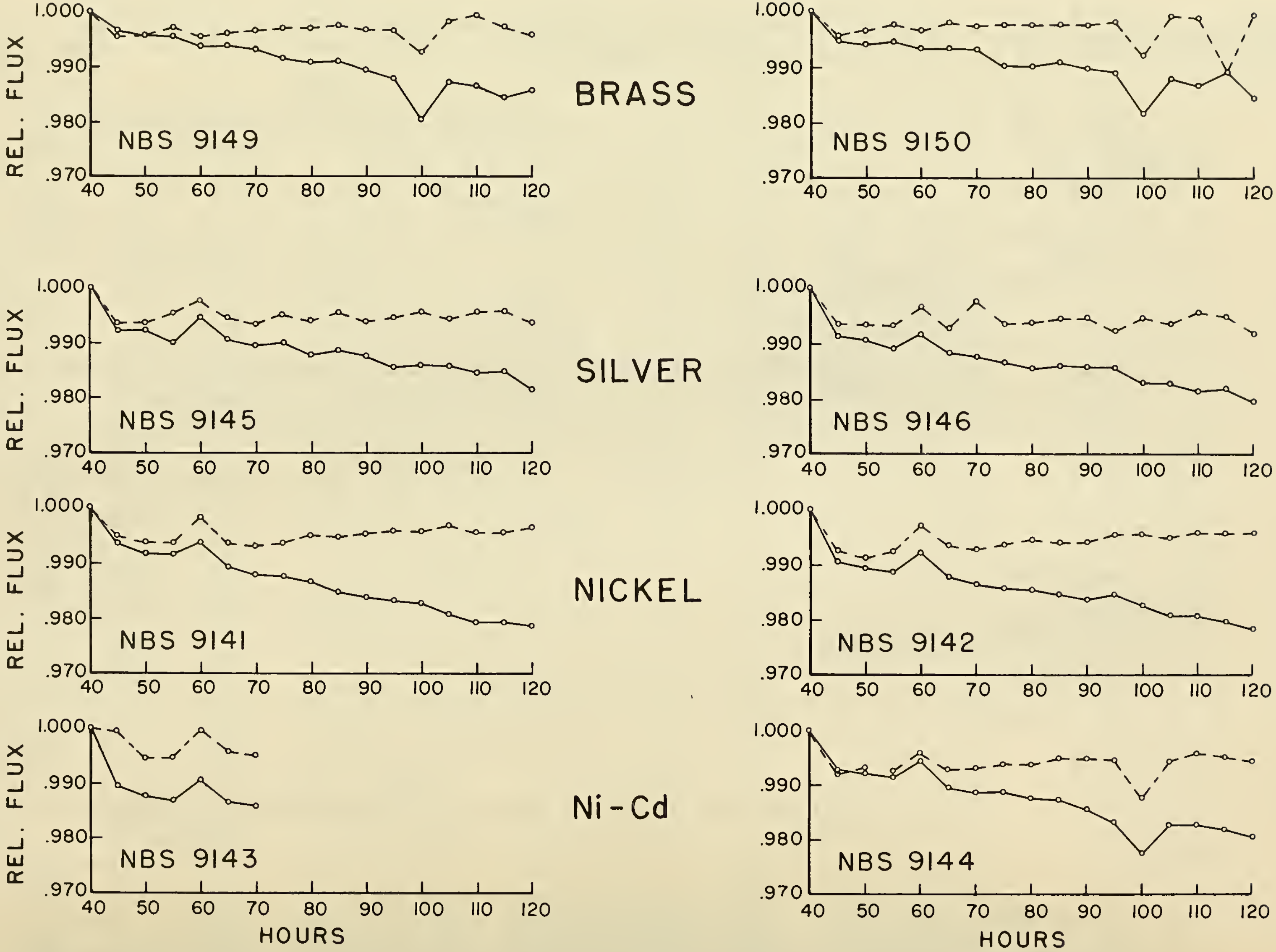


Figure 12. Total luminous flux output stability of 200 watt flux lamps run at 95 volts. In all cases, the lower curves indicate the flux readings made after setting the voltage. Where it occurs, the upper curves represent flux values read after setting the current. Elements indicate the lamp base plating material used.

are the nautical terms: pitch, roll and yaw. They were introduced in the discussion of the lamp mounts. Results for three different types of lamps will be given here. They are (1) 500 watt clear T-20 bulb ($2\frac{1}{2}$ inch diameter, tubular), medium bipost lamps with C-13 filaments (single coil with 7 or 9 supports in a monoplaner "W" configuration). (2) 100, 300, 500 and 1000 watt frosted bulb, medium bipost, C-13 filament lamps. The 100, 300 and 500 watt lamps of this type had T-20 bulbs and the 1000 watt lamp had a T-24 (3 inch) type bulb. (3) Tungsten-halogen lamps with a CC-8 type filament (coiled-coil supported only at the ends) and a 3/4 inch diameter, tubular, clear quartz envelope. Lamps of type 1 and 2 have been in use at NBS as standards of luminous intensity and type 3 as standards of spectral irradiance.

Equipment:

All the lamps were seasoned for 2% of rated life at rated volts. The photometric and electronic equipment used were described earlier. However, the detector amplifier for most of the measurements was a commercial DC current to voltage converter feeding into a five digit integrating digital voltmeter. For the pitch and yaw measurements of the clear T-20 bulb, C-13 filament lamps the sliding sphere mount was used. For all other measurements, the radiance lamp mount was used. In both these setups, the angles could be measured with a resolution of at least 0.1°.

Photopically corrected [8] selenium barrier layer cells and uncorrected silicon photodiodes were used as detectors. The results from both types of detectors were identical and, therefore, their specific instance of use will not be identified. The source to receiver distance was typically 2.5 to 3 m and the detector diameters ranged from 0.5 to 4 cm.

Results and discussion:

Figure 13 shows the variation of the relative intensity with the pitch and yaw angles for the clear bulb C-13 filament lamps. Four different detectors were used simultaneously. To obtain these plots a correction was made for the detector position relative to the optic axis. The most striking feature of this figure is the large variation of the intensity with the pitch angle: on the steepest part of the slope the intensity changes by as much as 2% per degree. Over a greater range the curve somewhat resembles a sine wave (see figure 17). This pitch dependence appeared to be common to all the lamps of this type that were measured. The positions of the maxima varied from lamp to lamp falling approximately in the range ±2° from the aligned zero position (relative to the plane of the filament supports). The relative intensity versus yaw angle plot in figure 13 is also typical of the lamps studied. However, there did not appear to be a correlation of the peak intensity with the aligned zero position and the curves did not appear to have a pattern over the range studied. The steepest slope was about 0.5% per degree. On studying the effects of different roll positions on the luminous intensity for these kinds of lamps, the effect could not be detected at the 0.2% level of the noise.

Figure 14 shows the pitch versus relative intensity plots for the 100, 300, 500 and 1000 watt inside frosted bulb, C-13 filament medium bipost lamps. The effect follows approximately a cosine curve, as shown by the solid lines. The total variation of output is almost 0.5% over the range covered and appears to be independent of the lamp size. At the 0.2% level of the noise there were no discernable effects due to a change in the yaw or roll angles over a range of ±5°.

The pitch and yaw variation of a typical CC-8 filament lamp is shown in figure 15. The lamps were operated with the filament in a vertical position, that is, the axis of the coil was vertical. The results for these lamps very nearly resemble those for the clear bulb C-13 filament lamps, except that in the region near the peak of the intensity versus pitch curve for the CC-8 filament lamps there is a slightly greater flat region. The yaw variation also appears to be smoother in the case of the CC-8 filament lamps. These are subtle differences, however, and a larger number of lamps would have to be examined before any general conclusions can be drawn.

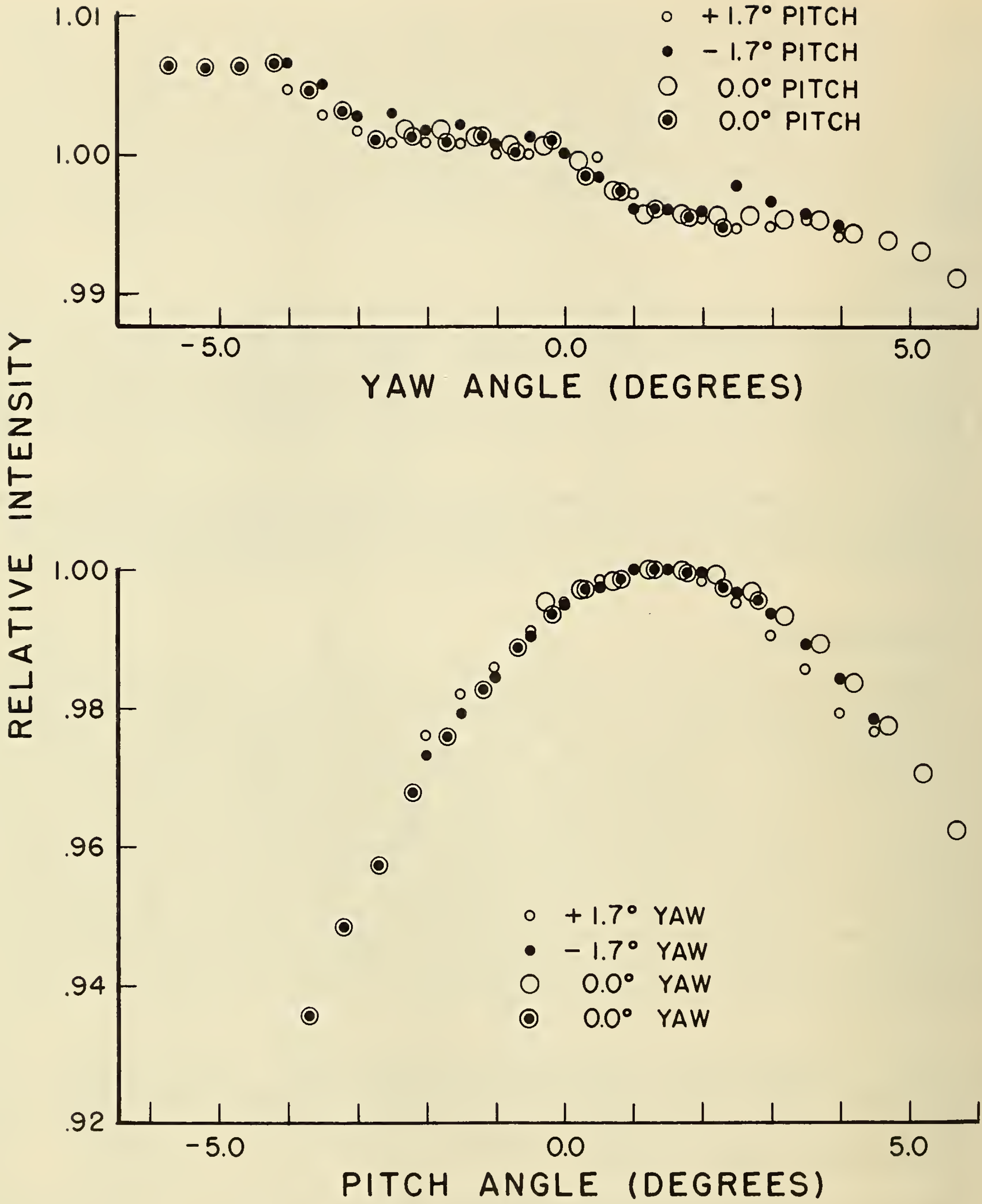


Figure 13. Orientational dependence of relative luminous intensity for clear bulb C-13 filament lamps. The different point symbols indicate measurements made by four separate detectors of intensity versus pitch dependency at several yaw angles and intensity versus yaw dependency at several pitch angles.

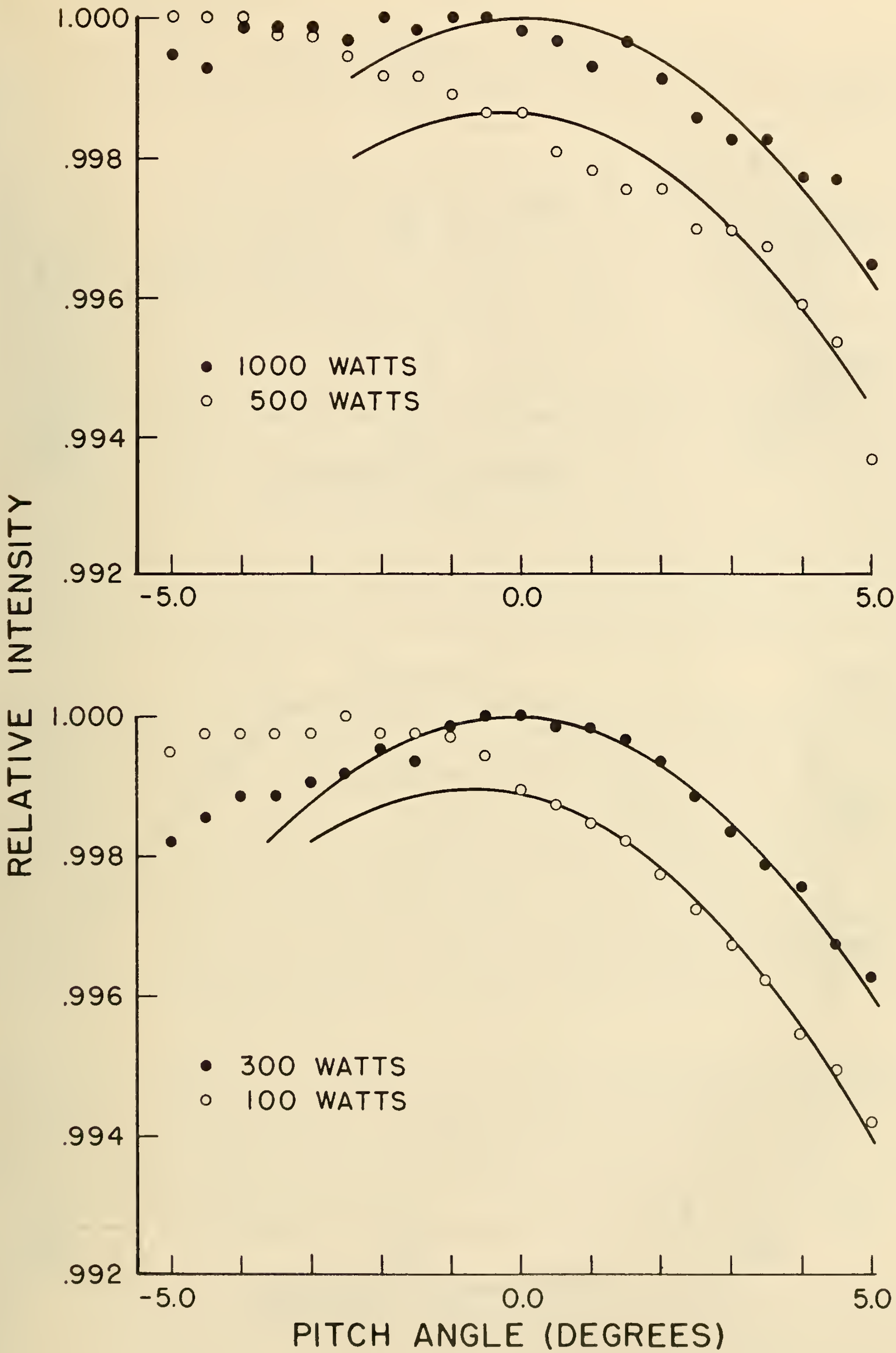


Figure 14. Relative luminance intensity versus pitch dependence of inside frosted C-13 filament lamps. The solid line indicates theoretical intensity versus pitch dependence for a perfectly diffuse cosine law emitter.

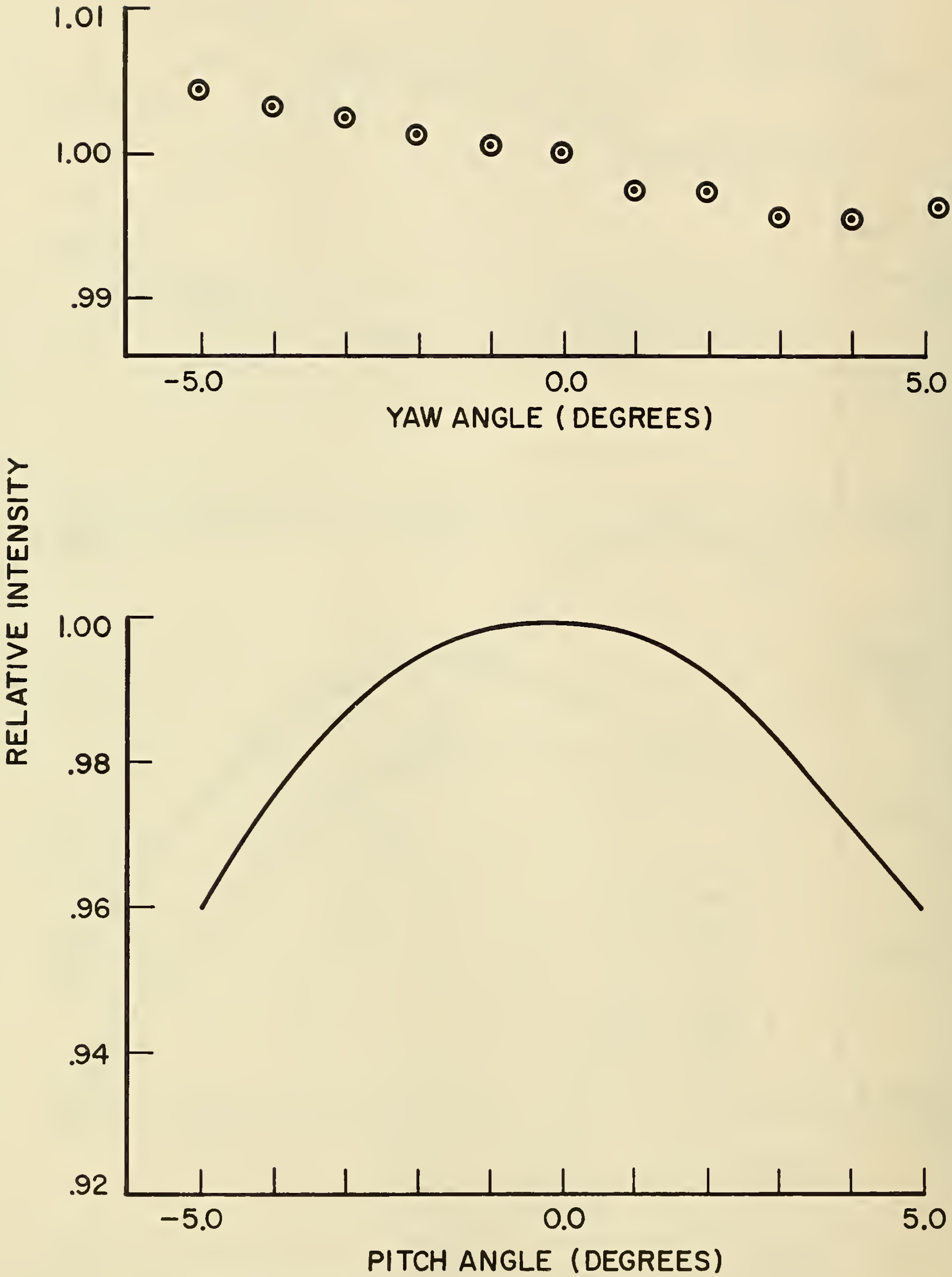


Figure 15. Orientational dependence of relative luminous intensity for CC-8 filament clear bulb quartz halogen lamps.

The origin of this effect:

Having established the order of magnitude of the orientation effect on the luminous intensity of these lamps, two experiments were performed to disclose the sources of the effect. The coiled structure of the lamp filament and possible lens effects due to striations in the envelope seemed to be the most probable causes of a nonuniform distribution.

In the first experiment a group of three lamps was obtained which had specially designed filaments. These filaments were essentially C-13 filaments except that they were not monoplanar. The two horizontal rods which hold the filament support pins were set at about 45° instead of being parallel to each other. This filament design was motivated by the suspicion that the pitch effect in regular C-13 filament lamps is due to the shadowing of the rear part of the filament by the front part. This kind of shadowing is inevitable in a coiled filament. If all the segments (lengths between support pins) of the filament are in the same vertical plane, as they are in regular C-13 filaments, then the extent of shadowing at any particular pitch angle is almost the same for each segment of the filament. The contributions of the individual segments of the filament to the pitch dependence therefore add up or, as one could say, "interfere" constructively to give a large pitch dependence for the whole lamp. In the non planar C-13 filament design used in the special lamps, one would expect the pitch dependences of the different segments of the filament to peak at different pitch angles. These dependences would thus combine in such a way as to yield a more flat pitch dependence curve for the lamp as a whole. Pitch dependence curves were run for the three lamps of this type. Figure 16 shows a typical pitch dependence curve. Here the pitch dependence on the steepest part of the curve is less than 1% per degree change in the angle: approximately half of the slope in the curve of the monoplanar C-13 filament. This leads to the conclusion that most of the effect is due to the shadowing effect of the filament coils, and the fact that in a regular C-13 filament the different segments of the filament are in the same plane.

In the second experiment an attempt was made to obtain an estimate of the contribution to the pitch effect due to the striations in the glass envelope. Two clear bulb lamps with C-13 filaments and noticeably striated bulbs were used. The pitch variation of the intensity was first measured. Then the glass envelope was cut vertically almost to the base. One half of the envelope was cut away and the remainder was left attached to the base of the lamp and the filaments were removed. These lamps were placed in front of and as close as possible to a frosted bulb lamp that had been totally masked except for a small rectangular area. This area was of approximately the same dimensions and at the same height as the filament in the original clear lamps. The frosted bulb lamp was kept in a fixed vertical orientation and only the sliced glass envelope was moved. A frosted bulb lamp was used to simulate the filament because of the possible interactions between the striations of two clear glass envelopes. Figure 17 shows the pitch dependence of the lamps before they were sacrificed and of their glass envelopes afterward. The variation due to the envelope is about 1% over a 10° interval.

As a final note, figure 18 depicts one of the more extreme examples of intensity variation as a function of pitch rotation. The slope is about 10% per degree at the steepest points. Such variations were observed on a few of the clear bulb, C-13 filament lamps studied. It has been suggested that this behavior is due to the planarity and straightness of the several coils in the filament. If this is true then it is ironic because of the natural inclination to choose the most symmetric and apparently defect-free lamps for possible standards.

Conclusions:

There are two conclusions that may be drawn from these experiments. The first is in regard to the amount of orientation control necessary in order to reproduce the luminous intensity output of clear bulb C-13 and CC-8 filament lamps. If no attempt is made to set the lamp at a position of zero gradient in pitch and yaw and if the pathological cases such as the one shown in figure 18 are eliminated, then the greatest pitch gradient one might encounter would be of the order of 2% per degree. Similarly, the greatest yaw gradient expected would be about 0.5% per degree. Therefore, in order to reproduce the intensity or irradiance to about ±0.1% based on orientational considerations alone, the

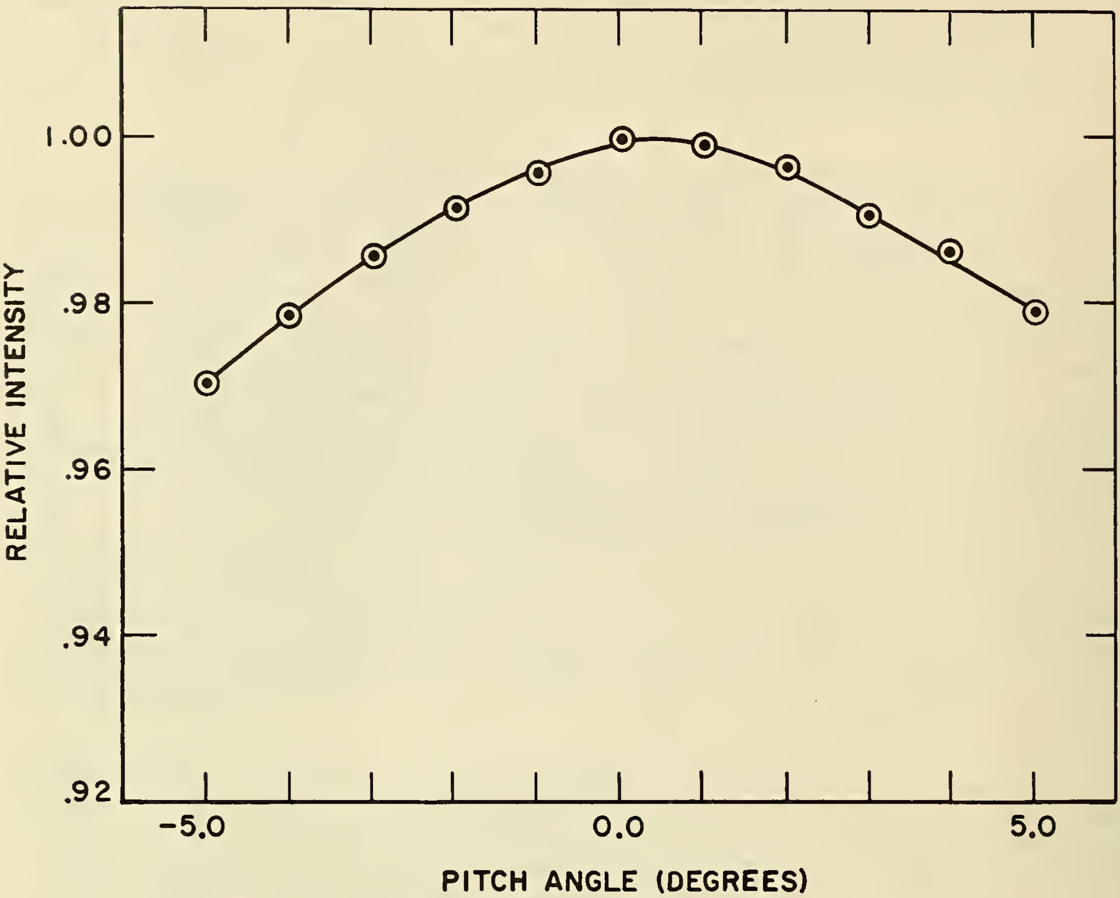


Figure 16. Relative luminous intensity versus pitch dependence for special nonplanar filament clear bulb lamp.

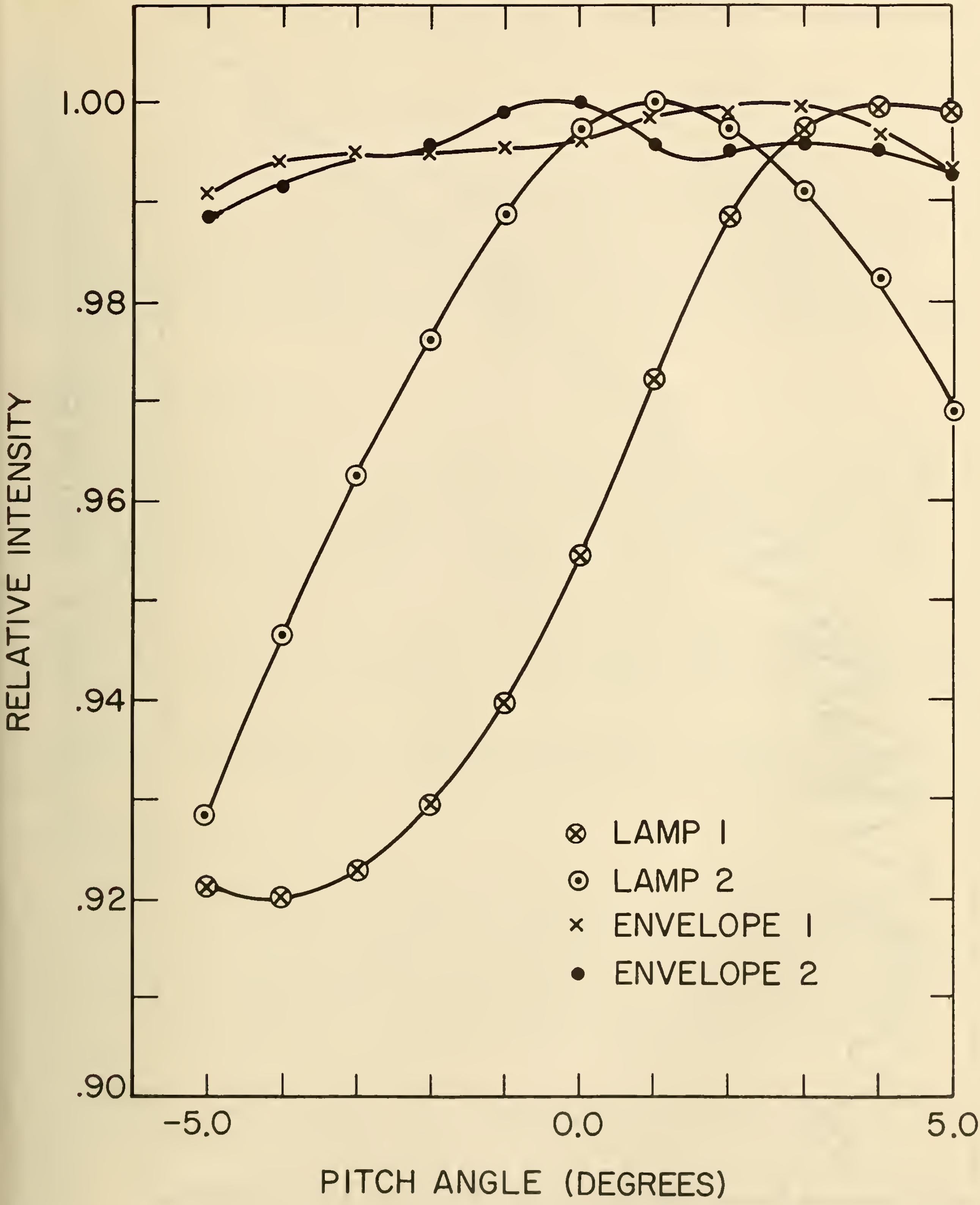


Figure 17. Contribution of glass envelope striations to relative luminous intensity versus pitch dependence.

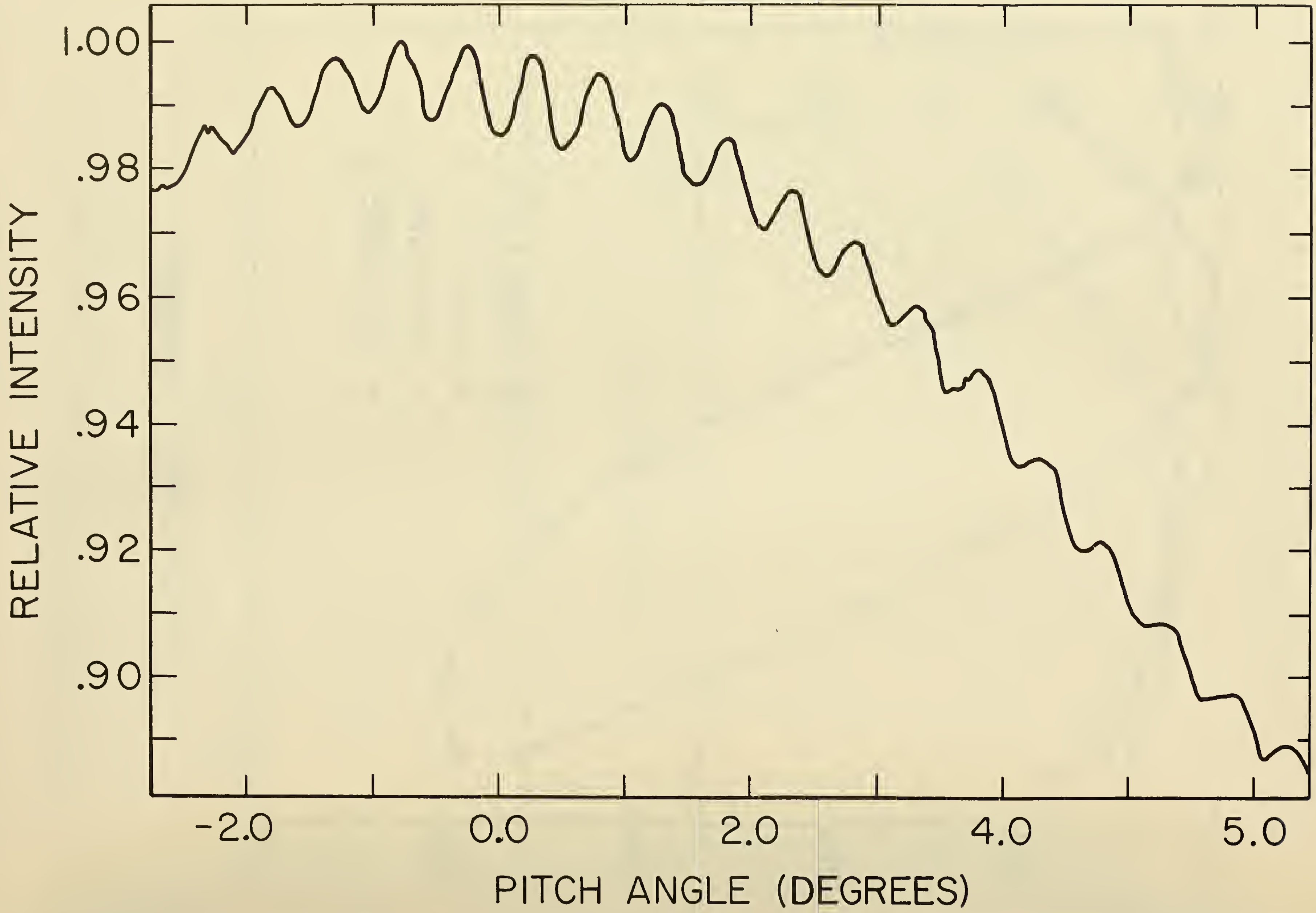


Figure 18. Extreme example of relative luminous intensity variation as a function of pitch rotation. The pitch angle subtended by the detector was about 1/4°.

pitch realignment must be less than ±0.05° and the yaw realignment must be less than ±0.2°. For the frosted bulb lamp the pitch realignment must be within ±0.5°.

The second conclusion is that in clear bulb lamps the major contribution to intensity variation is due to the coiled structure of the filament. The contribution from bulb striations is smaller by about a factor of ten.

Taken together, these two conclusions lead to a choice of a frosted bulb lamp as a standard lamp because of the looser restrictions on orientation. Two objections can be raised against such a choice. First, the realignment requirements quoted above were for the case of the largest pitch and yaw gradients. The lamps can be oriented to a position of almost zero gradient in both rotations in order to relax these requirements. Second, the use of a large source, such as the frosted bulbs, introduces a greater error in the assumed inverse-square law behavior of intensity standards. The last objection to the use of frosted bulbs can, of course, be eliminated if the source to receiver distances are large compared to the size of the source and the detector.

3.3 Intensity Lamp Stability

Scope of the experiment:

This experiment, as originally conceived, had several purposes. The main thrust of the measurements was to evaluate the reproducibility of six lamps of a type that have been used as standards of luminous intensity at NBS. The lamps were obtained from two manufacturers. Of the four lamps from manufacturer A, two were selected at the factory for quality of appearance (e.g. filament centered and vertical, envelope uniform, etc.), and two were obtained through normal commercial channels. The two lamps from manufacturer B were selected at the factory for quality of appearance.

The lamps were checked for relighting reproducibility in two ways. In one series of measurements they were relit after a cool-down period but were otherwise undisturbed. In another series the lamps were removed after cool-down and then replaced in the socket before relighting. In addition to the relighting reproducibility measurements, the lamps were run continuously for sixteen hours to check drift.

Besides monitoring lamp voltage, current, and the output from four different detectors during each run, the temperature was checked at four positions along the optical bench. Finally, this experiment served as a "shakedown cruise" for much of the equipment described earlier.

Equipment and procedures:

The lamps studied were 500 W, clear bulb, medium bipost, C-13 filament, gas filled lamps. They were seasoned for 2% of rated life at rated voltage (10 hours at 120 V AC). During each measurement run the voltage was set at 85.000 V as read on a five digit integrating digital voltmeter. The voltage was maintained by two Hewlett-Packard model 6274A DC power supplies set up in a master-slave, constant voltage, series configuration. The lamps were mounted in the commercial socket described earlier. Although this socket was affixed to the radiance lamp mount, the lamps themselves were not reoriented for each run because of the additional time it would have taken. The reproducibility of orientation depended, therefore, primarily on the socket.

The digital voltmeter mentioned above had remote programming capability and BCD readout. The voltmeter was controlled by a data acquisition system and its output was recorded on punched paper tape by this data system. The data system also had the capability of switching the inputs to the digital voltmeter.

Temperature was monitored with four thermocouples positioned within the optical bench enclosure. One thermocouple was set about one-half inch away from the back of the lamp bulb and another was set about twenty inches in front of the lamp and about ten inches below the optic axis. The thermocouple nearest the lamp was used to indicate the realization of a thermal steady state condition. The thermocouple below the optic axis indicated the approximate ambient temperature in that section of the enclosure containing the lamp.

The other two thermocouples were positioned to read the approximate temperature change of the detector mount and the approximate ambient temperature near the detector. These thermocouples were switched directly into the digital voltmeter via low-noise (< 5μV) reed switches in the data acquisition system.

The four detectors were all about the same distance from the lamp and were held symmetrically around the optic axis in a single mount. Two of the detectors were photopically corrected selenium barrier layer cells and the other two were uncorrected silicon photodiodes. The detectors were obtained from four different manufacturers. The detector outputs were switched into the current to voltage converter (first version design) via one set of switches in the data system and the output of the converter was switched into the voltmeter via a different switching circuit board in the same system.

About halfway through this experiment one of the selenium barrier layer cells failed and was replaced with a similar cell. Unfortunately during the process of changing this detector, the entire mount was moved and could not be returned precisely to its original position. This meant that the two series of measurements on each lamp could not be compared to the same initial detector readout.

Voltage was sensed at the lamp socket and current was measured with a resistor in series with the lamp. Both of these signals were fed into the voltmeter via the data system.

In the repeatability measurements, the lamps were run for thirty minutes before relighting or replacing. All ten measurements described (that is, lamp current and voltage, four temperatures, and four detector outputs) were taken sequentially by the data acquisition system once each minute during a run. During the sixteen hour run, the same data readout sequence was initiated every twenty minutes. The readout sequences were initiated by a clock in the data system itself. The time during each sequence was also recorded on the punched paper tape readout.

Results and discussion:

No significant temperature changes occurred during the short runs except for the thermocouple nearest the lamp. There was a temperature increase of this thermocouple which could be correlated with the lamp warm-up measured in terms of either the increase of the detector output or the filament resistance as a function of time. Temperature changes recorded during the long runs could not be correlated with the other changes in the system.

The detector outputs were noisier (±0.1%) than had been expected. It was later found that this noise was definitely in the current to voltage converter and could be reduced by connecting the operational amplifier common to ground. This was pointed out earlier in the discussion of the construction of these current to voltage converters. Because of this problem it was difficult to compare the relative noise or relative signal differences to less than ±0.1% in the output of each detector. Excepting the output of a failing selenium detector, the relative outputs of the four detectors were identical within the limiting noise band. That is, any output trend shown by a given detector followed that of the other three detectors. It was therefore assumed that the observed changes above the noise were most likely due to the lamps.

Voltage during each run was stable to ±0.002%. Between each run the voltage setting was reproduced to within ±0.005%.

The lamp output variations are summarized in the table. This table was compiled using the output of only one of the four detectors, since their outputs were all identical within the limit of ±0.1%. The "warm-up" is the time required for the detector output variations as a function of time to decrease to within the noise limit. The columns labeled "repeat" are the differences between the averages for the first and second 30 minute runs and the first and third 30 minute runs for each lamp. The averages were taken over the 15 minute time interval extending from the 10 minute to the 25 minute point of each run. Finally, the column entitled "average drift over 10 min." is the difference between the output averaged over the 5 minute intervals between 10 to 15 minutes and 20 to 25 minutes of each run.

TABLE I.

Lamp Repeatability Experiments

		Relit in Place			Repositioned			
Lamp Number	Manufacturer	Warm-up (min.)	Repeat (%)	Average Drift over 10 min. (%)	Warm-up (min.)	Repeat (%)	Average Drift over 10 min. (%)	Sixteen hour drift (% hr^{-1})
1-70	A selected	8	-	+0.04	8	-	+0.02	-0.008
		9	+0.05	0.0	7	-0.20	+0.03	
		7	-0.08	-0.02	7	-0.18	+0.11	
3-70	A selected	*	-	-0.04	12	-	-0.09	+0.020
		*	+0.14	+0.24	9	-0.61	-0.05	
		*	+0.08	-0.06	13	-0.60	+0.01	
9160	A unselected	22	-	+0.19	10	-	+0.10	+0.029
		11	+0.14	+0.02	8	+0.23	+0.13	
		9	+0.21	+0.02	8	-0.39	+0.13	
9162	A unselected	10	-	-0.12	8	-	+0.06	+0.024
		10	+0.16	-0.03	8	-0.16	-0.06	
		7	+0.06	-0.02	8	-0.19	-0.01	
9100	B selected	11	-	+0.06	11	-	+0.10	**
		10	-0.07	-0.04	8	-1.05	+0.03	
		13	-0.01	+0.01	7	-0.47	0.0	
9102	B selected	8	-	+0.03	7	-	-0.03	+0.004
		9	-0.08	-0.12	9	+0.11	-0.01	
		9	-0.08	-0.03	9	+0.05	-0.02	

* Lamp never stabilized below amplifier noise

** -7.4% discontinuity observed during this run

Conclusions:

Several conclusions can be drawn from the table. First, there is definitely a difference in the repeatability of "in-place" and "repositioned" relightings. This was attributed to the lamp socket design because of, first, the inherent inability of this type of socket to reproduce the lamp orientation and, second, the findings of the lamp orientation experiments of the last section. The kinematic lamp socket design described earlier in this paper was shown to be a definite necessity by this experiment.

Second, it appears as if the inherent repeatability of the lamps given by the "in-place" results is of the order of 0.1%. It must be remembered that this is at the level of the amplifier noise and cannot be entirely attributed to the lamps themselves. The inherent lamp repeatability remains a quantity to be evaluated by further experimentation.

Third, the average warm-up time for this type of lamp (and voltage) is about ten minutes and in almost all cases is less than fifteen minutes by a safe margin.

Fourth, there are a disturbing number of large drifts of the output (0.1% or greater) even after the lamp has warmed up (e.g., the second run of lamp 3-70, the first run of lamp 9160, etc.) indicated in the "Repeat, In Place" column. Again this is close to the noise limit but appears to be a real effect and merits further study.

Fifth, the tendency of the lamps to drift to higher output at constant voltage is inconsistent with a simple model of tungsten evaporation leading to higher filament resistance. This may be taken to mean that the lamps have not been fully seasoned; however, other effects such as thermal etching [12] could account for this tendency. The data from this experiment are insufficient to determine for these lamps the adequacy of the "2% of rated life at rated voltage" seasoning schedule typically used in photometry. However, they do point out the need for additional measurements to answer this question.

Finally, there does not appear to be a significant difference between the lamps of the two different manufacturers or between the "selected" and the "unselected" lamps. Although this is a very limited sample, it does mean that perhaps one type of lamp (for example a specific filament or bulb geometry) may be found to be more stable than another type. It also means that lamps selected for quality of appearance do not necessarily perform well.

4. Conclusion

The electronic and mechanical instrumentation has performed well thus far and will probably not be a limiting factor in our experiments in the near future. The problems that require immediate attention were indicated in the last experiment. They can be classified under two headings: detector characterization and lamp characterization. The limitations introduced into the calibrations by the lamp and detector reproducibility and drift need to be determined. Among other things a study of the detector linearity and spectral response must be undertaken.

The stability and reproducibility of lamps and detectors is presently being studied. Work on the other problems confronting luminous intensity and geometrically total luminous flux calibrations is planned. The fact that there is light has been established in the early literature [13]. The question of how much light there is, however, still remains with us.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This document was written primarily to serve two purposes. First, some of the basic instrumentation which has recently been developed for use in photometry at NBS is described. The design and application of photodetector amplifiers, lamp power circuitry, and mechanical instrumentation are discussed. Second, three photometric experiments are described: the stability testing of some flux lamps and intensity lamps and the determination of the dependence of relative intensity on orientation. These experiments and their conclusions have proven useful in pointing out areas which need further investigation and in planning the directions of future work.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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Optical Radiation Measurements:

Photometric Calibration Procedures

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Optical Radiation Measurements:

Photometric Calibration Procedures

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Washington, D.C. 20234

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature.

U.S. DEPARTMENT OF COMMERCE, Peter G. Peterson, *Secretary*
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Preface

This is the third issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series will consist primarily of reports of progress in or details of research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division and will appear about every six weeks.

The level of presentation in OPTICAL RADIATION MEASUREMENTS will be directed at a general technical audience. The equivalent of an undergraduate degree in engineering or physics plus familiarity with the basic concepts of radiometry and photometry [e.g., G. Bauer, Measurement of Optical Radiations (Focal Press, London, New York, 1965)] should be sufficient for understanding the vast majority of material in this series. Occasionally a more specialized background will be required. Even in such instances, however, a careful reading of the assumptions, approximations and final conclusions should permit the non-specialist to understand the gist of the argument if not the details.

At times, certain commercial materials and equipment will be identified in this series in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

Any suggestions readers may have to improve the utility of this series are welcome.

Henry J. Kostkowski, Chief
Optical Radiation Section
National Bureau of Standards

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Photometric Calibration Procedures

Velma I. Burns and Donald A. McSparron

The National Bureau of Standards supplies calibrations of luminous intensity, luminous flux and color temperature on a routine basis. The procedures, equipment and techniques used to perform these calibrations as of October 1972 are described. Details of the uncertainty information currently available, including estimates and procedures for determining uncertainties of the reported values, are also presented.

Key words: Calibration procedures; color temperature; luminous flux; luminous intensity; photometry; uncertainty.

1. Introduction

The Optical Radiation Section of the National Bureau of Standards recently announced a new calibration policy for radiometric and photometric standards (NBS Technical News Bulletin, June 1972). Detailed descriptions of the procedures and equipment used to perform these calibrations are being prepared as rapidly as possible. For the photometric calibrations of luminous intensity (candela), geometrically total flux (lumen) and color temperature, new procedural descriptions are now available and routinely supplied along with the reports of calibration. This Technical Note has been prepared to bring these descriptions together in a single document and make them available to people who have not obtained a recent NBS calibration.

Lamp standards of luminous intensity and lamp standards of color temperature calibrated in accordance with these calibration procedures are routinely available as "off the shelf" items from the Optical Radiation Section. Presently such lamps are calibrated twice (three measurements for each calibration) at least six months apart. Prices and ordering information can be obtained from NBS Special Publication 250.* Because of the sporadic nature of requests for luminous flux calibrations, such tests are performed only at infrequent intervals. The calibration description which appears here applies specifically to a recent luminous flux test involving some 180 calibrations from 10 laboratories. Requests for luminous flux calibrations can also be treated on an individual basis and, for the immediate future, will be performed in a manner very similar to the present description.

The material presented in this Technical Note has been limited solely to a description of the methods and procedures presently being used by NBS. In many cases the presently available uncertainty information is inadequate or incomplete. In the present document the attempt is

*See Measurement Users Bulletin Number 4 made to present that information which is available and point out its limitations. Major research efforts in the Optical Radiation Section are now devoted to improving methods and procedures for these measurements and determining their uncertainties. As improvements are made and as better estimates of uncertainty become available they will be reported in this Technical Note series and incorporated into the routine calibrations.

2. Description of Calibration of Inside Frosted Lamp Standards of Luminous Intensity

Inside frosted lamp standards of luminous intensity are calibrated at the National Bureau of Standards by a substitution method on a calibrated horizontal bar photometer. The photometer is calibrated at the time of the measurements in terms of the unit of luminous intensity (candela) at approximately the color temperature of CIE standard illuminant A (2856 K - IPTS 68) as maintained at NBS.

2.1 Test Lamps

Description

Gas-filled, inside frosted lamp standards of luminous intensity are calibrated by NBS in 100-, 500-, and 1000-watt sizes. The 100- and 500-watt lamps have T-20 bulbs; the 1000-watt lamps have T-24 bulbs. They all have medium-bipost bases and C-13B filaments. The 100-watt and 1000-watt lamps are designed to have approximately 1000 hours life when operated at 120 volts. The 500-watt lamps are designed to have 500 hours life at 120 volts.

Preparation

The lamps are seasoned by operating them at 120 volts ac for approximately 5% of their rated life and an identifying number is etched on each bulb.

Orientation

Test lamps are calibrated while burning base down on a horizontal bar photometer with the identifying number turned away from the detector. Lamp orientation is accomplished by aligning the lamp socket so that the lamp posts are held vertically with the plane formed by the axes of the posts perpendicular to the optical axis of the photometer. The bottom of the lamp bulb is 10.16 cm* below, and the lamp pins are equidistant from, the photometer axis. Source-to-receiver distances are measured from the

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*Some of the 500-watt lamps have light center lengths of 7.62 cm (3 inches). For these a distance of 7.62 cm is used between the photometer axis and the bottom of the lamp bulb. The distance used is stated in the individual "Report of Calibration" for the lamps.

plane formed by the axes of the biposts to the sensitive surface of the detector.

Before calibration the lamps are checked to ascertain that the luminous intensity varies by less than 0.1% for (1) a ±1.5° rotation about a horizontal axis intersecting the photometer axis in the plane formed by the axes of the posts (pitch) and (2) a ±1.5° rotation about a vertical axis contained in the post plane and intersecting the photometer axis (yaw).

Operation

All measurements are performed with the lamps operated on dc power. Electrical measurements are made potentiometrically to an accuracy of 0.02%. After positioning and alignment, the lamps are slowly (15-30 seconds) brought up to the designated electrical operating point and allowed to stabilize for at least 10 minutes before measurements are made. Normally, the lamp current is set and measurements are made of the luminous intensity and of the potential drop across the pins of the bipost base.

2.2 Photometer

Detector and Amplifier

The photometer detector is a selenium barrier-layer photocell [1][1] equipped with a filter which modifies its spectral response to approximately match the CIE luminous efficiency function [2]. Measurements are usually made at a photocell illumination level of approximately 80 lux. The entire photosensitive surface is directly illuminated by the entire test or standard lamp, and no auxiliary optics are used. The photocell is fully illuminated during the 10-minute stabilization period of the lamps.

The detector photocurrent is measured with an operational amplifier (current to voltage converter) arranged in a typical closed loop configuration. Thus the photocell is operating into a near "zero-resistance" circuit (no voltage across the terminals of the photocell) in accordance with the formula E output = I input χ R feedback. A five place digital voltmeter is used to measure the output of the operational amplifier.

Optical Bench

All measurements are made on a 4.5-meter optical bench. The optical bench is housed in an enclosure 61 cm wide and 117 cm high. The enclosure is covered with black "suedine" cloth on all four sides. The optical axis is 38 cm above the bench and is located approximately 69 cm

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[1]Figures in brackets indicate the literature references at the end of each section.

from the bottom, 48 cm from the top, and 30.5 cm from the sides of the enclosure. Source-to-receiver distances of 1.3 to 4.2 meters are typically used. For the 100- and 500-watt lamp sizes, a limiting baffle with an aperture 7.6 cm wide and 17.8 cm high is placed 25 cm from the plane of the biposts and centered with respect to the lamp bulb. For the 1000-watt test lamps, this baffle aperture is 10 cm wide and 23 cm high. Additional baffles are placed between the source and the detector to screen the detector from any directly reflected light. Light emitted by the lamp in the direction away from the receiver is absorbed with a light trap placed 40 cm behind the lamp.

2.3 Calibration Procedure

Photometer Calibration

The photometer is calibrated, at the time of the measurements, in terms of the illuminance produced at the detector by each of a group of 500-watt lamps of the same type and construction as the test lamps. The 500-watt lamps used to calibrate the photometer are periodically compared with a group of 10 similar lamps (group NBS 5612) which represents the unit of luminous intensity at approximately the color temperature of CIE standard illuminant A (2856 K - IPTS 68) as maintained at NBS.

An illuminance substitution method is used for the measurements. 500-watt lamps are calibrated at a photometric distance of 3 meters for both standards and test lamps. This produces approximately 80 lux at the photocell. When calibrating 100-watt lamps the photometer is calibrated with the 500-watt standards at a photometric distance of 3 meters (approximately 80 lux) and again with a distance of 4.17 meters (approximately 40 lux). The test lamps are then measured at two distances, one distance to produce approximately 80 lux and another distance to produce approximately 40 lux. The 1000-watt lamps are measured at 4.17 meters with the photometer calibrated with the 500-watt standards at a distance of 2.9 meters (approximately 80 lux).

Measurement Schedule

Test lamps are measured in groups of approximately 18. Normally 8 standards are used to calibrate the photometer. Measurements of the standards are interspersed before, after and within the group of test lamps to check for drifts in the detector sensitivity.

Data Reduction

Individual photometer calibration factors (lux per volt output of the operational amplifier) are computed for each standard lamp. After checking these factors to ascertain that no significant drift in the sensitivity of the photometer has taken place during the calibration of the test lamps, an average photometer calibration factor is computed. This average factor is used to compute the illuminance produced by the test lamps. Test lamp intensities are then computed by multiplying the measured illuminance by the square of the distance between the lamps and the detector. The entire measurement procedure is repeated at least three times, each with a different selenium barrier-layer photocell. The test lamp intensities reported are the averages of these determinations.

2.4 Discussion

Uncertainty

In the measurement of a property of a material object, such as the luminous intensity of an incandescent lamp, an uncertainty statement is an estimate of the possible discrepancy between the reported value and the physical parameter this value represents, that is, an estimate of the possible error in the reported value. Such uncertainties are usually based on a statistical treatment of the random variations of the measurements and on theoretical deductions together with direct measurements of the possible sizes and types of biases that one recognizes may be present. Of course, any bias not recognized or not measured is not considered in determining the uncertainty. Therefore, the true error is never known. Its possible value is merely estimated with varying degrees of sophistication and assurance ranging from that resulting from a few measurements and an approximate theory to years of investigation and continued validation using an "exact" theory. No useful way has been devised to quantify the reliability of the uncertainty. It can be judged qualitatively only from the extent and sophistication of its characterization and the degree to which it has been subjected to continuing validation.

Inherent in an uncertainty statement is the concept that it is unlikely that subsequent determinations of the same invariant physical parameter for the same material object will deviate from the original determination by more than the stated uncertainty. Such subsequent determinations may be in the form of replications (identical theory, instrumentation and procedures) or complete redeterminations (totally different theory, instrumentation and procedures) or any combination of the two.

The totality of the theory, instrumentation, and procedures which NBS uses in obtaining a given reported value and its uncertainty is designated the NBS process. Characteristic of a well-developed process is a complete and sophisticated investigation that led to its establishment. Characteristic of a well-run process is a continuing validation of the process parameters (precision, checks for possible biases, etc.) in the form of replications and periodic redeterminations. The greater the extent and completeness of the fundamental investigations and the higher the degree of redundancy in the continuing process, the greater the confidence that the discrepancy between the sought after value and the value being reported is not larger than the assigned uncertainty.

The photometric chain, which is used by NBS in realizing and maintaining the illuminant A candela, is subject to a number of biases.

These may be considered in terms of the three major steps used in the generation of the reported values.

A) Platinum point realization. Specific sources of possible biases include: the effect of impurities on the freezing point of platinum, the quality of the blackbody cavity and diffraction effects.

B) Photometric transfer to illuminant A. Specific sources of possible biases are the nonlinearity and spectral response characteristics of the detectors.

C) Substitution calibration of test lamps. Two distinct types of bias, constant and time dependent, are possible. If the operation of the working standard lamps does not duplicate in all essential respects the conditions under which their assigned values were derived or if these working standards have changed, a constant bias will be introduced into all measurements. On the other hand, if the photometric apparatus is sensitive to variations in an uncontrolled parameter, for instance environmental temperature or humidity, a time dependent (for example, day-to-day) bias will result.

The different biases will have varying effect on the uncertainty with respect to the three bases represented by (1) SI candela, (2) the world mean candela and (3) the NBS candela. For example, biases in the NBS realization of the platinum blackbody will have a direct effect on the uncertainty with respect to the SI candela, and an indeterminate effect on the uncertainty with respect to the world mean. The latest possibility arises because the various national standardizing laboratories have utilized similar equipment and techniques for realizing the primary standard of light, and thus may all have the same bias. Biases introduced during the transfer chain will have a direct effect on the uncertainty with respect to SI and world mean, but no effect on the uncertainty with respect to the unit as maintained by NBS. Only the biases of the substitution calibration will affect the uncertainty of a reported value with respect to NBS. The user of a lamp standard of luminous intensity will usually wish to know his uncertainty with respect to one or more of these bases. The remainder of this section presents data and procedures currently used to assign uncertainties to the illuminant A luminous intensity calibrations.

Three biases will affect the uncertainty of a reported value with respect to the candela as maintained by NBS. These are: (1) constant biases of the substitution calibration of the test lamps, (2) time dependent biases of the substitution calibration and, (3) random variation of the measurements. No detailed investigation has yet been made of the possible constant biases of the substitution calibration. The uncertainty due to the other two biases was determined in 1970 from a study of 124 measurements on 36, 500-watt lamps and 80 measurements on 20, 100-watt lamps. These data indicate that time dependent biases are present in the process and usually amount to 0.2-0.3% though a few as large as 1% have been observed. These bias percentages include short-term lamp instabilities. Occasionally, for example, changes of 0.5% have been observed in merely turning a lamp off and then on again. Assuming that these time dependent biases are due to the random variation of an uncontrolled parameter, a statistical analysis has been made of the measurements. A pooled estimate of the standard deviation of a single measurement has been calculated to be 0.3%. In assigning a value to the uncertainty, an allowance of 1.0% is made for the time dependent bias in the data and an additional allowance of 0.5% is made for the random variation in the measurements (three times the standard deviation of the mean of three measurements). The uncertainty assigned to a reported value with respect to the candela as maintained by NBS is the sum of these two components or 1.5%.

The most recent international intercomparison of the candela at the color temperature of CIE illuminant A showed a range of 1.7% among the eight participating national standardizing laboratories including NBS [3]. Adding the calibration uncertainty of transferring the NBS candela to a test lamp (1.5%) to one half this range (0.85%) yields our current uncertainty of 2.3% for a reported value with respect to world mean.

The uncertainty of a reported value with respect to the SI candela will be subject to several sources of bias in addition to those discussed above. Although extensive investigations of these additional sources of bias have not been made, some relevant information exists on which to base an uncertainty. The same intercomparison referred to earlier [3] showed that the candela at the color temperature of CIE illuminant A, as realized in the national standardizing laboratories of the world, was inconsistent with the candela realized at the color temperature of freezing platinum by as much as 3.5% [4]. Also, recent theoretical work has indicated that previous realizations of the platinum point blackbody may have been in error by as much as 1.5% [5]. Thus in our current process there are six individual biases or sources of bias relative to the SI candela for which uncertainties have been assigned. These together with the uncertainties associated with them are listed below:

Biases	Assigned Uncertainty
I. Substitution Calibration	
A. Time dependent bias	1.0%
B. Constant bias	0.0
C. Random variation	0.5
II. Transfer Chain	
A. International intercomparison at 2856 K (1/2 range)	0.85
B. International intercomparisons; inconsistency in realizing the candelas at the platinum point and 2856 K	3.5
III. Platinum Point Calibration	1.5

It is unlikely that all these individual uncertainties would have the same sign resulting in a total uncertainty of 7.3%. Therefore a combination in quadrature (square root of the sum of the squares) resulting in 4.1% is considered to give the uncertainty of a reported value relative to the SI candela.

Recently a program was established at NBS for developing improved luminous intensity standards and methods of transfer and for more thoroughly characterizing biases and uncertainties. Results of this work will be published as they become available.

Precautions

Lamps supplied to other laboratories as standards of luminous intensity represent the unit of luminous intensity (candela) as maintained at the National Bureau of Standards with the best precision now available. They are expensive laboratory equipment and deserve the utmost care in handling and use.

In addition to some obvious precautions, such as keeping the lamps clean and avoiding mechanical shock to the filament, the following are a few precautions, sometimes overlooked, which should be used with these standards.

1. The lamps should be turned on and off slowly (15-30 seconds), and great care should be taken so that at no time will the current appreciably exceed the value stated in the report. The lamp should not be moved while lighted.

2. In order to prolong the useful life of the lamps, it is recommended that they be used sparingly and that for general use, working standards be prepared by calibrating them relative to the lamps supplied by NBS. When a laboratory procures standard lamps from NBS it is well to obtain at least three such lamps in order to be able to detect any changes that may occur.

3. The lamps should be carefully aligned in accordance with the procedures described above. Photometric measurements should be made only after the lamp has stabilized (approximately 10 minutes after turn on).

4. Stray light must be excluded. One source of stray light that is sometimes overlooked is the standard lamp itself. The background of the lamp on the side away from the detector should not reflect light back along the photometric axis. NBS uses a light trap made of two pieces of black glass set at approximately 60° to each other and set behind the lamp. Black cloth positioned 45 to 60 cm behind the lamp is convenient and usually adequate.

5. Baffle aperture edges should be very thin or beveled so as not to reflect light to the detector. It is of little use to coat baffle

edges with black paint or black cloth, since most flat surfaces reflect light reaching them at large angles of incidence regardless of whether or not they are blackened.

6. It is preferable not to confine the lamp to a small space, especially with poor ventilation. Excessive noise in the measurements often results.

7. The variation of luminous intensity of a gas-filled tungsten lamp is approximately related to the variation in its current by the formula:

$$\frac{dI}{I} = 6.25 \frac{di}{i}$$

where I is the luminous intensity and i is the lamp current [6,7]. Thus a current measurement accuracy of at least 0.032% is required if it is not to affect the luminous intensity to greater than 0.2%.

2.5 References

[1] V. K. Zworykin and E. G. Ramberg, Photoelectricity, Chapter 11, John Wiley & Sons, Inc., New York, N. Y. (1949).

[2] IES Lighting Handbook, Fourth Edition, p. 1-3, 2-4 (1966), Illuminating Engineering Society, New York, N. Y.

[3] Comite Consultatif de Photometrie, 5^{e} Session (1962) p. 84.

[4] Comite Consultatif de Photometrie, 6^{e} Session (1965), Annexe 3, p. P28.

[5] Ibid., Annexe 1, p. P17.

[6] J. W. T. Walsh, Photometry, p. 532, Dover Publications, Inc., 180 Varick Street, New York, N. Y. (1965).

[7] A. Kingslake, Applied Optics and Optical Engineering, p. 61, Academic Press, New York, N. Y. (1965).

3. Color Temperature

3.1 Description of Calibration of Incandescent Lamp Standards of Color Temperature

Incandescent lamp standards of color temperature are calibrated at the National Bureau of Standards by a substitution method on a red-blue ratio, color temperature comparator. The color temperature comparator is calibrated at the time of the measurements in terms of the color temperature scale maintained by NBS.

3.1.1 The NBS Color Temperature Scale

NBS has established and maintains a scale of color temperature. Careful distinctions should be made between the concept of color temperature and the related concepts of correlated color temperature and distribution temperature. Color temperature is defined as the "temperature of the full radiator which emits radiation of the same chromaticity as the radiation considered" [1]. That is, the test source and the full radiator (i.e. blackbody) have the same appearance to a human observer. Note particularly that the corresponding relative spectral power distributions are not necessarily identical or even similar. If the test source and the corresponding blackbody have identical relative spectral power distributions in the spectral region of interest, the correct designation is distribution temperature [2]. If one wishes to assign a "temperature" to describe a source whose appearance, and hence whose relative spectral power distribution, is markedly different from a blackbody, such as a fluorescent lamp, the correct designation is correlated color temperature [3]. Mathematical procedures are available for determining the correlated color temperature of any source [4]. In applying the values of color temperature reported by NBS, the user should bear these distinctions in mind. Particular care should be exercised in utilizing the widespread practice of treating color temperature values as synonymous with distribution temperatures.

The present NBS scale of color temperature was established in 1934 [5] by visual comparison of monoplane, coiled tungsten filament, incandescent lamps with three melting point blackbodies: platinum at 2045 K, rhodium at 2236 K, and iridium at 2720 K. The nine lamps thus calibrated (three at each temperature) were then used to calibrate three working standard lamps across the color temperature range. An empirical approach was adopted for interpolating between the three fixed temperature points. Taking advantage of the cavity effect due to filament coiling, pyrometric determinations of the radiance temperature* were made at a position on the inside of a single turn of the coiled filament. It was observed that

*Radiance temperature, also called luminance temperature and brightness temperature, is defined as the temperature of a blackbody for which the spectral radiance at the specified wavelength is the same as that of the radiator considered.

the difference between the radiance temperatures so determined and the color temperature of the lamp as a whole was a smoothly varying function of the voltage applied to the lamp. Pyrometric determinations of the radiance temperatures of three different coil turns of the test lamps yielded consistent color temperature values for the interpolated region. Further, from this data it was empirically determined that an equation relating the color temperature (T_c) and the applied voltage (V), of the form:

$$T_c = A + B(V)^{1/2} \tag{1}$$

was adequate to express all of the data within the estimated uncertainties. The 1934 color temperature scale was also extrapolated up to 3200 K and down to 1500 K. Sources with known color temperatures in the extrapolated regions were produced by modifying incandescent lamp outputs (assumed to be sources whose distribution temperatures equalled their color temperatures), with blue and amber filters whose spectral transmittances had been measured. Incandescent lamps and associated equations of the form of eq. (1) have been used since 1934 to maintain the NBS color temperature scale. The scale has been adjusted twice, in 1949 [6] and in 1970 [7], to take account of changes in the International Practical Temperature Scale.

The present scale of color temperature resides in nine incandescent working standard lamps. Lamps BS 9021, BS 9022, and NBS 1005 are used in the range 2000-2600 K; lamps NBS 1923, NBS 1924, and NBS 1925 are used in the range 2300-2900 K; and lamps NBS 1926, NBS 1927, and NBS 7875 are used in the range 2700-3200 K. These working standard lamps were originally calibrated by visual comparison with the lamps used to establish the scale in 1934. In addition to the calibrations at fixed color temperature points, associated empirical equations of the same form as eq. (1) are used to establish the scale in interpolated and extrapolated regions. Empirical equations of the form,

$$i = A + BT_c + CT_c^2 , \tag{2}$$

relating the color temperature and the current through the lamps, i, have also been found to be completely adequate to represent the data within the associated uncertainties.

3.1.2 Test Lamps

<u>Description</u>

Airway beacon lamps designated 500T20/13, are issued by NBS as lamp standards of color temperature. They are 500-watt, 120-volt lamps with clear T-20 bulbs, C-13B filaments and medium bipost bases. They have a rated life of 500 hours at 120 volts.

Preparation

Initially, the lamps are seasoned by operating them at 120 volts ac for 20 hours (4% of rated life). An identifying number is then etched on each bulb.

Orientation

Test lamps are calibrated while burning base down with the etched identifying number turned away from the comparator. The lamps are aligned so that their planar filaments are centered on and perpendicular to the optical axis of the entrance aperture of the collecting sphere of the color temperature comparator. No auxiliary diaphragms are used, and thus light from essentially the entire test lamp is viewed by the comparator.

Operation

All measurements are made with the lamps operating on dc power. Electrical measurements are made with a digital voltmeter to an accuracy of 0.1%. After positioning and alignment, the lamp is slowly (15-30 seconds) brought up to approximately the required electrical operating point and allowed to stabilize for at least 10 minutes before measurements are made. Measurements are then made of the current through the lamp and the potential drop across the pins of the bipost base necessary to produce a color match to a comparison source.

3.1.3 The NBS Color Temperature Comparator

At present, all routine color temperature measurements at NBS are made on a device which compares the ratios of the "red" portion of the visible spectrum to the "blue" portion of the visible spectrum for test and standard sources. Equality of these two red-to-blue ratios is interpreted to mean equality in color temperature. Since the measurement involves the inference of a visual property of the test source (chromaticity match to the standards) from the measurement of a different physical property, severe requirements are placed on the test and standard sources. Specifically, their relative spectral power distributions must be identical throughout the entire visible region of the spectrum. Only test lamps substantially identical to the working color temperature standard lamps (clear bulbs, monoplane coiled tungsten filaments) are calibrated by this method.

Numerous devices based on the red/blue ratio principle have been described in the literature [8]. The present NBS instrument has not been optimized, either in the electronics used for signal sensing or in the optical components (filters and detector). It has, however, been shown to possess adequate sensitivity and precision. The standard deviation of a single measurement for repeated measurements of the same color temperature on the same test lamp is about 2 K. The chief virtues of the present instrument are precision, speed, and convenience.

The figure on page 15 is a block diagram of the major components of the comparator. Radiation from the test or standard source is collected in a $BaSO_4$ coated entrance sphere (20 cm diameter, 7.5 cm entrance aperture). The sphere is mounted so that it can be rotated about the optical axis of its exit aperture and thus view a comparison source. (The function and use of the comparison source will be discussed in Section 3.1.4, Calibration Procedure.) Radiation leaves the entrance sphere through a 3.8 cm diameter exit aperture and passes through an infrared absorbing filter (Corning No. 4600). This infrared absorbing filter is placed in the optical chain to alleviate the effects of the temperature sensitivity of the red filter. The radiation next passes through either the red filter (Corning No. 3486) or the blue filter (Corning No. 5562) and is detected by a photomultiplier (S-11, EMI 9514S). The red and blue filter are mounted on a rapidly spinning wheel (1400 rpm) so that radiation passing through the two filters is alternately presented to the photomultiplier. Two synchronously driven electronic gates assure that the signal from radiation passing the red filter, and only radiation passing the red filter, is diverted to one amplifier-integrator chain while the signal from radiation passing through the blue filter is diverted to a second amplifier-integrator chain. After passing the amplifier-integrator chains, the two signals are compared on the null meter. Suitable adjustments are made to either the lamp electrical parameters or the signal attenuator and adjustable voltage divider to obtain equality between the two signals (see Section 3.1.4, Calibration Procedure). Constant loading of the photomultiplier over the course of a given test run, is assured by referencing one of the two signals (either the red or the blue) to a stable dc reference source (0.1% stability) servo controlling the photomultiplier high voltage supply. A front panel reversing switch allows the operator to select which signal passes which amplifier-integrator chain and hence which signal references the high voltage supply. The instrument as described is capable of measurements in the range 2400 K to 3000 K. For color temperatures outside this range, there is not sufficient compensation available in the electronics to achieve a null between the red and blue signals. For measurements in the range 2000 K to 2400 K, a blue "accessory filter" (Corning No. 5900) is introduced immediately after the infrared absorbing filter. A yellow filter (Kodak Wratten 2A) is similarly used for measurements above 3000 K.

3.1.4 Calibration Procedure

Color temperature measurements made on the red-to-blue ratio color temperature comparator are made by a strict substitution procedure. Test and standard lamps are placed in the same geometrical position with respect to the comparator, the optical path through the comparator is the same and finally, at null, the comparator indicates a spectral match between the sources.

At the beginning of each calibration run the comparator is calibrated against each lamp of the relevant working standard group in turn. One member of the working standard group is placed in the measuring position and allowed to operate at the current required for the desired color temperature for 10 minutes. The signal attenuator and adjustable voltage divider are adjusted to produce an exact equality between the red and blue signals from the photomultiplier. The entrance aperture of the collecting sphere is then rotated to view the comparison lamp and the voltage across the comparison lamp is adjusted to produce the same equality of red and blue signals. This comparison lamp voltage is noted and the entire procedure is repeated for each member of the standards group. The average comparison lamp voltage is computed and the comparison lamp set to that voltage. The red and blue signals now obtained when viewing the comparison lamp are nulled by adjusting the electronic controls. During the remainder of the calibration run, the comparison lamp is periodically viewed to assure that the red-to-blue null condition still prevails. Thus the calibration of the comparator depends on the stability of the comparison lamp and not on the stability of the electronics or the photomultiplier. If a drift from null is observed, the electronic controls are again adjusted to restore the null condition. Test lamps are then placed in turn at the same position previously occupied by the standard lamps and after warming up for 10 minutes the exact current required to match the comparison lamp is determined.

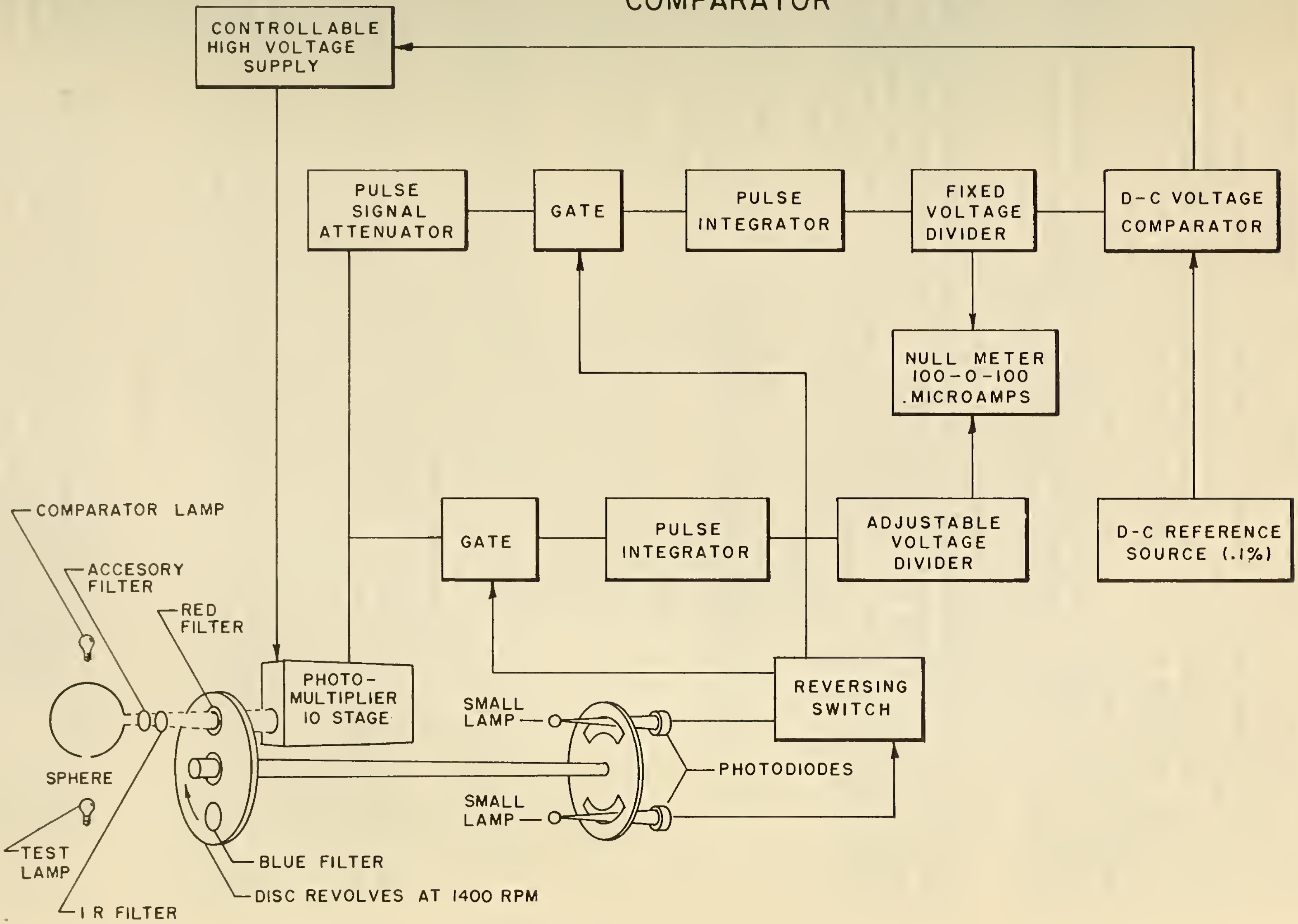
Typically nine test lamps are run at one time. The entire calibration procedure, including calibration of the comparator against each member of the working standard group, is repeated three times on successive half days. In order to check for possible shelf effects (drifts that occur while the lamp remains unused on the shelf) in the test lamps, at least one additional set of three runs is made six months later. Thus the values reported for a test lamp are the average of at least six runs made over a period of at least six months.

3.1.5 Uncertainty

The color temperature scale presently maintained by NBS is considered to be a "gage" standard, that is, a standard which NBS has not investigated sufficiently to assign defensible uncertainties relative to SI units. However, control relative to NBS standards does exist and provides at least a uniformity in measurements relative to these standards. The present scale has not been checked against absolute standards since it was established in 1934. NBS is presently in the final stages of a program to realize an absolute scale of spectral irradiance. An early reevaluation of the present color temperature scale in terms of this new scale of spectral irradiance is planned. Results of this work will be published as they become available.

Although nothing definite can be said about the uncertainty of the NBS color temperature scale with respect to SI, information is available about the precision of the transfer of the NBS scale to the test lamps. An analysis of three runs of 7 lamps at 2000 K yielded a standard deviation of a single measurement of 1.1 K. A similar analysis of three runs on twenty lamps at 2856 K yielded a standard deviation of a single measurement of 1.4 K. From these data an allowance of 1.9 to 2.4 K is made for the uncertainty of the transfer of the NBS scale to a test lamp

NBS BLUE-RED COLOR TEMPERATURE COMPARATOR



in a set of three closely spaced runs (three times the standard deviation of the mean of three measurements). The procedure to check for shelf effects in test lamps has only recently been instituted, and thus only preliminary data is available. Two sets of three runs each 18 months apart have been made on a group of nine test lamps calibrated at 2856 K. These lamps exhibited a directional drift averaging 2 K, but in one case as large as 7 K. Until a more definitive body of data is obtained on typical shelf effects, an allowance corresponding to the maximum observed shift of 7 K is made in assigning an uncertainty to the transfer of the NBS scale to the test lamps. Thus the estimated uncertainty of the reported value with respect to the NBS scale is 9 K (precision plus the allowance for shelf effects).

One international intercomparison of national scales of color temperature has been conducted [9]. Two methods of making the color temperature comparisons were used at the Bureau International des Poids et Mesures: red/blue and spectroradiometric. The table below shows the range (combined for the two methods of comparison) observed among the 7 participating national standardizing laboratories.

Nominal Color Temperature*	Observed Range
2042 K	9 K
2200	9
2353	11
2600	29
2854	31
3000	47

*Temperature based on IPTS-48.

The entries in the table are indicative of the range of color temperature measurements that might have been encountered in the world in 1965. Since only one such intercomparison has been conducted, no information is available on the stability of the various scales over long periods of time. Hence, although NBS was quite close to world mean at that time (maximum difference between NBS and world mean was 10 K at 3000 K) no inferences are drawn about the relationship of the present NBS scale to world mean.

3.1.6 Discussion

Lamps supplied to other laboratories as standards of color temperature represent the color temperature scale as maintained by NBS. They are expensive laboratory equipment and deserve the utmost care in handling and use. In addition to some obvious precautions, such as keeping the lamps clean and avoiding mechanical shock to the filament, the following are a few precautions, sometimes overlooked, which should be used with these standards.

1. The lamps should be turned on and off slowly (15-30 seconds), and great care should be taken so that at no time will the current appreciably exceed the value stated in the report. The lamp should not be moved while lighted.

2. In order to prolong the useful life of the lamps, it is recommended that they be used sparingly. For general use, working standards should be prepared by calibrating them relative to the lamps supplied by NBS. When a laboratory procures standard lamps from NBS it is well to obtain at least three such lamps in order to be able to detect changes that may occur.

3. Measurements should be made only after the lamp has stabilized (approximately 10 minutes after turn on).

4. Stray light should be excluded from the measuring instruments. This includes light from the standard which may be reflected from the background or from instruments being used.

5. Differentiation of equation 2 yields:

$$di = (B + 2CT_c)\, dT_c \tag{3}$$

Typical values of the constants A, B, and C in eq. (2) for the airway beacon lamps of the type 500T20/13 are, $A = -.45$, $B = 1.0 \times 10^{-3}$ and $C = 1.4 \times 10^{-7}$. Evaluating eq. (3) in the range 2000 K to 3000 K, shows that the sensitivity of the current setting ranges from 0.0016 to 0.0018 amps/K. Since these lamps typically draw about 4 amps at 2856 K, a current setting accuracy of at least 0.1% is required if the color temperature of the lamp is not to be affected by more than 2 K.

3.1.7 References

[1] International Lighting Vocabulary, 3rd Edition, CIE Publication, No. 17, Section 45-05-270, p. 29 (1970).

[2] Ibid, Section 45-05-265, p. 29.

[3] Ibid, Section 45-15-260, p. 74.

[4] K. L. Kelly, Lines of Constant Correlated Color Temperature Based on MacAdam's (U,V) Uniform Chromaticity Transformation of the CIE Diagram, J. Op. Soc. Am., 53, No. 8, pp. 999-1002, August 1963.

[5] H. T. Wensel, D. B. Judd, and W. F. Roeser, Establishment of a Scale of Color Temperature, Bur. of Stand. J. Res., 12, pp. 527-536, May 1934.

[6] D. B. Judd, The 1949 Scale of Color Temperature, J. Res. Nat. Bur. Stand., 44, January 1950.

[7] Color Temperature, Luminous Efficacy and the International Practical Temperature Scale of 1968, Nat. Bur. Stand. Technical News Bulletin, pp. 206-207, 54, No. 9, September 1970.

[8] See for instance:
J. S. Preston, Phys. Soc., Proc. 47, 1935, p. 1012.
H. G. W. Harding, Phys. Soc., Proc. 63, 1950, p. 685.
J. Sci. Inst., 29, 1952, p. 145.
W. J. Brown, J. Sci. Inst., 31, 1954, p. 469.

[9] Comité Consultatif de Photométrie, 6^{e} Session (1965), Annexe 7, p. 47.

3.2 Inside-Frosted Lamp Standards of Color Temperature

Inside-frosted incandescent lamp standards of color temperature at 2856 K are calibrated at the National Bureau of Standards by a substitution method in accord with the procedures described in Section 3.1, "Description of Calibration of Incandescent Lamp Standards of Color Temperature". For inside-frosted lamps, the exact procedure used differs from the previously described procedure only in the type of lamp calibrated and the standards used for the comparison.

3.2.1 Test Lamps

The test lamps and their preparation are described in Section 2.1, "Description of Calibration of Inside-Frosted Lamp Standards of Luminous Intensity". The test lamps are calibrated while burning base down with the identifying number turned away from the comparator. Lamp orientation is accomplished by aligning the lamp socket so that the lamp posts are held vertically with the plane formed by the axes of the posts perpendicular to the optical axis of the comparator. The light center of the lamp is on, and the lamp pins are equidistant from the optical axis of the comparator (see calibration report for specific light center lengths).

3.2.2 The NBS Color Temperature Scale for Inside-Frosted Lamps

Three inside-frosted, 500-watt incandescent working lamp standards of color temperature have been calibrated at 2856 K and are maintained by NBS. These lamps (NBS 9171, NBS 9172, and NBS 9173) are of the same type as described above. Initial calibration of these lamps was performed spectroradiometrically against the 500-watt, clear-bulb working standards of color temperature (NBS 1926, NBS 1927, and NBS 7875). The spectroradiometer used for this calibration [1] determined the ratios of the spectral radiant powers of the test and standard lamps at every 10 nm from 380 nm to 760 nm with a spectral bandpass of 5 nm. The data reduction assumed that the relative spectral power distribution of the clear-bulb standards was the same as the relative power distribution of a Planckian radiator. The relative spectral power distribution of the inside-frosted lamps thus determined was used to compute their chromaticity coordinates. The procedure described by Kelly [2] was then used to compute the correlated color temperature of the inside-frosted lamps.

3.2.3 References

[1] D. A. McSparron, K. Mohan, R. C. Raybold, R. D. Saunders, and E. F. Zalewski, Spectroradiometry and Conventional Photometry An Interlaboratory Comparison, Nat. Bur. Stand. (U.S.) Tech Note 559, pp. 5-12, November 1970.

[2] K. L. Kelly, Lines of Constant Correlated Color Temperature Based on MacAdam's (U,V) Uniform Chromaticity Transformation of the CIE Diagram, J. Op. Soc. Am., 53, No. 8, pp. 999-1002, August 1963.

4. Description of the Calibration of Incandescent Lamps for Luminous Flux

In response to several requests from the users of luminous flux standards, the National Bureau of Standards has calibrated a group of general-purpose incandescent lamps. The lamps range in size from 10 watts to 1000 watts and are approximately 120-volt, base-up burning lamps. They were calibrated in a 2-meter integrating sphere photometer.

4.1 Test Lamps

The lamps to be calibrated were submitted by the users and were stated to have been properly seasoned before submission. Each lamp bears an identifying number etched on the bulb.

4.2 Sphere Photometer

The lamps were calibrated while burning base up in the center of a 2-meter integrating sphere photometer. The sphere is coated with Burch sphere paint. A 7.6-centimeter diameter observation port is located in the sphere wall and is covered with a white diffusing plastic (Plexiglas, color W2447 Rohm and Haas white) flush with the sphere wall. A baffle, also coated with Burch sphere paint is placed between the lamp and the window, 0.55 meters from the window. When measuring 10-watt to 500-watt lamps, the baffle used was a circular disk 17.5 centimeters in diameter. When measuring the 750-watt and 1000-watt lamps, the baffle was shaped roughly like a projection of the lamp and was 15 centimeters by 23 centimeters.

Because of the somewhat selective spectral reflectance of the sphere coating and transmittance of the window, a blue filter is inserted adjacent to the window. The blue filter was selected from a set of filters of graded color temperature altering power, so that the net spectral effect of the sphere reflectance, window transmittance and the blue filter is that the spectral distribution of the flux arriving at the detector is approximately the same as that leaving the lamp. In order to select the proper filter, a lamp was operated at 2856 K color temperature in the sphere. The filter was then selected such that light from the lamp operating in the sphere and transmitted through the window and filter had a color temperature of 2856 K. The proper filter was determined just before this test was started (about four months after the sphere was painted). The correction at that time was approximately 640 K. The correction was determined again after about half of the data had been taken (three months later) and the correction needed was approximately 700 K (a change of about 60 K). At the conclusion of the test the correction needed was still 700 K.

A selenium barrier layer photocell [1] (Weston model 856) equipped with a filter to correct its spectral response to approximately match the CIE luminous efficiency function [2] is placed in a brass tube fitted to the window. The brass tube is coated on the inside with mat black paint. The photocell photocurrent is measured with an operational amplifier (current to voltage converter) arragned in a typical closed-loop configuration. Thus the photocell is operating into a near zero resistance circuit (no voltage across the terminals of the photocell). A five-place digital voltmeter is used to measure the output of the operational amplifier.

Three selenium photocells were used in this test and the deviation from linearity of the response of the detection system with each photocell was determined. This determination was made on a horizontal bar photometer by an inverse square method. The photocell was mounted on the bar at a known distance from a stable monoplane straight-wire filament lamp. The filament was approximately 2 centimeters square. The photocell was moved along the bar and its response noted at various distances from the lamp. The deviation of the response from that which one would expect by applying the inverse square law was attributed to the nonlinearity of the detection system. Distances used were 0.63 meters to 4.17 meters. The lamp was operated at two voltages in order to cover the desired range within these distances. For illuminance at the detector of 3 lux to 800 lux, maximum deviations from linearity for two of the detectors were -4.5% and for the third detector the maximum deviation from linearity was +6.5%.

4.3 Standards

A group of six 300-watt opal bulb lamps (Group NBS 526) operating at a color temperature of approximately 2720 K serves as the NBS standard of luminous flux. The lamps were calibrated by measuring their luminous intensity distributions relative to their luminous intensity in a single direction. The luminous intensity in the single direction was measured by comparison with the NBS standard of luminous intensity. The total luminous flux was then determined by integrating this luminous intensity with respect to angle of view. This work was done about 30 years ago and some check measurements were made about 14 years ago and about 5 years ago. The lamps are used very infrequently to calibrate NBS working standards.

The NBS working standards were recalibrated at the start of this test by comparing them in six runs, using four photocells (the three photocells mentioned above and one silicon photodiode), with the 300-watt opal-bulb lamps. The NBS working standards are listed in the following table. Each group of standards consists of six lamps.

Lamp Group Designation	Nominal Wattage	Bulb	Filament	Approximate Color Temperature	Lumens
NBS 162	500	PS 35 clear gas-filled	C-7	2800 K	6440
NBS 6807	200	PS 30 frosted gas-filled	C-9	2900 K	3260
NBS 3158	100	A-21 frosted gas-filled	C-9	2900 K	1641
BS 5470	60	S 21 clear vacuum	Squirrel Cage	2450 K	446

Corrections for nonlinearity of the detection system were applied. These corrections varied between -0.58% and +1.25%. In addition, corrections for the difference in the lamp absorption between the opal-bulb lamps and the working standards were determined and applied. In order to determine the correction due to lamp absorption, a 200-watt lamp was placed at the bottom of the sphere and held at constant voltage. Light from the 200-watt lamp was baffled from the sphere window and from unlighted lamps placed in turn at the center of the sphere. Readings were made of the detector output when each of the opal-bulb lamps (unlighted) was in the socket at the center of the sphere and again when each of the working standards (unlighted) was in the socket at the center of the sphere. The correction is the ratio of the average reading taken with each group of working standards to the average reading taken with the opal-bulb lamps in the sphere. For these lamps the corrections varied between -0.16% and -0.32%.

4.4 Calibration of the Test Lamps

The test lamps were calibrated in groups of approximately twenty. Three measurements were made on each lamp in the group, one on each of three days. Each lamp was placed in the sphere and allowed to operate at its designated current or voltage for ten minutes before measurements of voltage, current, and luminous flux were made. The lamps were measured in the following order: 2 standards, one half of the test lamps, 2 standards, the other half of the test lamps, and the remaining two standards. The lamps submitted by any single laboratory were distributed throughout the group and not measured successively. The three photocells described above were used, one on each of the three days. Test lamps were compared with standards which were closest to them in wattage. Corrections for the non-linearity of the photocell were applied. These corrections were greatest for the 10-watt lamps. For one photocell the correction was as high as 2.4%. Corrections for the difference in absorption were determined by the same method as described for the calibration of the working standards. Absorption corrections ranged from +0.66% to -0.07%.

4.5 Uncertainties

The geometrically total luminous flux output of the prime reference group (the six 300-watt opal-bulb lamps) was obtained by measuring the luminous intensity of the lamps in a large number of directions relative to the intensity in a reference direction (distribution photometry). Determination of the luminous intensity of the lamp in this reference direction, together with integration of these relative intensity measurements then allowed computation of the total luminous flux output of the lamps. Distribution measurements were made three times, twice in 1938 and once in 1958, on three different instruments. No detailed error estimates were made for these measurements. In the absence of more fundamental error estimates, the maximum observed range among the three sets of measurements, for any member of the prime reference group, will be taken as the estimate of the uncertainty of the distribution photometry measurements. This range is 0.7%.*

The uncertainties associated with the direct substitution comparison of the luminous intensities of two identical inside-frosted lamps have been discussed in section 2.4 [3]. For this type of direct substitution transfer the uncertainty assigned is 4.1% relative to SI (individual components combined in quadrature). For the luminous intensity determination on the prime reference flux group, an additional uncertainty must be allowed because of the difference between the luminous intensity standard lamps and the flux standard lamps. Specific differences that will affect the measurements are: (1) the different physical sizes of the lamps (23 cm long, PS-40 bulbs for the flux lamps versus 17.8 cm long, T-20 bulbs for the luminous intensity standards); (2) different spectral distributions (2720 K for the flux lamps versus 2856 K for the luminous intensity standards); and (3) inability to repeat the alignment of the flux lamps due to inadequate reference positions on the lamps. Inverse square law considerations lead to an estimate of 0.5% for the uncertainty introduced by the differing physical sizes of the lamps. Spectral differences of the magnitude encountered here have been observed to produce differences of up to 0.25% in other similar luminous intensity measurements. Finally, misalignment, particularly a systematic difference in alignment between the distribution photometers and the photometers used for the luminous intensity determinations might produce an error of 0.25% (based on a study of the distribution curves and an estimated ability to align the lamps to ±2°). It is unlikely that these uncertainties would have the same sign and therefore, they are combined in quadrature. This results in an uncertainty relative to SI of 4.2%.

*The uncertainties being discussed are listed in the table on page 25.

The uncertainty of transfer from the prime reference flux group to the NBS working standards may be divided into three parts, those uncertainties due to: (1) geometric effects; i.e., the presence of objects, such as the lamp, its support, and the baffle, in the sphere and their geometrical arrangement; (2) spectral effects, i.e., differences in the spectral distribution of the lamps being compared or a difference between the spectral response of the detector being used and the CIE spectral luminous efficiency function; and (3) random variations of the measurements. No detailed analysis of the geometric and spectral effects have been made. However, regarding the geometric effects, differences as large as 1% have been observed when using a sphere geometry described above compared to a very different geometry requiring more objects in the sphere during the measurements. An allowance of 1% has been made for this source of error. Uncertainties due to the spectral effects have not been extensively evaluated. An allowance of 1% is the best guess estimate for these. For random variations, the standard deviation of a single measurement obtained from a population of 144 measurements (6 measurements on each of the 6 lamps on each of the 4 groups of working standards) was 0.14%. The uncertainty assigned for the random variations was three times the standard deviation of the mean of the 6 measurements on each lamp or 0.2%. These uncertainties combined in quadrature give an uncertainty of 1.4% relative to the prime reference group and when combined in quadrature with the SI uncertainty of the prime reference group yield 4.4%.

The uncertainty of the transfer from the NBS working standards to test lamps supplied to other laboratories depends on the size and operating color temperature of the test lamps relative to the standard group used to calibrate them. For the test lamps which are the same size and color temperature as the standards used, the uncertainty is estimated from the random variations. This was computed as three times the standard deviation of the mean of the three measurements made of each of the test lamps and is 0.4%. For the uncertainty of the transfer from NBS working standards to test lamps of other sizes and color temperatures, additional uncertainties as large as 1.0% for geometric differences and 1.0% for spectral differences must be included. Combining these in quadrature results in an uncertainty of 1.5%.

The total uncertainties of the test lamps relative to SI or to the NBS prime reference group are obtained by combining in quadrature either the above 0.4% or 1.5% with the 4.4% or the 1.4% referred to above and listed in the table. The resulting SI total uncertainty is 4.4% to 4.7% and the total uncertainty relative to the prime reference group is 1.5% to 2.0%. The specific value depends on the relative size and color temperature of the test lamps and the NBS working standard lamps used to calibrate them.

TABLE OF UNCERTAINTIES

Uncertainty of the Prime Reference Group		
Uncertainty of the distribution measurements	0.7%	
Uncertainty of the NBS luminous intensity scale relative to SI (individual uncertainties combined in quadrature)	4.1%	
Additional uncertainty of the luminous intensity transfer because of:		
(1) different physical sizes of the lamps	0.5%	
(2) spectral differences	0.5%	
(3) alignment of flux lamps	0.25%	
Total uncertainty relative to SI		4.2%
Uncertainty of the NBS Working Standards		
Uncertainty of the transfer from the prime reference group because of:		
(1) geometric differences	1.0%	
(2) spectral differences	1.0%	
(3) random variations	0.2%	
Total uncertainty relative to the NBS prime reference group		1.4%
Total uncertainty relative to SI		4.4%
Uncertainty of the Test Lamps		
Uncertainty of the transfer from the NBS working standards		
(1) for lamps of the same size and color temperature as the working standards	0.4%	
(2) for lamps of other sizes and color temperatures	1.5%	
Total uncertainty relative to SI	4.4% to	4.7%*
Total uncertainty relative to the NBS prime reference group	1.5% to	2.0%
Total uncertainty relative to the NBS working standards	0.4% to	1.5%

*depending on the relative size and color temperature of the test lamps and the NBS working standard lamps used to calibrate them.

NBS participated in the fifth international intercomparison of national standards of luminous flux in 1969. The results of this intercomparison [4] showed the NBS luminous flux standards to be 0.7% above world mean. However, later investigations have shown that the technique used for calibrating the lamps for this intercomparison resulted in the assignment of luminous flux values which were low by 0.6% relative to the technique used in the present test. Thus the values assigned to the lamps calibrated at this time are estimated to be higher than world mean by 1.3%.

The NBS 200-watt group of working standards (group NBS 6807) and 200-watt lamps of the same type which have been submitted for calibration several times appear to be drifting in luminous flux output relative to lamps of other sizes and relative to the NBS prime reference group (approximately 1% since 1962). Therefore, these lamps should be checked frequently.

4.6 Care and Handling

Lamps supplied to other laboratories as standards of luminous flux represent the unit of luminous flux (lumen) as maintained at the National Bureau of Standards with the best precision now available. They are expensive laboratory equipment and deserve the utmost care in handling and use.

In addition to some obvious precautions, such as keeping the lamps clean and avoiding mechanical shock to the filament, the following are a few precautions which should be used.

1. The lamps should be turned on and off slowly (15-30 seconds), and great care should be taken so that at no time will the current through a lamp appreciably exceed the value stated in the report.

2. In order to prolong the useful life of the lamps as standards, it is recommended that they be used sparingly and that for general use, working standards be prepared by calibrating them relative to the lamp standards supplied by NBS. When a laboratory procures standard lamps from NBS, it is well to obtain at least three such lamps in order to be able to detect any changes that may occur.

3. A baffle should be used between the lamp and the observation window. The baffle should be as small as possible but large enough to prevent any light from the lamp reaching the window without undergoing at least one reflection. The baffle surface should be coated with the same material as the sphere wall.

4. The variation of luminous flux of a tungsten filament lamp is approximately related to the variation in its current by the formula: [5,6]

$$\frac{d\phi}{\phi} = K \frac{di}{i}$$

where ϕ is the luminous flux, i is the lamp current and K is 6.25 for gas-filled lamps and 6.05 for vacuum lamps. Thus a current measurement accuracy of at least 0.032% is required if it is not to affect the luminous flux to greater than 0.2%.

5. Most detectors are not linear in their response. Detectors of a single type made by a single manufacturer sometimes differ significantly in this respect. If lamps of different flux outputs are to be compared, the response of the detector should be studied to determine its departure from linearity.

6. Most sphere coatings are somewhat spectrally selective in reflectance. Diffusing windows commonly used in spheres also have spectrally selective transmittances. Corrections should be made when comparing lamps operating at different color temperatures. In addition to this, a detector whose spectral response agrees with the CIE luminous efficiency function should be used.

7. Lamps of different physical size and blackening absorb different amounts of the flux reflected to them by the sphere wall. The amount of flux absorbed also varies with the size of sphere being used and with the reflectance of its coating. Therefore, when lamps of different physical size, bulb material and blackening are being compared, corrections for the lamp absorption should be made. The absorption correction should be determined in the sphere in which the comparison is made.

8. When comparing lamps which are nearly identical in physical size, absorption, luminous flux, and color temperature, the corrections listed above in 5, 6, and 7 may not be significant.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The National Bureau of Standards supplies calibrations of luminous intensity, luminous flux and color temperature on a routine basis. The procedures, equipment and techniques used to perform these calibrations as of October 1972 are described. Details of the uncertainty information currently available, including estimates and procedures for determining uncertainties of the reported values, are also presented.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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Optical Radiation Measurements:

The Impact of Radiometry and Photometry and the Role of NBS

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[2] Part of the Center for Radiation Research.
[3] Located at Boulder, Colorado 80302.
[4] Part of the Center for Building Technology.

Optical Radiation Measurements:

The Impact of Radiometry and Photometry and the Role of NBS

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Preface

This is the fourth issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series consists primarily of reports of progress in or details of research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division and appears about every six weeks. The current issue, however, is an exception. It presents the impact of radiometry and photometry on a number of problems of national concern and NBS' role in the measurement aspects of these problems. The document was originally prepared for internal use. It is being included in this series because of the belief that it would be of interest and use to a much wider audience.

Henry J. Kostkowski, Chief
Optical Radiation Section
National Bureau of Standards

Foreword

Individual scientists and scientific institutions are being asked increasingly to identify specific long-term effects of their work. This identification is at best difficult and imprecise. Nevertheless it provides as quantitative a basis as is possible for establishing specific programs and priorities.

This examination of potential effectiveness has been stimulated by the increased concern for national problems, such as the energy crisis, pollution, and public safety. In the development of solutions for these problems, the suitability of technical approaches must be assessed. The promise of specific experimental and theoretical procedures must be evaluated. Thus increasingly the relationship of various technical fields to national goals and problems must be identified.

One technical area of major potential impact on many problems of national concern is the field of electro-optics. This field has experienced exceptionally rapid growth in the last five years. Though this growth has strengthened markedly the ability of the field to provide solutions to certain problems, it has created its own problems in terms of increased disagreements among measurements. Disagreements in optical radiation measurements of commercial and public significance are now widely evident and are growing in severity.

Therefore the National Bureau of Standards is now reviewing its traditional concern for optical radiation measurement accuracy, the new emphasis on national needs, and the application of sophisticated technical measurement to national problems. Its review of these national questions, the answers to which depend on progress in optical radiation measurement, may interest a wider audience than the Department of Commerce, for which this report was initially prepared.

The study is designed not only to describe present important problems but to concentrate on those of future impact. It must therefore anticipate the development of technology and its problems. It must extrapolate. Therefore this review presents only a cursory summary of many complex issues and some supporting evidence.

Commercial questions are also intimately involved. Any improvement in industrial technology stems from and in turn will stimulate keen competitive interest. We are indeed extremely grateful to our correspondents in industry, especially those in the Council for Optical Radiation Measurement, for the insights that they have given us. But because of the commercial impact of technical forecasting in this area, this version of the NBS study excludes individual reference to particular companies and the exact data they have given us.

A comprehensive study of the issues might well be expected to include a detailed program for action. In Chapter 5 some general comments are made that suggest such a program. Detailed programs have in fact been constructed separately in the various projects covering areas of this review. A comprehensive, centralized solution has not been proposed here. Nevertheless one initial component in a new NBS approach to these problem-studded fields is the present survey of the issues ultimately involved. In an improved measurement system, NBS must make a sensible contribution derived from an understanding of these ultimate issues.

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THE IMPACT OF RADIOMETRY AND PHOTOMETRY AND THE ROLE OF NBS

Bruce Steiner

Serious measurement discrepancies universally plague quantitative measurement in the electro-optics industry. The impact of the resulting problems is reviewed and the role of NBS explored. The measurement discrepancies arise chiefly through the recent explosive expansion of this industry. The growth has precipitated a complex development in the variety and accuracy of measurements required. The impact of problems in optical radiation measurement falls in many areas. One is the increasing Federal responsibility for public life defined in recent legislation. Another is the influence of good optical radiation measurement on the technical development of the electro-optics industry. The impact of these measurements on a number of public issues is reviewed: public health, public safety, the energy crisis, meteorology, pollution, agriculture, crime prevention, and surveillance from air and space. The economic impact of improved measurement both on a fair domestic market and on the balance of payments operates through unit production cost, quality control, product improvement, and innovation. Leadership by NBS has been urged by the industry not only in fulfillment of its legislative responsibility but also to permit the focus of elaborate and impartial resources on the complex problem of optical radiation measurement. In keeping with its mission to help improve industrial technology and the competitiveness of American industry, NBS has an opportunity of major proportions in the electro-optics industry. Leaders of this industry are calling for NBS initiatives to resolve many of the measurement problems now hindering further progress.

Key Words: Agriculture; clinical analysis; economic impact; energy crisis; meteorology; photometry; phototherapy; pollution, radiometry; remote sensing.

1. THE PROBLEM IS SERIOUS DISCREPANCY

Quantitative measurements of optical radiation typically disagree seriously with comparable measurements. Such discrepancies vary in size between several percent and several hundred percent. They arise both within and among laboratories, nationally and internationally. They occur in all spectral regions, in the ultraviolet, visible, and infrared.

This situation is widely considered to be intolerable. Concern has been expressed in conversations and in voluminous correspondence with industry, other governmental agencies, and universities. It has also been expressed by the electro-optics field as a whole through the organization of the Council for Optical Radiation Measurement. Reports of Working Groups of this Council furnish the beginning of an industry-wide consensus on the broad incidence and the great urgency of the problem.

The basic purpose of this study is to examine the issues. These are studied in Section 3. Alternatives for dealing with them are covered in Section 4. The contributions NBS can make and why it should do so are covered in Section 5. The fundamental question, however, is the general technical basis for this situation: "How we got here and why?" This is reviewed in Section 2. It must be examined first, because it bears on the severity of the problem. This technical basis also suggests the ultimate range of solutions.

2. THE REASON IS GROWTH: WORKING AT THE STATE OF THE ART

2.1 Introduction

Primary responsibility for serious disagreement in optical radiation measurements rests on technical growth. On the one hand, there is the recent exceptionally rapid growth of electro-optics technology. Moreover, expansion also in public concern is making new demands on this technology. Specific issues will be cited and examined in the next chapter. However, both the significance of these issues, and the present ability of NBS to respond to them, are strongly affected by three factors: 1) the rapidity of recent growth, 2) the present undeveloped nature of radiometry* and photometry*, and 3) the polydimensionality of recent development. Both commerce and the public interest require measurement frequently at or beyond the state of the art. The implications of this situation are severe.

2.2 Rapid Growth

a. U.S. Growth

The present rapid expansion of our electro-optics industry is characterized by two types of growth. In some cases, established companies are expanding rapidly. At the same time, new high-technology companies are proliferating in number.

Large sections of the industry are expanding by a factor of two to four every nine years (Table 1). The lamp (light bulbs) and lighting fixtures industries are doubling every nine years. The manufacture of television receiving sets triples in nine years. The dollar value of cathode ray tubes production quadruples after nine years. The manufacture of light sensitive diodes nearly doubles in four years. The value of equipment for photogrammetry nearly tripled in the four years between 1963 and 1967. Optical instrument manufacturing quadruples in nine years. The manufacture of photographic equipment triples in a nine-year period. Several of these components are now individually multibillion dollar industries.

Table 1. Examples of growth in optical radiation industry

Millions of Dollars

(Source: U.S. Census of Manufacturers)

Industry	1967	1963	1958
Lamps (Bulbs)	756.	546.	394.
Lighting Fixtures	1,543.	1,116.	765.
TV Sets	2,260.	1,092.	727.
TV Tubes	766.	249.	177.
Light Diodes	19.	11.	not separated
Photogrammetry	5.9	2.2	not separated
Optical Instruments	452.	270.	116.
Photographic Equipment and Supplies	3,138.	1,631.	1,061.

Much of this growth has been reflected in the growth of industrial giants such as Eastman Kodak and General Electric. But the electro-optics industry also contains a large number of small companies. In fact, the most recent Optical Industry and Systems Directory lists over 1,400 suppliers, a number of which are small businesses.

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*Radiometry: science of quantitative optical radiation measurement
Photometry: eye-response-weighted radiometry

The most rapid growth is now found in non-Federally related activity. By contrast, the initial impetus had been furnished by the defense and space efforts. This Federal activity formerly provided administrative as well as financial focus. But with the slowdown in these communities, growth is reflected by a change from centralized Federal sponsorship to diverse Federal and private interests. This change requires an even greater intercomparability of measurements than would have otherwise been the case.

b. Foreign Growth

Other countries have just begun to move into this very promising field [1][1]. An important indicator of the rate of growth is the number and variety of demands that the whole industry is presenting to its national laboratories. The severity of the American situation is yet approached abroad only by NRC in Canada. Figure 1 gives a qualitative picture of the development of this field with time. In the figure, assistance requested and time are both normalized in terms of the point at which national expectation of assistance seriously outdistances the capacity of the respective national laboratory to respond. The data is taken from personal conversations of the author with those responsible for the programs in radiometry and photometry in the various national laboratories. NBS and NRC find themselves in a position to anticipate problems and provide leadership in a situation that will surely arise in the other national laboratories: NPL, PTB, ETL, NSL, BNM, and IMM. It is interesting to observe that there is a rough correlation between the severity of their present optical measurement crisis and proximity to the U.S. We shall return to the important foreign trade implications of this picture in Section 3.

2.3 The Rickety Technical Base

a. Radiometry

The initial demands of defense and space technology have been met in radiometry by the establishment of a few basic standards. These of necessity were tied to fundamental physical measurement, but as often as not only loosely by contemporary standards. Very few pillars of this radiometric foundation go to bedrock as seen today. And those few that do are available only at an enormous cost in effort by highly trained and painstaking workers. The utilization of these standards for measurements of immediate practical interest is so challenging that most efforts become research projects in themselves. The level of agreement among measurements is frequently no better than that in exploratory research.

The previously modest commercial requirements in radiometry were met by spin-off. They were accommodated within the focused attention of DOD and NASA in a few basic areas. However, DOD interest in radiometry and photometry is now being curtailed at a time of rapidly increasing non-defense need for attention. In a similar way, a modest amount of accurate radiometric measurement of academic long-range interest has also been entertained within this Federal framework. However, academic requirements are now increasing in severity at the same time that this skeleton framework has ceased to develop.

b. Photometry

Visual evaluation of light preceded the ability of the physicist to measure its spectral power distribution. But the best photometric measurements are still comparable only to an accuracy of a few percent. Their conversion to and from purely physical quantities, e.g. watts, is even now possible at best to about 3%. In the absence of a firmer physical foundation, agreement among photometric measurements has depended heavily on the limited variety of objects measured and the limited types of measurements made. It has also been aided by the traditionally modest level of agreement expected.

This system held together tolerably well for incandescent lamps. For a small variety of film types, it also worked: film and the photographer were relatively "forgiving" of imprecise exposure. In other more specialized areas of interest, DOD was able to fund the

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[1]Figures in brackets indicate the literature references at the end of this paper.

GROWTH OF ELECTRO-OPTICS INDUSTRY

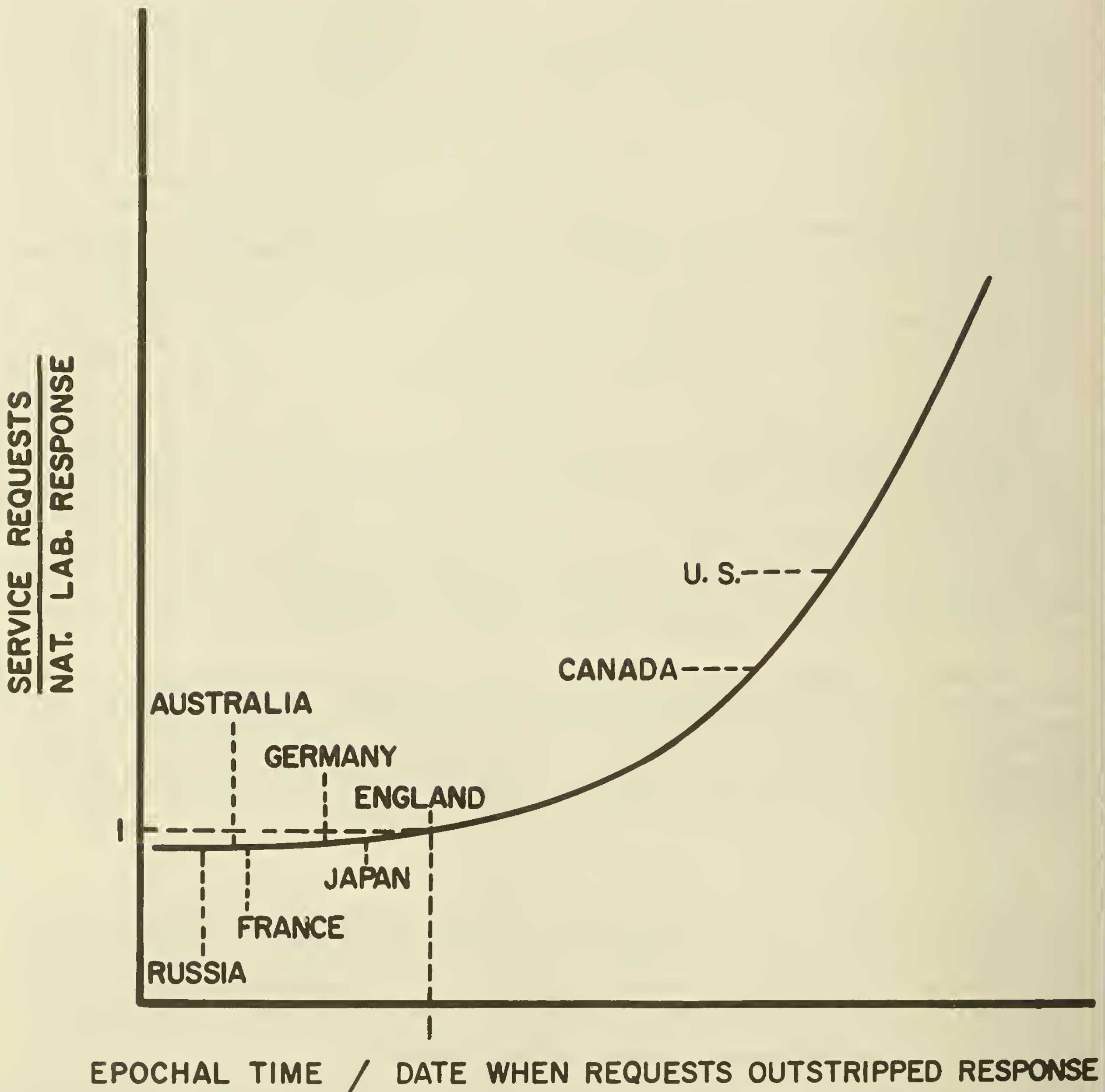

FIGURE 1

establishment and separate maintenance of special standards, gages that were not tied closely to basic physical measurement.

But no longer. Apart from the comparison of similar incandescent lamps and a few other specialized objects, photometric measurement can now be performed only with unacceptable agreement and even then only with great effort by contemporary standards. Since the archaic structure has a weak physical basis it cannot be patched or extended.

c. Recapitulation

For differing reasons, then, the structures of photometry and radiometry have been minimally responsive to relatively undemanding isolated and non-interrelated requirements. That era has ended. We shall see that the existing small but firm radiometric foundation achieved by great labor will accommodate neither the quantity, the variety, nor the interrelation of present needs of the electro-optics industry. A major new thrust will be required for NBS to make substantial progress in meeting the rapidly evolving expectations of its constituency in radiometry and photometry.

2.4 Wide Diversification of Growth in the Art and in Public Interest

A few specific examples of recent growth may provide a useful framework for understanding Section 3.

a. New Kinds of Technology

A dominant feature of the present growth of the electro-optics industry is the development of very new technology. This technology throws into relief the limitations of much of classical radiometry and photometry [2]. For present measurements to be meaningful, they must be comparable with others. One cannot continue arbitrarily to set up new gages.

(1) Light Emitting Diodes

The newest and most rapidly growing type of source is the light emitting diode (LED). It has a unique spectral distribution (color) very different from that of the incandescent lamp. The use of this lamp has developed very rapidly within the past year [3]. It promises ultimately to replace the incandescent lamp at low levels. Measurement of these new lamps is becoming a very serious problem [4-7; app. A].

(2) Other New Lamp Types

The proper role of NBS with respect to the lamp industry will be examined closely in Sections 4 and 5. For the moment we postulate the argument that accurate measurement of total flux of a variety of lamps is in the national interest and clearly relates to the mission of the Bureau. The recent rapid development of new lamp technology then places an enormous new burden on the present system [8]. The variety of lamps produced is such that the few incandescent lamp standards now available are inadequate to the job.

(3) New Detectors

The rapid development of new detectors has led to a new emphasis in an area that formerly received little attention. The stability of new solid state detectors has aroused serious interest in a detector that might serve as a secondary standard. This is an attractive idea particularly for photometry, a field built conceptually on a natural detector, the eye [7,9]. Furthermore, a need has arisen for characterization of totally new detectors such as vacuum photomultipliers incorporating III - V compounds. These provide an unusually flat wavelength response [10].

(4) New Optical Instrumentation

The growth of the entire electro-optics field is leading to the entry of a number of new radiometers and photometers that offer substantially higher reliability than in the past [2]. Firms already established in other areas are now entering the field [11]. With the increasing commercial availability of optical measurement technology and its increasing precision, the need for both higher accuracy and more reliable verification of measurement performance is becoming a pressing problem.

b. Broadened Spectral Range and Distribution

The growth in demand for better measurements is particularly keen in the infrared [6,12-13; app. B]. Measurements in this region promise to be particularly useful in finding solutions to a number of social problems explored in Section 3 [6].

The growth in ultraviolet requirements is also remarkable. Both spectral radiance and irradiance are becoming of primary interest to the ultraviolet user [13]. In addition, the measurement of ultraviolet total flux is important to the manufacturer of equipment, production and replacement part verification, serving photochemistry, graphic arts, and chemical production [5].

Sources of light with a spectral distribution different from that of current standards become more important [7] as the distribution of natural daylight is recognized to be of considerable health and safety significance (Section 3) and as the spectral distribution of artificial light sources becomes increasingly bizarre (Plate 1).

c. Low Level

Measurements at low light levels have presented a new set of problems. Commercially important sources are presenting serious measurement problems at these lower levels [4-7, 14; app. A].

Looking to the future, the ultimate feasibility of photon counting as a basic measurement tool, whether as a primary realization or a secondary standard, will depend on the ability to couple single photon techniques with classical power measurement. A far-sighted program in radiometry will have to include work in this area if NBS is to prepare itself for future demands of a basic nature. No standards here presently exist.

d. High Level

At the other extreme, the measurement of high level sources is also increasingly important [7]. High total flux measurements bear on foreign trade as we shall see in Section 3 [8]. The importance of high irradiance measurement in new safety requirements [15] for the photographic industry is now recognized by Underwriters Laboratories. NBS presently has no high level standards in the range of this new concern.

e. Pulsed Measurements

An area of desultory NBS activity that generally has a very low level of reliability, but one of increasing commercial and technological importance, is the measurement of pulsed sources. These are used in photography and traffic control; they are of great importance in growing laser technology [4,7,14; app. A].

f. New Public Interest

The growth of public concern, as reflected in new and anticipated governmental action, poses many new measurement problems that require firm, reliable solutions.

(1) Transportation

Recent Federal entry into the regulation of safety in transportation is leading to new requirements in automobile lighting. Both head lighting and tail lighting [7] are involved. Newer materials are complicating the measurements and making obsolete most former measurement techniques [16].

The problems in this as well as related fields are complicated by the lack of recognition that even the barely tolerable level of past agreement is no longer possible. Diversification in the types of sources and materials being measured is further complicated by new types of instruments now used to measure them [9]. Continued lack of attention to this

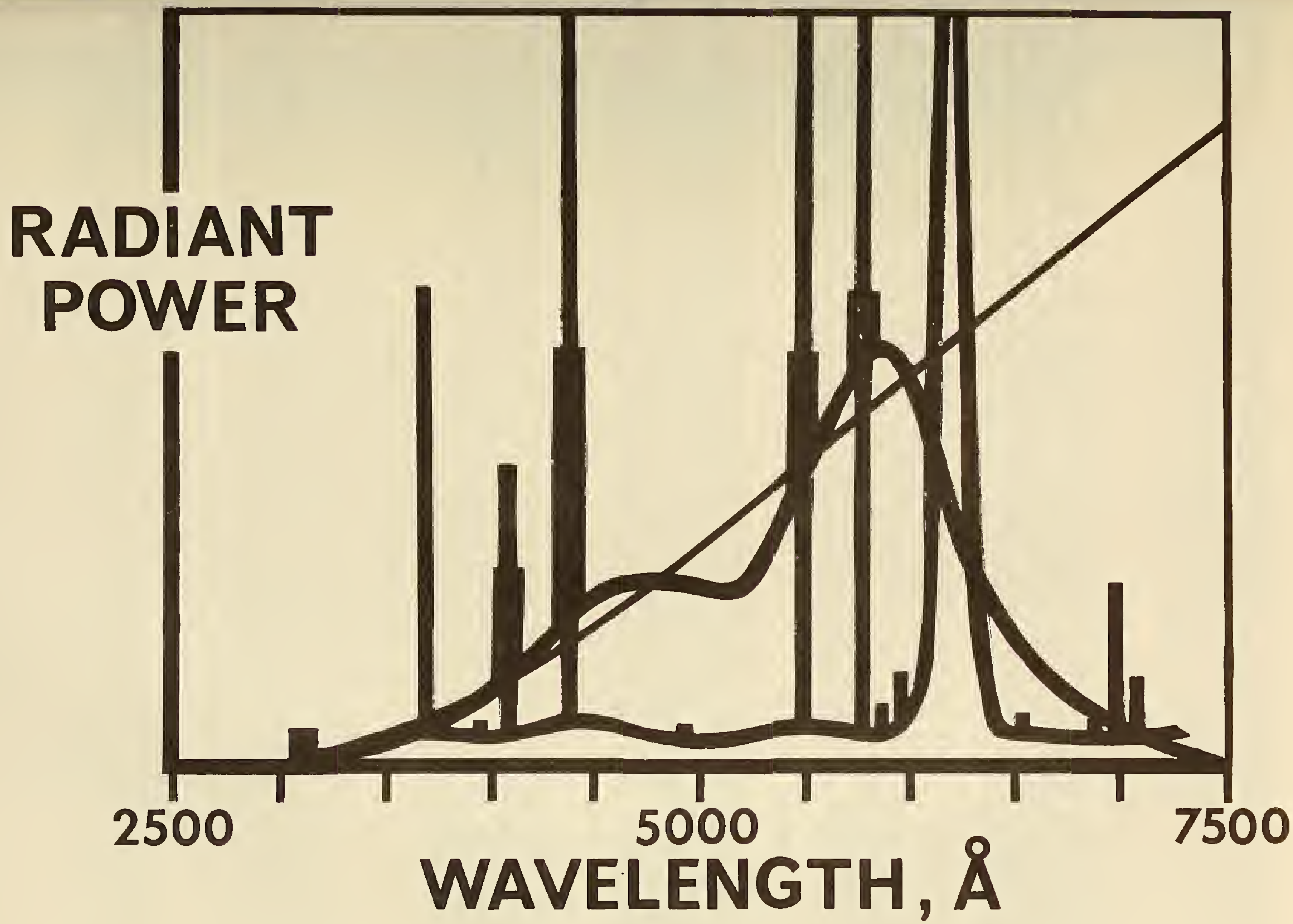

PLATE 1. Spectral power distribution of an incandescent lamp (monotonically increasing with wavelength), a fluorescent lamp (double-humped structure), and a high intensity discharge lamp (many-lined structure).

problem will result in much larger future measurement discrepancies. But at the same time, broad recognition of the influence of lighting on safety is calling for even tighter tolerances [17]. The transfer of responsibilities in this area to the Federal Government moreover provides a new focus for concern. This focus will make the poor measurement situation more visible, and thus more intolerable.

(2) Public Safety

The growth of concern for public safety is illustrated by activity after the ignition of clothes by lights on a movie set. Underwriters Laboratories are in the process of propagating for the first time a specification on the radiant heat a given distance from movie lights [15]. This particular specification calls for measurements not possible with current NBS standards.

Another example is the increased medical concern about the ultraviolet flux from lamps. Biological activity in this spectral region is being very widely recognized and will be covered in more detail in Section 3. Present standards go back 30 to 40 years with consequently very questionable accuracy [5]. The basis for new Federal administrative action has already been laid: new legislation will require both new total flux measurements not now possible and more reliable spectral irradiance measurements than are now available.

(3) Governmental Activity

Recent Federal activity in transportation has been noted. Increasing public concern about the environment has led to greater Federal concern with optical radiation measurement in the Radiation Health and Safety Act [5]. NBS is in the interesting position of a Federal agency asked by industry to become more actively involved in interaction with private enterprise [4]. The electro-optics industry clearly desires to fulfill its contractual agreements reliably, not by an unsatisfactory adherence to sparsely available standards [14].

g. Other Anticipated Areas of Impact

Among the many applications that are, or shortly will be, strongly affected by rapidly changing technology are: aerospace cockpit lighting [7]; photographic instruments and associated filters, sources, and detectors [7,18]; cathode ray tubes; and computers [7]. Graphic arts and television may shortly be greatly affected by a relatively unfamiliar type of color image production: liquid crystals [19].

2.5 Measurement Impact of Growth

a. Increased Necessity for Intercomparability

The general diversification of types of measurements made with rapidly developing technology places a severe strain on the use of a relatively static number of standards. That is, a new measurement will necessarily imply new techniques and new procedures. In general these will differ in a given laboratory from those in another in "geometry, polarization, and instrument spectral response" [4].

Although outside agencies have no legal power to commit NBS resources in order to provide "traceability", industries and other government agencies increasingly rely on NBS via "traceability" requirements. Our response to this situation will have broad impact on a substantial segment of industry. NBS, as noted above, has a unique opportunity here as well as some serious hazards to be avoided. Industry is looking actively to NBS.

b. Relationship of Photometric to Radiometric Measurements

A most important type of intercomparability now demanded is that between photometric (eye-response related) and radiometric (physical) quantities. Because photometric measurements preceded the more basic radiometric ones, a separate system arose. It has become hallowed first by usage, then by enshrinement as a "Base Unit", the candela, and finally, by a special legal responsibility of the Secretary of Commerce for maintenance of a special set of photometric standards (Section 3). Nevertheless, the physical separateness of the photometric system from the more clear radiometric system has become a serious commercial liability. In areas where both eye-response and power units are required, two separate not legally convertible sets of units are no longer economic [6-7,13,18,20]. Although few people question the advisability of using eye-related units for visually important quantities, the existence of a detached system for this purpose is increasingly a liability. Growth in both areas of measurement requires firm convertibility.

c. Generality of the Difficulty

The problems that have been described are widespread problems, as the redundancy in the referenced comments indicates. It is indeed largely the growth in the redundancy of these problems [6] that calls for a major new effort. Because of the wide number of measurements made and the interdependence of the results, a comprehensive program for attention is required. The constraints that this factor places on feasible NBS programs will be examined in Section 4.

3. THE ISSUES

3.1 Statutory Obligation

a. Direct Responsibility

(1) Organic Act

Direct NBS responsibility for national standards of measurement is defined in 15 U.S. Code 272, which authorized the Secretary of Commerce to undertake: "the custody, maintenance, and development of the national standards of measurement, and the provision of means and methods for making measurements consistent with those standards, including the comparison of standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government".

Authorization that: "The Bureau shall exercise its functions for the Government of the United States: for any state or municipal government within the United States; or for any scientific society, educational institution, firm, corporation, or individual within the United States engaged in manufacturing or other pursuits requiring the use of standards or standard measuring instruments" has a renewed significance in connection with more recent legislation described below.

In carrying out these functions, activity for: "(1) the construction of physical standards; (2) the testing, calibration, and certification of standards and standard measuring apparatus; (3) the study and improvement of instruments and methods of measurements" is also authorized. Authorization for "(9) the investigation of radiation, radioactive substances, and X rays, their uses, and means of protection of persons from their harmful effects" is an incredibly broad responsibility with respect to the marked growth characterizing the electro-optics industry. "Cooperation with other governmental agencies and with private organizations in the establishment of standard practices, incorporated in codes and specifications; advisory service to Government agencies on scientific and technical problems, invention and development of devices to serve special needs of the Government" will be increasingly demanded as legislation and its authorized Federal activity expands rapidly.

(2) Specific Photometric Responsibility (Visible Light)

In addition to the important but general authorization in the Organic Act, 15 U.S. Code 224, Public Law 81-617, goes considerably further with respect to photometric (eye-related, that is, visible light) units: <u>"It shall be the duty of the Secretary of Commerce to establish the values of the primary electric and photometric units in absolute measure, and the legal values for these units shall be those represented by, or derived from, national reference standards maintained by the Department of Commerce."</u>

The growth described in Section 2 bears directly on the rapidly increasing obligation of NBS in connection with photometric units. As the variety of the applications of such measurement grows, the public expectation of NBS performance, with the substantial backing of the cited legislation, increases apace. This expectation is particularly demanding with respect to increasing industrial desire for the strong coupling of photometric and radiometric units [6-7,13,18,20].

b. Indirect Responsibility

(1) New Legislation

The preceding citations stressing cooperation with other government agencies convey renewed significance after the recent passage of several pieces of Federal legislation: "The Federal Hazardous Substances Act", 15 U.S. Code Chapter 30, The Radiation Health and Safety Act of 1968, Public Law 90-602, and the Occupational Safety and Health Act of 1970, Public Law 91-596. This significance for optical radiation measurement at NBS follows.

The "hazardous substances" referred to in the U.S. Code include: "any substance or mixture of substances which (i) is toxic, (ii) is corrosive, (iii) is an irritant, (iv) is a strong sensitizer, (v) is flammable or combustible, or (vi) generates pressure through decomposition, heat, or other means, if such substances or mixture of substances may cause substantial personal injury or substantial illness during or as a proximate result of any customary or reasonably foreseeable handling or use, including reasonably foreseeable ingestion by children." This act provides for the removal from commerce of substances found by the Secretary of HEW to be hazardous. The lamp industry is already concerned about the compliance of some of its products [5]. As the biological effects of ultraviolet light become more widely recognized many other conventional lights may be brought shortly under this legislation. In addition, eye damage produced by flash lamp radiation in the IR, may also be recognized within the foreseeable future [20]. Laser damage will be of increasing concern. Provision has already been made for the monitoring of hazardous substances.

The Radiation Control for Health and Safety Act of 1968, Public Law 90-602, also implies a similar major new thrust of government concern and government action. It covers "any manufactured . . . product which . . . acts as part of an electric circuit and emits . . . ionizing or nonionizing electromagnetic . . . radiation". The Secretary of HEW is authorized to "plan, conduct, coordinate, and support radiation research" . . . to minimize the emission of . . . unnecessary electronic product radiation" and to "consult and maintain liaison with the Secretary of Commerce . . . on techniques, equipment, and programs for testing". HEW is to monitor "measures to assure consistent and effective control of the aforementioned health hazards" and to "invite the participation of other . . . agencies having related responsibilities and interests". "The Secretary of HEW shall by regulation prescribe performance standards . . . "and shall give consideration to . . . "the adaptability of such standards to the need for uniformity. "In case of actual controversy . . . any person who will be adversely affected . . . may at any time . . . file a petition with the United States Court of Appeals". Provision is made also for inspection of testing procedures.

With the increasing public concern for biological effects of radiation, both of visible and of near visible ultraviolet described later, these provisions indicate a substantial growth in radiometric expectation. This will evolve into support service requests in the next few years.

Finally, the Occupational Safety and Health Act of 1970, Public Law 91-596 notes that "occupational health standards present problems often different from those involved in occupational safety". The Secretary of Labor is responsible for assuring that "no employee will suffer material impairment of health or functional capacity even if such employee has regular exposure to the hazard dealt with by such standard for the period of his working life". Provision is made for complaint by any employee and subsequent investigation by Labor. "The United States district courts . . . have jurisdiction, upon petition of the Secretary to restrain any conditions or practices . . . If the Secretary arbitrarily or capriciously fails to seek relief under this section, any employee who may be injured by reason of such failure . . . might bring an action against the Secretary". Initiative is thus in the hand of the general public as well as in the Federal Government. Penalties are also prescribed.

Action may come more quickly than expected in this growing area of biological interaction with radiation. The Secretary of HEW is empowered here also to "conduct . . . research . . . relating to innovative methods, techniques, and approaches for dealing with occupational safety and health problems". The National Institute for Occupational Safety and Health is created by this act "to develop and establish recommended occupational safety and health standards". The Secretary is empowered to "develop and maintain an effective program of collection compilation, and analysis of occupational safety and health statistics", a provision which could place very great burden on radiometric capabilities. One initial effect of this legislation is already apparent in requests from NIOSH for calibration [21].

In addition, NBS as an employer will be expected to "establish and maintain an effective and comprehensive safety and health program".

If the anticipated connection between radiometry and medicine is shown to be as close as present experiments suggest, the indirect statutory obligation that NBS is acquiring will strain the present capability for measurement far beyond its design performance.

Measurements now made with primary concern for great reliability do not lend themselves readily to massive, inexpensive repetition and extension.

(2) Secondary Calibration Laboratory Support

The NBS has not been able to meet all or even most requests for calibration and other technical assistance. Commercial calibration laboratories have been founded to fill the gap. But the performance of these laboratories has not met the requirements of the marketplace. Discrepancies are common [6]. This whole small industry must depend on NBS not only to stay in business but to provide more consistent service. Some sort of direct NBS assistance will be called for. This aid will probably take the form of measurement intercomparison and the dissemination of techniques. NBS will also have to be prepared for a formal request for the establishment of an accreditation procedure [22].

3.2 Technological Issues

Although the recent rapid growth of electro-optics technology was illustrated by a few examples in Section 2, the specifically technical implications of this development should now be examined in more detail. The public interest and finally the commercial implications of this technology will then be examined.

a. New Lamps

In the traditional lamp industry two types of lamps are replacing incandescent lamps: fluorescent lamps for inside use and high intensity discharge lamps for outside use. Fluorescent lamp measurement is not new. Nevertheless, except under special circumstances that cannot economically be extended, the level of measurement agreement among lamp companies, 5-22%, is presently intolerable [23]. High intensity discharge lamps are so much more difficult that NBS is not in a position to measure them at all.

One source of this difficulty lies in the greatly differing spectral distribution of discharge lamps both from each other and from incandescent lamps. Typical spectral power distributions were illustrated in Plate 1. The photometric system had performed barely satisfactorily for incandescent lamps, whose spectral distribution could be roughly matched with one another by adjustment of the filament power. This flexibility is no longer possible for discharge lamps. In addition, differences in shapes and in sensitivity to operating temperature sensitivity, as well as other factors, also cause fluorescent lamps to strain the traditional photometric system [8]. The resulting disagreement is an order of magnitude larger for fluorescent lamps than that for incandescent lamps [23]. High intensity discharge lamps, whose spectra consists largely of spectral lines, now strain the system to the point that routine measurements have not even been attempted at NBS. The difficulty arises here primarily because of the dominant spectral lines and high levels. So many different lamp types are now on the market [8] that a full set of direct substitution standards is no longer feasible.

The higher UV output of these lamps is an additional new factor in their measurement. Moreover the potential public health influence of this output, as described later, is expected to lead to increasingly tight Federal regulation, either under the legislation just described or by new laws.

Light emitting diodes present problems similar in character to those of the high intensity discharge lamps: spectral distribution and level. The level involved here, however, is not higher but lower than normal [3-7; app. A]. As noted before, these diodes promise to replace all low level signal lights, a potentially very great usage.

b. New Detectors

Until recently most light detectors have been so unstable both in spectral sensitivity and in total response that they could be used only as comparative devices. That is, they could compare reliably only similar sources. Moreover, measurements had to be made in rapid succession. With many new types of detectors these limitations are now becoming less confining however. The spectral sensitivity of new solid state detectors is now sufficiently stable to make worthwhile reliable measurement with accuracy and precision [7,9]. Silicon diodes are being widely used in the visible and near infrared. A wide variety of new diodes is being used throughout the infrared, where technology is moving very rapidly. New vacuum diodes and multipliers with photocathodes of III - V compounds such as galium arsenide are highly sensitive and display a relatively flat spectral response in the visible, an exciting development [10].

This new technology presents new demands on NBS for characterization and measurement. But these developments also provide new opportunities for new technical solutions to radiometric problems.

c. New Instrumentation

Optical instrumentation is also developing very rapidly. Beyond the obvious problems associated with the fidelity of color TV as presently produced, for example, new technology for TV picture reproduction is on the horizon and will require new techniques. Liquid crystals are one promising approach [19]. Thin film electroluminescent surfaces are another [24]. The development of low level imaging tubes has outstripped the ability to measure their gain accurately. A measurement capability is now desirable; it will become necessary [25-26]. Recent developments in the film and camera technology are leading to requirements for 1% measurements [27], and new radiometric standards [2,18,28].

With recent technical advances, then, better standards are indeed required to support continued technical growth [2]. Recent developments in all of these fields also make possible new solutions to radiometric problems, but their effective utilization will require a major new effort.

3.3 Public Issues

a. Public Health

(1) Phototherapy

The relationship of radiometry to health has been noted by George Zissis, Chairman of the NAS-NRC Radiometry and Photometry Evaluation Panel [29]. A review of a number of biological effects of lighting has appeared in the MIT Reports on Research for April 1970 [30]. The jaundice that occurs in 10-20% of premature infants [31], if allowed to persist, can cause permanent neurological brain damage [32]. It is treated now by phototherapy [33]. The herpes virus infections that cause cold sores and the genital area infections that often precede cancer of the cervix are also responding to such treatment [34]. Another direct effect of light is seen in calcium absorption in elderly men. The amount of absorption has been shown to be a function of the lighting environment [35-36].

Indirect effects are also observed. A number of neuroendocrine functions both by humans and animals have been shown to be so controlled. For example, the effect of illumination level and duration on gonadal size has been shown [37-39]. The working ability of school children has been shown to be affected by the spectral distribution of room illumination [40].

Wurtman and Neer have editorialized in the New England Journal of Medicine: "perhaps it is not too early to suggest than an appropriate Federal body give thought to the ultimate necessity of regulating the spectral composition of commercially available light sources . . . It seems safe to state that, whether we like it or not, light is another thing that physicians must worry about" [41].

NBS now has no geometrically total flux standards or techniques in the spectral region probably of greatest importance in biological activity 200-400 nm.

(2) Clinical Analysis

A separate medical issue is the increasing interest in spectrofluorescence as a new tool in clinical analysis. Professor G. A. Crosby stated in a recent symposium at NBS that he had received over 500 requests for a recent unquantitative article of his on quantum yields in fluorescence. Most of these requests were from hospitals, with which he had had virtually no previous contact. The development of this promising chemical analysis field, in contrast to transmittance or reflectance measurements, will depend on accurate radiometric standards.

The Task Group for Industrial Activity of the National Academy of Engineering feels that: "Standards for and acceptance of uniform clinical evaluation procedures required for successful development and marketing of biomedical products have not been achieved [42].

b. Public Safety

Three general areas of increasing importance will depend on new capability in radiometry.

(1) Atmospheric Transmission of Ultraviolet Light

"It has been suggested that the emission of oxides of nitrogen and possibly water vapor [by the SST] may reduce the ozone content of the stratosphere. Since ozone plays a vital role in screening undesirable ultraviolet radiation from the sun, any significant reduction in ozone is viewed with concern. Indeed, several alarming estimates of increased skin cancer have already been made public" [43]. Accurate measurement of this radiation thus assumes great importance.

(2) Biomedical Engineering

The regulation of germicidal, sun, and ozone-producing lamps under the Federal Hazardous Substances Act has been noted above. In addition, the Task Group for Industrial Activity of the National Academy of Engineering has listed a number of questions that imply a strong probability for future governmental activity involving radiometry. This Group notes that "the question of medical device safety and efficacy has been repeatedly posed. The high possibility of device safety legislation being passed in the near future . . . causes industry to be very concerned about this topic. That an appropriate type of governmental regulation and control is needed is not challenged by responsible industrial leaders . . . The Task Group recognizes these valid concerns of industry. Because of the critical nature of many products in direct contact with the patient or used in the diagnosis of diseases, however, there must be greater assurances than that currently available that adequate protection is given to persons exposed directly or indirectly to biomedical products or services . . . There is an urgent need to develop a rational program that includes procedures for the development of standards" [42].

Not only the National Academy of Engineering but, at the operational level, secondary calibration laboratories are already feeling the pressure of biomedical problems [7].

(3) Transportation

The increasing public concern for safety in transportation and particularly for highway safety has led to the transfer of safety monitoring from the states to the Federal Government.

This transfer is leading to the instigation of new highway lighting research and to new regulation, e.g. for headlights [44]. These will replace the flexible Society of Automotive Engineers (SAE) agreements. At one research institute research is in progress on optimum automobile illumination, both for a driver's own car and for those he meets on a highway. These measurements are being taken with a single instrument and without reference to NBS standards. Thus equipment made to comply with the new Federal regulation based on these experiments may not duplicate the optimum lighting conditions actually found.

This particular issue is an example of a requirement for photometric standardization that is not recognized as a problem even by those responsible for it. More generally, this is an important aspect of the increasing Federal activity in regulation. Those with new measurement responsibility do not always recognize the severity and complexity of the measurement and standardization problems. Without NBS cognizance, new regulations can be written that bear very little resemblance to the research data on which they are in principle based. Such regulations could be a danger to public safety, not its protector. Surely, if the potential hazards were not severe, no regulation would have been required in the first place.

The shift in responsibility from the SAE to a Federal agency implies two future trends. It foretells a tightening of the specifications. It also will mean the first monitoring for conformance of production to specifications. Partially in response to this movement, industry is developing new photometric capability [45]. This capability will create new demands for measurement.

As noted in Section 2 photometric problems in transportation have been aggravated not only by regulation, but also by the new technology itself. One example is the development of new red plastic signal light covers that differ substantially in character (spectral transmission) from the former glass covers. This difference makes obsolete the formerly satisfactory techniques of color monitoring used when only one type was available. To support this new safety-related technology, far more sophisticated techniques will be required [16].

Low level signal lighting measurements are related to other widely recognized safety problems. One consequence of such problems is the expensive rejection of a major fraction of signal panels for aircraft cockpits because these parts fail to conform to present tolerances [46], tolerances that are believed to cause difficulty in aircraft guidance. Dark adaption of the pilot must be protected so that he can see external objects; he must also see the inside panels distinctly.

c. The Energy Crisis

The rapid and increasing growth in the use of energy in this country is now front page news [47]. It has also been well documented [48-50]. Our per capita rate of consumption of energy is increasing at a time when the availability of sources of power is becoming questionable [51]. The Chairman of the Atomic Energy Commission has predicted the probable eventual rationing of electricity [47]. The efficiency of utilization of available power is thus now a matter of great importance.

<u>Approximately one quarter of our electricity consumption is used for lighting</u> [51]. It is here that precise light measurement becomes significant. The efficiency of lighting has increased from 15 lumens per input watt for standard incandescent lamps to 50 lumens per watt for early fluorescent lamps to 75 lumens per watt for typical modern fluorescent lamps and more than 100 lumens per watt for the most efficient "high intensity discharge" lamps. Some of this progress has occurred in steps, with the introduction of new lmap types. But the 50% increase in efficiency of fluorescent lamps and advancement in other lamp types has occurred in small steps over a long period of time [52-53]. The technical ability to evaluate such improvement depends strongly on the stability of reference standards. Not only an industrial standard is involved. Stability is required in all standards to which reference is made.

In addition to the necessity to detect reliably small increases in luminous flux, <u>the absolute total luminous flux of different new types of lamps must now be intercompared on a common basis if the superiority of advanced types is to be demonstrated reliably</u>. This capability does not now exist. The issue here is not narrowly commercial, although it has commercial implications that will be examined later. The strong balance of payments implications of improved lighting efficiency will also be explored later.

d. Meteorology

Meteorology [29] is more limited by present radiometric capability than probably any other technical field. Conversely, it can make proportionally great progress with better radiometric measurements. Radiometric information with an accuracy of 1%, but with a long-term precision for the detection of changes of 0.1%, is being requested. Both of these requests are now beyond the state of the art [13] although not beyond achievement within a modest period of time given the appropriate determination to do so.

Ten percent discrepancies are apparent, for example, between Japanese and American atmospheric profile measurements [54]. Such discrepancies and the even more serious lack of global data have caused the World Meteorology Organization to take action [55]. New international attention through the Global Atmospheric Radiometric Program (GARP) has been focused on the physical collection of the proper amount and distribution of data now unavailable.

Even within the U.S. serious discrepancies in data from the pyranometric network remain [56-58]. The projected requirements can be achieved only by very few institutions such as NBS with a proper variety of technical resources to make the necessary progress.

Three areas of meteorology will be affected by improved radiometric capability. First, short-term weather forecasting depends on radiometry for atmospheric temperature profiles and indirectly to check mathematical models of the atmosphere. The validity of a short-term forecast depends on the sophistication of the mathematical model used and also on the reliability of the measured temperature profiles of the atmosphere. That is, the more accurately the temperature distribution is measured, the more accurately the local weather can be predicted [58]. Such measurements were not feasible on a broad enough scale to make a substantial impact before the advent of weather satellites. But these satellites present revolutionary opportunities for large scale sophisticated measurements such as the temperature profiles. These measurements in turn will lead to more reliable models. Before this promise is realized, however, new technical problems will have to be solved. Calibration in flight will have to be consistent with ground-based observation. Accuracy is involved here and not mere stability or precision.

In contrast to short-term weather forecasting, long-term weather projection depends on the global heat balance, i.e. the amount of heat incident on, absorbed by, and radiated from the earth. It is the heat absorbed by the atmosphere that "drives" the weather. Thus measurements by satellites must be accurately correlated with ground observations to provide a meaningful measurement. Long-term drifts cannot be tolerated.

An issue closely related to natural long-term heat balance changes is the influence of pollutants. To detect such an influence, reproducible measurements over a period of years are required. Time is running out for the initiation of such measurements. This question is critical at the 0.1% level because of the lead time for effects to become manifest. Time is required also for controls to be instituted.

NBS has completed the initial phase of work applicable to this goal. However, much more remains to be done. The value of this work has been noted by Robert White of NOAA [55].

e. Pollution Monitoring

The field of pollution is so large and moreover so rapidly changing that a quantitative definition of future requirements is much more difficult than in other fields. Nevertheless, the potential payoff for a development of radiometry here is so great that it is worthwhile to examine [29,59]. Although interrelated, air and water pollution may be separated here for this analysis.

Air pollution at the top of the atmosphere has been indicated to be of significance because of its potential for long-range climate modification [60]. In addition, pollution introduced at the bottom of the atmosphere may have a short-range immediate effect, both in space and in time. Although work in this field is just beginning, crude radiometric and photometric techniques are already being used [61]. These will have to be made more precise and accurate. They will have to be placed on a continuing basis and provision made for rapid response levels that suddenly become hazardous. Such an evolution is technically possible. Pollution experiments on aerosol monitoring are already taking place in Boulder in a joint NOAA-NCAR effort [62].

The influence on the upper atmosphere chemistry of potential supersonic transportation was examined by Harold Johnston recently [63]. The implications of the changes produced in transmitted solar energy on life were so great [43] that a National Academy of Sciences panel was convened to examine the subject. This panel observed that "the importance of obtaining base line data [of the solar ultraviolet flux] in advance of any era of substantial pollution needs to be strongly emphasized" [64]. The technological challenge to radiometry both quantitatively and qualitatively is enormous. Primary work in this area is now being proposed by NOAA. NBS has been asked to be of assistance: "NBS calibration assistance is vital to a successful endeavor" [43].

Water pollution is another large area of concern. Thermal pollution particularly is susceptible to radiometric monitoring [6,51,65], but the challenge is increased by relatively high levels of atmospheric humidity. Other types of pollution are also susceptible to monitoring [66] through their characteristic spectra. The opportunity that space observation offers in this area is large. The corresponding challenges to radiometry will be great.

f. Remote Sensing

The field of remote sensing is a technological tool applicable to a wide variety of ultimate social uses. Some of these were covered in the preceding sections on meteorology and pollution monitoring. Remote sensing involving optical radiation promises to transform these fields. In addition, however, other uses are also foreseen [29]. These potential applications are collectively so important that the Panel on Science and Technology held a review of this field in January 1972 before the House Committee on Science and Astronautics. The paper of Thiel and C. D. Graves prepared for this Congressional review is included here [67]. Thiel and Graves note that by the most conservative calculation the benefit from remote sensing will be $59 billion. About half of this will accrue to agriculture in stress analysis, meaning for example, crop disease, infestation, and meteorological influences on agriculture. The other half is distributed among human disease, agricultrual inventory, fishing, animal disease, natural disaster, solid waste disposal, resource management, mapping, tax assessment, search and rescue, geophysics, water pollution, forestry, nautical charting, ship routing, and air pollution. The savings in the last field at $1 million are the smallest of those mentioned.

Performance specifications of current NASA earth resources observational components have not been determined by the quality of the data that would be effectively utilized by these various fields, however. It is limited by the necessary constraints placed by the state of the art of radiation measurement [68]. This is a case in which the limitations presented by the state of the art are indeed costing a substantial, but as yet undetermined, amount.

The launching of the first Earth Resources Technology Satellites (ERTS) this spring will provide the second NASA earth observation system. The data produced by the first system, the "Michigan Scanner", will then be comparable directly with other NASA data for the first time [69]. Initial comparison will present an interesting test of the degree of correlation of remote sensing data produced by equipment that has seen minimal laboratory calibration.

The specific limitations of this data for use by the Department of Interior and the Department of Agriculture will probably become evident only after several such platforms are in operation. Private concerns operating from airplanes over a long period of time are already suffering from the lack of standards and have requested general assistance from NBS [66].

This field is still in its infancy. Its growth is widely believed to be hindered by its ability to demonstrate economic accomplishment. This in turn is very likely limited by the performance of the systems themselves. These in turn are limited by the state of the art of practical radiation measurement [68].

One of the most promising techniques in much of the accessible spectral region, the infrared, is Fourier spectroscopy. The application of this technique to remote sensing is probably only a question of time. Development of this field presents an opportunity for NBS to work at measurement frontiers of immediate utility.

g. Crime Prevention

The issue of crime is relatively straightforward: there seems to be a direct correlation between effect of street lighting and the incidence of crime [70]. A variety of statistics indicate that crime has decreased 30-40% in streets where new more intense street lights have been installed. The new highly efficient lamps are of a type that NBS is not now able to measure reliably. Inauguration of manufacture of these lamps by several companies produces commercial incentives for measurements as well as the social and technical ones.

h. Botany

The small, but presently growing interest among botanists in the influence of light parallels the growing interest of the medical profession and photobiologists [71]. This new interest in the influence of light on plant growth will indirectly create a demand, not only for new lamps and their measurement, but also for simple but reliable spectroradiometers and their calibration.

3.4 Economic Issues

The economic issues that derive from optical radiation measurement are first of all questions of productivity: unit cost, quality control, product improvement, and product innovation. These, however, in turn bear also on equity in domestic trade in a manner that affects the consumer's ability to make intelligent choices. Foreign trade and the balance of payments also will be strongly affected.

a. Unit Production Cost

Unit production cost is a basic industrial concern. Indeed this issue probably more than any other is immediately responsible for the great industrial concern recently for improved optical radiation measurement. A lamp industry technological forecast notes: "Growth stimuli in the market will include . . . improved lighting economics" [72]. A product testing group is currently looking at its own program activity within the framework of the widely disseminated internal slogan, "Best Buy Our No. 1 Goal" [73]. The lamp industry in fact sells efficiency, as illustrated 22 February 1972 in the Wall Street Journal [74]. Such a marketing approach is demonstrably not in vain. Special 96" fluorescent lamps with a 10% greater efficiency than normal production for one manufacturer are sold by him for an approximately 10% higher price than that for his conventional lamps.

Productivity or efficiency, in turn, is greatly affected by present measurement techniques. In general, insufficient and discrepant measurements may add hours to a given measurement [4]. The absence of confidence between the lamp industry and other producers who incorporate lamps into their own products is now so pronounced that a number of these lamp-buying producers are installing new acceptance testing laboratories at great expense. This expense is, of course, paid indirectly by the purchaser of the end product [76]. Moreover, this solution has aggravated another problem in efficiency: the maintenance of several different unit sizes. For example, a Kodak lumen may differ from a Xerox lumen [8]. Both must be maintained by suppliers at added expense. In addition, purchasers of lamps will pay indirectly for the extra costs of a supplier whose production is rejected by another purchaser. A similar problem of even greater magnitude is that faced by LED manufacturers in their rapid growth stage [4,6]. The LED problem is part of a more general low-level problem [app. C]. Productivity problems traceable to measurement are being faced by the laser industry as well. Photodetector production costs also depend on measurements [6,18]. In addition the cost of complete radiometers, a growing industry, is being affected by current measurement problems [app. A].

b. Quality Control

An issue closely related to unit product cost is quality control. Some of the major components of the electro-optics industry both individually and together have testified that present quality control in the industry is being affected by the state of optical radiation measurement. The photographic industry is being adversely affected [14,18; app. A]. The laser industry is also affected [77].

c. Product Improvement

Reference has already been made in the section on the energy crisis to the fact that improvement in the efficiency of lamps has come in small steps [52,53]. It was shown in that section that improved capability in measurement is of great significance here and bears directly on improvement throughout the industry. Improvement in radiation measurement techniques will also influence photodetector development [10].

d. Innovation

The rapid growth of the electro-optics industry described in Section 3 is based primarily on innovation. But in addition to the technical implications of this growth already discussed, the commercial value of innovation should be noted also. This value determines commercial consequences of the related measurement problems. The rapid growth and commercial promise in light emitting diodes, for example, has been cited [3-5; app. A]. The influence of measurement on the commercial development of the rapidly innovating infrared industry has been noted [6]. The connection between innovation and measurement precision in the photographic industry, particularly in connection with camera automation, has been noted in conversations between NBS and the Physikalisch Technische Bundesanstalt [78]. The commercial importance of new discharge lamps has been observed [74] as well as of new detectors [10].

e. Equity in Trade

Equity in trade, a dominant issue with those who turn to NBS for assistance in optical radiation measurement, involves three separate factors.

(1) The Consumer's Concern with Technical Data

The consumer can be the "little old lady" comparison-shopping in the supermarket, the "commercial and industrial" purchaser, or the "original equipment manufacturer" [8]. These last two groups account for 60% of the market in the lamp industry. They are exceedingly cost-conscious. The consumer, primarily large but also small, currently has technical problems of three types derived from measurements. He has problems of equipment compatibility. He has the efficiency problem of dealing with various manufacturers employing discrepant units [8; app. D, app. E]. In addition, he sometimes needs to compare a commercially derived number with a natural or more purely scientific one. An example is a comparison of artificial illumination with natural light [5]. Commercial optical radiation measurement must be more firmly based than at present to be comparable with other measurements. Measurement problems are particularly severe in the ultraviolet.

(2) Government Purchasing

GSA purchasing of light bulbs is of importance not only to economy in government. Government purchasing is substantial enough to affect the lamp industries themselves [52]. The leverage that it exerts affects the entire market, particularly the purchases of other governmental agencies, state and local governments.

(3) An Orderly Market

The issue of an orderly market in lamps, photodetectors, or other instruments is different from that in a government regulated market such as gas-flow or electrical-power meters. With the diversity of the electro-optics industry, an important question is, "are competing values comparable?" Manufacturers both large and small in the lamp industry feel that they are not [8,52]. Rather than seeing a potential commercial hazard in new measurement capability, the industry is looking to NBS for assistance [app. E].

This remarkable industry interest in greater activity by the NBS in part stems from actual experience in that the lamp companies have had, in some cases, to derive independently their own luminous flux assignments. The result on the market is deplored by all concerned.

With the development of new high intensity discharge lamps, the absence both of NBS standards and of accepted procedures necessarily lead to a separate discharge lamp lumen for each manufacturer.

The thrust of industry concern here is not: U.S. Government, stay away; but rather, NBS please help! [app. E].

f. The Balance of Payments

The present adverse balance of payments is widely recognized. Secretary Stans pointed out in his testimony before the Subcommittee on Science on 27 July 1971: "The major element which we can influence decisively for the long run is the level of technological development. It may be our only hope of maintaining a future trade position adequate to support our balance of trade payments in years to come" [79].

But the Secretary noted also: "From 1950-1965 our productivity growth rate trailed Europe by 35% and Japan by 60%. The trend since 1965 shows an even more rapid relative decline: United States rates trailed Europe by 60% and Japan by 84%" [79].

The high technology electro-optics industry is growing very rapidly in this country and abroad [1]. As demonstrated above, American productivity is affected by measurement capability through unit product cost, quality control, product improvement, and innovation.

The instrumentation industry as a whole is concerned with foreign trade expansion. "There will certainly be an unfavorable foreign trade impact if electro-optical devices of U.S. manufacture cannot be relied upon to yield uniform NBS traceable quantities. The cost impact in this area can easily run into millions of dollars" [4]. A working group of the Council for Optical Radiation Measurement has also noted: "discrepancies on an international basis, which have occurred, result in lost sales and decreased exports" [app. A].

The light detector industry is also involved. "We expect . . . to measurably enhance our position in both domestic and foreign markets. The latter is an area where our competitors, largely nondomestic, have made serious inroads . . . Recent developments in the international monetary scheme are a great assist, also, and your efforts in resolving the problems outlined above will help solidify our international position of leadership" [10].

A working group of the Council for Optical Radiation Measurement notes "the lack of standardization of calibration methods and standards among manufacturers and users of light emitting diodes and displays". It cites as an important concern the "very large market domestically and internationally" [app. A].

The photographic industry is likewise concerned: "Lamps are calibrated for our associated companies throughout the world" [80]. "International trade depends on the world-wide acceptability of such measurement" [14].

The working group on total flux measurement of the Council for Optical Radiation Measurement with representatives of the lamp industry notes that "many purchases are made on the basis of promised performance. A difference of one or more percentage points in promised performance will, therefore, determine the business to be done, either domestic or foreign, by a given manufacturer or even by an industry. This can run into millions of dollars" [app. E].

"One company in the lamp industry, at least, has run into the fact that their lumen levels, for some, if not all lamp types, are different by several percent as compared to this country. Sales of our industry off-shore have been slowed down because the European lamp manufacturers are talking loudly about the inflated lumen level of the United States products. Under such conditions, especially in a competitive business, it is very difficult to grow much of a market at least in Europe where a considerable effort has been expended" [8]. "If we are to export lamps, our foreign customers must again know that Boston lumens are the same as Paris, London, Tokyo, or Istanbul lumens" [52].

The lamp industry is sufficiently concerned enough about international measurement agreement as it expands its markets abroad to be sending its measurement people abroad after its sales ads [81-82].

3.5 Scientific Issues

a. An Opportunity

The rapid technological development already described leads to scientific opportunities that did not previously exist. The promise of Fourier spectroscopy, for example, has only begun to be realized in science as a whole. It has not yet been applied to quantitative radiometric measurement of scientific interest. It is much faster, more sensitive, and less noisy than other techniques. It also averages entire spectra simultaneously, a great advantage in drifting and fluctuating systems.

Every object radiates: this is useful information for material characterization, always about the state of the surface and usually about the internal state of the systems as well. The opportunity to acquire and evaluate this knowledge rapidly and with much less noise than previously will permit realization of new opportunities. If it is to be exploited fully for material characterization it must be evaluated quantitatively. Remote sensing of the earth is one area of immediate application.

b. "One-shot" Experiments

One area of opportunity to which radiometry is of great importance because few other tools exist is astronomy. This field has been transformed by the utilization of satellites outside the earth's atmosphere. But calibration problems have been intensified. Satellite measurements made by the Smithsonian Observatory differ by a factor of three from those made by the Naval Research Laboratory [83]. Evaluation of the solar and other stellar spectra in the UV will be held up until such uncertainties are clarified. Large amounts of money are already being spent on such programs and the scientific payoff will be far greater, with relatively little increase in cost, with more sophisticated radiometry.

c. Atomic Physics

In addition to the new spectacular space spectroscopy, cross section data in atomic physics is still being limited by the accuracy of radiometry [84]. Relatively large amounts of time are now being spent on reducing the uncertainties in radiometric measurement to the level of other limiting parameters in these measurements.

Conventional astronomy and earth-bound stellar astrophysics are sufficiently concerned about the status of radiometry that a recent symposium on astronomy devoted nearly one quarter of its time to a review of recent developments in radiometry [85]. This concern reflects both the limiting nature of the present state of the art and great interest in its advancement.

4. ALTERNATE SOLUTIONS

These are the impact areas of optical radiation measurement and some of its implications. The question now is, "Why not leave the solutions to those who are most affected?" There are both technical and nontechnical reasons for not doing so.

4.1 Technical Factors

Each radiometric measurement is extremely complex. There are in fact, four sets of parameters to be controlled or evaluated: spectral, spatial, temporal, and polarization. To understand and control these four parameters the radiometrist must be highly trained in optics and heat transfer. He must also be experienced in these and other fields. An exhaustive examination of each of these parameters even by an expert is expensive and time-consuming. At some point, of course, even the most careful worker must make a compromise. If this compromise does not occur in the initial measurements then it will reduce either repetition or the systematic variation of all parameters. But even the simplest measurement requires intelligent compromise. The technical difficulty is further complicated by the lack of commercial instruments available to evaluate many parameters. Ultimately the development of technology in this area will make a new generation of instruments possible.

A large investment in time and effort is thus now required in order to make independent measurements that are reliable and comparable with other independent measurements at the 1-10% level. For example, one must select and characterize his detector for these four parameters. He must select and characterize his electronics. He must select and characterize his sources and then his optical system. Since generally accepted techniques and highly accurate commercial equipment is rarely available, he must usually develop or evaluate these himself. Moreover, he will also have to attenuate either the beam to be measured or that from a standard; his attenuation techniques will have to be characterized as well.

In short, the independent worker is left to work without any comprehensive assistance either in equipment or techniques. The independent development of comprehensive expertise in every laboratory making photometric and radiometric measurements is an impossibility for most companies in this industry. It is an uneconomic solution even for the large ones.

4.2 Nontechnical Factors

Large companies are not reluctant to spend considerable sums in the optical standards area. Indeed they are doing so through automation in this field. But they are not making so much of an investment in technical development. -- Why?

Being right is not enough in the highly competitive field of optical radiation measurement. The really important question is, "Does my measurement agree with another institution's?" If I am selling, "Does it agree with that of the purchaser?" If I am buying, "Does it agree with that of the seller?" If I am being regulated, "Does it agree with that of the regulatory agency?" In a bilateral situation, agreement based on an adjustment can generally be made. But the typical market and its regulation involves many different agencies.

The development of a complex system of bilateral agreements among companies to enable them to deal with the real market situation has been forced, but it is uneconomical. It is uneconomical in terms of the number of measurements required. It is uneconomical in the maintenance required of separate units of varying size. It is uneconomical in the effort required for identification of sources of the differences in measurements. The cost even of rejected purchases is borne by other purchasers who come along later. It is uneconomical in productivity. The international consequences of this reduced productivity are both more evident and more severe than the domestic ones.

There is also the legal question. In all photometry and in all radiometric areas contingent on Federal activity, the basic legal question is not, "Is it right?", but rather, "Does it agree with NBS?" This necessity for agreement means that norms must be selected and values adjusted to them. Particularly when a complex system of bilateral arrangements is illegal, industrial investment in expensive competence will not purchase legality.

Thus even the largest companies will not be inclined to make a major investment or expenditure where agreement with the next fellow is paramount.

4.3 Other Agencies

The coordination of other Federal Agencies with NBS is really a part of the preceding consideration -- agreeing with others. In photometry, legal measurement must always be coupled with NBS. But for radiometry in government purchasing and for regulation through HEW and DOL, an identification with NBS measurement is also highly desirable. In order to preserve Federal measurement credibility, it is essential that Federal agencies have coordinated measurement facilities. Without a proper NBS system, a GSA lumen or a DOT candela will necessarily come into existence.

4.4 Synopsis

To recapitulate, therefore, both technical complexity of optical radiation measurement and the need for comparability and interchangeability dictate a unified solution to the presently severe optical radiation measurement problems.

5. THE ROLE OF NBS

5.1 What Needs to be Done

A nationally centralized competence in optical radiation measurement is highly desirable for two purposes. First it would provide for the most economical solution to problems in the characterization of complex optical radiation components and systems. Secondly, it could also provide a framework for the achievement of uniformity in such measurements on a national basis.

a. The Characterization Required: Research

The research endeavor implicit in the foregoing review of the issues involves three separate problem areas: 1) source characterization, 2) detector characterization, and 3) the characterization of certain general problems in radiometric technique.

The first two problem areas involve the following separate steps:

(a) Realization of a scale

(b) Transfer of the scale to secondary standards

(c) Development of techniques for the extension of these standards to dissimilar measurement objects.

The output of the first two steps includes both hardware and software. That is, it includes the derivation and characterization of objects. It also includes the development of techniques. The output of the third step is almost exclusively software. This software is the description of new techniques associated not with the generation of standards but with their utilization for other purposes.

The third separate problem area focuses on the optics employed both with sources and with detectors. It includes general spectral techniques, diffraction, and attenuation.

(1) Source Characterization

(a) Realization of Scales

The realization of scales in both radiometry and photometry is widely recognized as basic to the NBS mission. In addition, new strong industry desire for the rigid coupling of photometry and radiometry is now evident [6-7,13,18,20].

(b) Transfer to Secondary Standards

(i) Characterization of Present Standards

"Firm uncertainty information is extremely important to us" [11]. "The necessity to provide an estimate of the precision/accuracy/uncertainty for both color temperature and luminous intensity of the individual stages of calibrations as well as an accumulative value" has been considered to be paramount [80; cf. 13]. Once the size of the present uncertainties is recognized in these and other areas, requests follow for a reduction in size.

(ii) Improvement of Present Standards

In the few cases where the uncertainty is already established, the immediate requirement is for its reduction [10]. "The need is that of more accurate radiance and irradiance measurements. The need is for one percent or better standards" [18]. "There is a pressing need for increased accuracy in the N.B.S. maintained (and transferred) standards of spectral radiance and irradiance" [13]. "A standard of spectral irradiance accurate to 1 percent" is desirable [20].

(iii) Description of Procedures for Present Standards

A recent request of one of the working groups of the Council for Optical Radiation Measurement states a widely held desire for, "Provision by NBS of detailed, written description of the methods and techniques through which NBS calibrates standards of spectral radiance, spectral irradiance, luminous intensity, color temperature, etc." [app. F; cf. 13, 86].

Such descriptions are now being initiated by NBS where procedures are already established and preparation of the description is straightforward. However, when a change in standards or procedures is desirable, time spent in preparing detailed descriptions must be weighed against the benefit to be gained from a more immediate improvement of the standards instead.

New types of information are being requested explicitly. One is the influence of the environment on the measurement process [app. B]. A widespread desire [6,8,13,87] for help in the selection of lamps for calibration is evident. This request is particularly crucial with the phasing out of industrial standard lamps manufactured by the main U.S. supplier [7,18].

(c) Extension of Present Standards

The need for a general description of techniques and methods has been recognized: "Because of differences in methods of measurement, a standards handbook would give the basic setup for measurement of radiance and irradiance in the UV, visible, and I.R. range . . . A tutorial treatise should complement the handbook" [18]. Moreover, "NBS should take the steps necessary to provide easy access to existing written descriptions of techniques and methods" [app. F].

Extension in level is of great concern. Extension of irradiance to lower levels has been requested [7,86,88; app. A]. It is stimulated by the advent of light emitting diodes, the general increase in use of low level devices, and the increasing attraction of photon counting as an absolute standard. Conversely, higher intensities are increasingly important as Underwriters Laboratories begins writing specifications for lamps used in photography [15]. Optical system calibration is presenting similar requirements [20]. As lamps become more efficient higher total fluxes are also being generated and must be measured reliably by lamp manufacturers [5].

Extension to new spectral regions and improved standards at the present extremes have also been requested. Infrared is one area where progress is being made but new problems are anticipated. One example is "Extension of blackbody sources to operating temperatures down to 77 K (mainly for the purpose of calibrating detectors employed in the far infrared region)" [13]. "Many problems will develop that are not now recognized [in the infrared]" [6]. Extension of the range to 25 μm has been requested [app. B].

In the other direction, the importance of extending geometrically total flux measurements into the ultraviolet has been noted [5]. This desire will increase as the biological effects of this radiation become more widely recognized.

In addition to work in relatively uncharted spectral ranges, the measurement of light with a nonconventional spectral distribution is a rapidly increasing problem [7,20,87]. Sources with a spectrum similar to daylight have been requested by a working group of the Council for Optical Radiation Measurement [app. A]. Light emitting diode measurement problems are traceable to their new spectral distribution as well as to their low level. High intensity discharge lamps are breaking a total flux measurement system already strained by fluorescent lamps [8]. The problem of spectral lines as well as new measurements outside of the visible are involved. High priority has been requested for the development of spectroradiometric techniques [89].

In addition to the extension of present measurements in level and spectrum a spatial problem has arisen in the infrared. Extended sources need to be evaluated both theoretically and experimentally [app. B; 90].

And finally, the development of new source measurements in the time domain is being requested. Pulsed irradiance and illuminance measurements are required [7,20,87]. Total flux pulsed measurements are also required [app. A].

(2) Detector Characterization

Detectors can be usefully divided into three subgroups: electrically calibrated, thermal but nonelectrically calibrated, and quantum.

(a) Realization of the Scale: Electrically Calibrated Detectors

It is recognized that a series of electrically calibrated detectors is basic. Both because of their self calibration and because of their relative freedom from wavelength dependence they are essential to a detector characterization program [13; app. B, app. D].

(b) Thermal, Nonelectrically Calibrated Detectors

Dependence on many detectors as transfer devices has been hindered by the absence of reliable characterization techniques. An electrically calibrated detector can in principle be used not only as an absolute standard, but as a tool to characterize gray detectors for spectral response. Such a capability is badly needed both for conventional radiometry [6,11; app. A] and for laser measurement [app. G].

(c) Quantum Detectors

Quantum detectors have not yet reached sufficient development to qualify as absolute photon counters. In general they are not gray spectrally either. Nevertheless, the recent development particularly of solid state photodiodes has led to high stability and sensitivity that make them attractive as secondary standards. A new approach to photometric units, based as the units themselves are conceptually on an "idealized" detector approximating human visual response, is particularly attractive in principle. Characterization of promising new photometric detectors has been urged [87-88]. Characterization of spectral response is particularly desirable [7,13, app. D]. Temperature sensitivity is another area for attention [app. D]. The evaluation of linearity and performance at low levels is basic [app. D]. And finally, the examination of time response and utilization of detectors for pulsed measurements has been urged [app. D].

(3) Characterization of Certain General Problems

Finally, the evaluation of certain techniques used to make comparative measurements is highly desired. Attenuation techniques are requested very frequently [6-7; app. A, app. C]. Other optical system components that have become the foci of questions are the use of diffusers and integrating spheres in general [7].

A special very important area of general concern is the characterization of spectral techniques not only for spectral irradiance measurements [18] but particularly for use with flux measurements [5,89].

b. Dissemination and Verification

Until the standards and techniques developed by the research program have been applied not only to the internal generation of standards but also to the verification of measurements made in a variety of laboratories, the maximum benefit will not have been realized. A proper research program will lead to economical measurement. But the full practical utilization of this research program will become evident only after the compatibility of measurements has been actually demonstrated among users [11].

The Radiometric and Photometric Calibration Program has been greatly expanded, and twenty-five regularly scheduled calibrations are now routinely available to the public. In addition to the scheduled items, special calibrations are also available to satisfy special needs.

But "of equal importance is standardization of technique for transferring these standards from NBS to the user, regardless of whether an intermediary is used" [10]. Reliable transfer will involve a "method of supplying and checking secondary laboratories issuing standards and calibratee sources", in other words, a "method of specifying NBS traceability" [13]. Such desires almost certainly imply "Determination of suitable intercomparison techniques at the various laboratories, and evaluation of the issued product", that is, "Participation of issuing laboratories in intercomparison" [13]. "Another recommendation would be to periodically have round-robin measurement comparisons between laboratories" [app. C]. "When NBS is unable to provide full calibration services, they should provide some method of guaranteeing that commercial standards labs are providing measurements on the NBS scale . . . Small scale, simple interlaboratory intercomparisons utilizing NBS techniques . . . with NBS acting as referee, would be desirable . . . [app. F]. "Secondary standards laboratories will build detectors and participate inperiodic round-robin calibration exercises with NBS" [app. D].

5.2 Why NBS?

a. Fractionated Market

Two reasons for a centralized national competence in optical radiation measurement were stated in the previous section. The first of these was the diversified nature of the industry involved. Only very few of the companies in this market are large enough to fund the complex research and development required to make competent measurements in this field. The Director has suggested that NBS might "explore ways of aggregating the research and development capabilities of many companies vying for a fractionated market" [91]. Another aspect of such problems in infrared has been described: "In the component area, the documentation procured during the development contract is frequently inadequate to support the procurement of spares later" [12].

b. Agreement Rather than Accuracy

The second issue addressed in the previous section is the need for agreement of measurements in various laboratories. Since being right is less immediately important than agreeing with the fellow with whom one is doing business, a centralized focus for achieving this end has been widely requested.

c. NBS Mission

In addition to these issues which point merely to the designation of the single national laboratory, certain aspects of the Bureau's mission and program lead specifically to its desirability as the proper national laboratory.

The first of these is the statutory obligation of NBS covered in Section 3. The specific NBS obligation with respect to photometric units (visible light) was noted as an important addition to the more general mission cited in the Organic Act. Indirect statutory obligation was also anticipated through increased reliance on optical radiation measurement by other Federal agencies.

In addition, however, other aspects of the general NBS mission, apart from its standards function, are increasingly the focus of attention. The specific impact of strengthening the photon measurement capability on a variety of public issues was covered in Section 2. Most of these bear directly on the overall NBS goal "to strengthen and advance the Nation's Science and Technology and to facilitate their effective application for public benefit" [92].

More specifically, improvement in optical radiation measurement bears directly on the various subdividions of this goal. The general necessity for "promotion of accurate, meaningful, and compatible scientific measurement" has been demonstrated by the number of requests for improvement in the agreement of optical radiation measurements reviewed in the previous sections and included in virtually every letter in the Appendices. Moreover "the more effective use of science and technology" has been called for implicitly both in these letters and in the working group reports of the Council for Optical Radiation Measurement. "The promotion of strength in the economy and equity for the buyer and seller in trade" [92] has been reviewed in detail in Section 3. The impact of such equity on foreign trade balance was noted specifically. This impact follows directly from several other factors that bear on domestic trade as well as in the entire electro-optics industry. "The provision of standards and test methods for protection of the public from specific hazards" is already important in view of the demonstrated effects of ultraviolet radiation and will grow in public concern as this field develops.

The "provision of technical information services" not only through the technical journals but through the new "Optical Radiation News" column of the NBS Technical News Bulletin has drawn a flood of requests for inclusion on the mailing list.

The growth of problems in optical radiation measurement that act as a "barrier to effective use of technology" has been cited by most recent industrial respondents. They are concerned with the application of optical technology both to problems of domestic impact and those of foreign trade. The influence of measurement on this rapidly growing high technology domestic industry is of recognized importance.

The "[promotion of] economic growth through product improvement and [the promotion of] equity in the market place" [29] have been cited in Section 3.3.

d. Past Accomplishment

Does NBS have the competence to perform the needed job?

Its accomplishment in this field is widely known. NBS is the only laboratory in the world that furnishes spectral radiance standards accurate to one percent. It is one of two laboratories that generates its own spectral irradiance laboratory standards. Indeed, many other national laboratories are dependent on these standards for their own work. NBS achievement in the development of electrically calibrated detectors has been widely recognized also [55].

There is abundant testimony to NBS competence: "the state-of-the-art measurements accuracies achievably by NBS" have been recognized [77]. "Ideally, highest echelon standard would be available from a completely objective, impartial source that enjoys the respect of the entire technical community: i.e. NBS" [88].

In addition to acknowledged radiometric competence, the recognized application of sophisticated statistical techniques by NBS permits maximum effective utilization of its technical expertise. "NBS application of sophisticated statistical techniques to the calibration of standards has been a welcome addition to its endeavors" [52], "the work reported in NBS Technical Note 559, 'Spectroradiometry and Conventional Photometry, An Interlaboratory Comparison' [is] a splendid start" [88].

e. Organizational Contacts

The position of NBS on international standards committees places it in the unique position to work for the solution of international problems that concern American industry in this technical area. Its reputation for accomplishment places it in a position moreover to exercise leadership that is very greatly needed internationally.

In addition, the close contact of NBS with DOD technical problems and solutions in this area puts it in a position to secure the application of relatively unknown work to new problems of nondefense interest. This opportunity will be of great importance in the application of IR technology, developed largely by DOD, to a growing civilian activity.

f. Industrial Desire for NBS Activity

In a period of wide industrial concern about the effect of Federal activity, it is clearly remarkable that industry is turning actively to NBS for assistance in research and development in this area: "We look to NBS" [77]. "A U.S. Government-operated laboratory is in the best position . . . and it would again seem that NBS has the best facility to do this work" [52]. "NBS should provide the national focus . . . Industry would much prefer to get this kind of help from NBS" [14].

The enthusiasm for NBS activity extends particularly to the desire for verification, the question of "traceability". NBS has been urged by industry even to inspect its commercial facilities periodically [4]. However, this is an area of expansion that will have to be closely examined before action is taken.

In still another area of its program, NBS has been urged to continue its activity to anticipate future needs: "It is imperative that NBS work with aerospace, medical, agricultural, and other industries to keep abreast of these problems as they occur" [6].

And finally, industry has "voted" with its feet. On 10 February 1972, sixty representatives of industry and government met at NBS to consult with one another and establish a a position for future action. They formed the Council for Optical Radiation Measurement to coordinate the definition of needs, to discuss alternative approaches, to coordinate technical projects, to ask NBS for assistance, and to coordinate activity with other organizations [93].

g. Future Savings

Another factor indicating the desirability for NBS to mount a comprehensive program now in optical radiation measurement is in the influence that this program will have ultimately on savings both in NBS expenditure and in costs to those served by the program. If the present partial gage system of interrelated standards were to be expanded to meet present needs, the impact on future budgets would be increasingly severe. A systematic approach leading to a general solution of measurement problems in this area by application of modern technology will ultimately lead to a more economic solution.

5.3 Present Program

In the absence of increased resources, the program at NBS for the next year or two will be devoted largely to realizing and improving the radiometric and photometric scales required. Only a few of the extensions and characterizations called for in Section 5.1 will be possible.

5.4 Other NBS Resources to be Applied

One resource available to NBS in the development of its program in this area not previously cited is the Optical Physics Division effort in the vacuum ultraviolet. Cross fertilization between these two programs is already taking place. In addition, the presence of a strong statistics competence has been noted; it is a highly valued additional resource. Without it, in fact, a viable program for traceability could not be effectively built.

5.5 Non-Monetary Support

Non-monetary support is present in the form of an industrial research accociate provided by the lamp industry through the Lamp Testing Engineers Conference via the Electrical Testing Laboratories. With the increased development of an NBS program in this area and the demonstration of its competence it is entirely possible that other components of the electro-optics industry will provide similar assistance.

In addition, several companies have already offered to perform parallel experiments and to check new procedures in their laboratories. The use of major equipment not available at NBS has also been offered.

6. RECAPITULATION

Serious measurement discrepancies universally plague quantitative measurement in the electro-optics industry.

These problems arise chiefly through the recent explosive expansion of this industry. It triples in dollar volume in a period of nine years. It now represents substantially more than $10 billion in annual sales.

This growth has precipitated a complex development in the variety and accuracy of measurements required. Virtually each measurement is thus a state-of-the-art study. The distress that the resulting disagreement costs the industry as a whole is growing rapidly. At the same time growth in public concerns that have a strong technical base in this industry are just beginning to find a focus for expression. Resulting governmental activity is undergoing a strong expansion.

The impact of these problems falls in many areas. One is the growth of Federal obligation. The levering on technical development by good measurements here has been acknowledged and documented. Public issues encompass public health, public safety, the energy crisis, meteorology, pollution, agriculture, crime prevention, and a variety of opportunities in connection with aerial surveillance. These latter promise savings of $59 billion in the most conservative estimate. The economic lever of improved measurement operates through unit production cost, quality control, product improvement, and innovation to equity in domestic trade and the balance of payments abroad. Basic scientists have a vocal stake in progress here too.

Leadership by NBS in this area is dictated not only by legal authorization. The fundamental problems are too complex to be tackled economically outside of a national laboratory. Moreover, the necessity for measurement agreement requires the assumption of responsibility by a central agency. The opportunity to lever a large market through technical advancement falls squarely within recent conception by NBS of its mission. NBS has the in-house expertise for the job and the required organizational contacts. The electro-optics industry with one voice is calling for NBS leadership.

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8. APPENDICES

Appendix A. Council for Optical Radiation Measurement: Summary of Comments of the Working Group on Classical Radiometry (III), prepared by Michael Mellon, Chairman.

Appendix B. Council for Optical Radiation Measurement: Summary of Comments of the Working Group on Infrared (IV), prepared by Russell Yokley, Secretary.

Appendix C. Council for Optical Radiation Measurement: Summary of Comments of the Working Group on Techniques including Spectrophotometry (VI), prepared by Jack Coulter, Chairman.

Appendix D. Council for Optical Radiation Measurement: Summary of Comments of the Working Group on Detectors, prepared by Richard Leftwich, Chairman.

Appendix E. Council for Optical Radiation Measurement: Summary of Comments of the Working Group on Geometrically Total Flux (I), prepared by Ernest H. Salter, Chairman.

Appendix F. Council for Optical Radiation Measurement: Summary of Comments of the Working Group on Dissemination (VII), prepared by Donald McSparron, Secretary.

Appendix G. Council for Optical Radiation Measurement: Summary of Comments of the Working Group on Laser Measurement (II), prepared by Howard Pinsky, Chairman.

8. Appendices

Appendix A

A. SCOPE OF DISCUSSION

The extent of the subject areas that could possibly be discussed by this Working Group is obviously extremely broad. For example, variables such as the following are inextricably linked together:

a. quantity of interest: irradiance, radiance, intensity, etc.
b. radiometric or photometric calibration standards needed?
c. specific spectral power distribution of source? Monochromatic or broadband?
d. spectral sensitivity of detector used?
e. spectral or total radiation calibration?
f. absolute power levels
g. time-independent or time-dependent (e.g. pulsed) quantity?
h. coherent or non-coherent?
i. accuracy, relative or absolute
j. repeatability (unit-to-unit)
k. methodology: supporting operational techniques/equipment instructions
l. importance and ramifications of work: effects on sales, profits, trade, jobs, etc.

Rather than attempt a full discussion of each of these factors in the very limited amount of time available for discussion on February 10, it was decided that each participating member summarize the problems most familiar to him from his own experience. Individual comments were, of necessity, limited to approximately 20 minutes. Written summaries of individual's comments on these and other topics were encouraged by NBS.

B. STATEMENT OF PROBLEM: Lack of NBS-traceable standards of spectral irradiance and radiance in the 90-250 nM (vacuum UV) spectral region.

PROPOSED SOLUTION: Development of such standards and associated measuring techniques. Need 5% accuracy and/or 2% relative (spectrally).

JUSTIFICATION/APPLICATION: (1) Radiation level measurements in spacecraft and stellar investigations. (2) environmental health studies (e.g. eye damage)

COMMITTEE CONTACT(S): Howard McDevitt, David Sliney

C. STATEMENT OF PROBLEM: Lack of daylight-spectrum sources, needed for applications in photographic film, TV and color-matching fields. Need sources with spectral power distribution matching daylight solar radiation, various CIE defined spectrums, several cm^2 in size and calibrated spectrally at 10 nM intervals from 350 to 700 nM.

PROPOSED SOLUTION: Development of such standards.

JUSTIFICATION/APPLICATION: The economic repercussions of poor quality control for example, in the above industries are clearly very pronounced, particularly when involving consumer markets. Estimated potential losses can be provided by committee contacts.

COMMITTEE CONTACTS: Richard Becherer, Polaroid
William Heaps, Macbeth

D. STATEMENT OF PROBLEM: Lack of availability of current types of lamps for calibration purposes.

PROPOSED SOLUTION:

COMMITTEE CONTACT: J. Gordon Hoffman

E. STATEMENT OF PROBLEM: Better standards and methods of measurement of luminous intensity (candela) of low color temperature are needed for current applications in, for example, aircraft visual display systems (cockpit lighting). Present lack of agreement among parties involved, users and manufacturers.

PROPOSED SOLUTIONS: Development and implementation of such standards.

JUSTIFICATION/APPLICATION: Safety, linked to readability of displays; consequent economic repercussions of disagreements.

COMMITTEE CONTACT: J. Gordon Hoffman

F. STATEMENT OF PROBLEM: Lack of adequate methods for very low illuminance (footcandles) measurement. Needed, for example, in measurements of low reflected power from retro-reflectors used for highway markings etc., which are illuminated by 1 footcandle incident power density and where the reflected radiation is measured at 100 foot ranges and levels are 10^{-6} footcandles. Reflected light is filtered (green, amber, red, etc.)

PROPOSED SOLUTION: Investigate and propose method and/or revision of existing standards of measurement.

JUSTIFICATION: Safety concerned with visibility of highway and other reflectors.

COMMITTEE CONTACT: Pablo Smester

G. STATEMENT OF PROBLEM: Lack of standardization of calibration methods and standards among manufacturers and users of light-emitting diodes and displays.

PROPOSED SOLUTION: A relatively comprehensive statement was made concerning the need for and the implementation of a specialized LED calibration system including standard sources, detectors, procedures, etc. Basic measurement units suggested are radiant intensity (watts/sr), irradiance (watts/cm^2) and radiance. Conversion to photometric units would be performed numerically using spectral radiometric data and photoptic/scotopric conversions. It was suggested that a re-examination of the CIE Standard Observer Curves be undertaken. The general statement was said to represent the consolidated viewpoint of many of the major manufacturers of LED's (perhaps all).

JUSTIFICATION: Typical standardization ramifications. Very large market, domestically and internationally.

COMMITTEE CONTACT: Joseph Horwath

H. STATEMENT OF PROBLEM: Inadequate methods of spectral/total radiometric and photometric measurement of pulsed-type sources such as Xenon flash lamps. Spectral output of these lamps changes as function of duty cycle, percluding extrapolation of CW calibrations. Extrapolation also difficult due to reciprocity failure of photographic films.

PROPOSED SOLUTION: Development and standardization of method and equipment.

JUSTIFICATION: Highly important to quality determination and control in photographic film industry. Also highly important to development and testing of visual warning and identification systems such as stribe lights on aircraft beacons, emergency vehicles, etc. where visibility and safety are prime concerns.

COMMITTEE CONTACT(S): Pablo Smester
Dick Becherer
William Heaps

I. STATEMENT OF PROBLEM: Difficulty of present situation in reliable calibration of laboratory radiometers. Generally speaking, it was felt that the radiometric calibration standards and services of NBS (speaking primarily of incandescent lamp standards) is presently inadequate from several standpoints.

First, there is a notable lack of information from NBS available on exactly what standards are available, precisely what their characteristics are, methods used to calibrate the standards at NBS and recommended operational procedures for their use.

Second, the estimated uncertainties of these standards are not well established either within the industry or apparently within NBS itself.

Third, there is a need for calibration standards of spectral irradiance beyond the present 0.25 to 2.5 micrometer range. In particular, sources other than tungsten-filament lamps are needed (e.g. low and medium temperature balckbody radiators.)

Fourth, it would be desirable to upgrade the accuracy of the present standards to permit better instrumentation accuracy in general.

Fifth, there is a specialized but very widespread need for calibration sources which can be readily used for the calibration of thermal type detectors and radiometers that are equipped with window materials such as fused quartz, KRS-5 etc. The nature of these devices requires such a window, for operation at low levels. The far IR spectral response may frequently not be known with any certainty. What is needed then, is a lamp-filter combination which exhibits a spectral power distribution which is fully included within the range of the window under consideration. The filter must be arranged to eliminate self-emission (i.e. at the detector temperature) which is the problem currently encountered with standards of irradiance, for example. That is, a significant portion of the total radiation is emitted by the envelope of the lamp and is located spectrally in the mid to far IR where the quartz (for example) window does not transmit. This is an immediate need.

JUSTIFICATION: Thermal type radiometers are universally used as calibration (transfer) devices in the field. Improper calibration results in much increased confusion for the users of such instruments. Discrepancies on an international basis, which have occured, result in lost sales and decreased exports. Domestic sales have been affected as well, with consequent effects of employment levels etc. for manufacturers.

COMMITTEE CONTACT: Michael Mellon

J. STATEMENT OF PROBLEM: Need to accurately calibrate "flat" neutral density attenuators with transmission factors as low as 10^{-6}. Spectral range not specified.

PROPOSED SOLUTION:

JUSTIFICATION:

COMMITTEE CONTACT:

K. STATEMENT OF PROBLEM: Measurement of low power lasers for environmental health studies.

JUSTIFICATION: NBS Boulder Calorimeters do not operate at low enough level.

COMMITTEE CONTACT: Dave Sliney.

Appendix B

Recommendations:

(1) Expand NBS calibration temperature range downward (e.g. 170 K - 360 K and extend λ range to say 25 μm and uncertainty to 1%).

(2) Such calibrations to also include effects of source environment.

(3) Need information on the use of extended sources

  (a) goniometric problems (in some cases)

  (b) verification of specifications on such sources

(4) Need application of absolute detector to source calibration

  (a) evaluate such a detector

(5) Since much interest (and emphasis) is in the lower temperatures, what about the development of low temperature freezing point standards (e.g. freezing point of mercury, gallium, etc.).

Appendix C

I. SPECTROPHOTOMETRY

A. Problems

There has been difficulty in the past in checking the transmittance accuracy of conventional spectrophotometers, especially those without integrating spheres. Possible sources of error are (1) non-linearity of photodetectors and/or the pen slidewire, (2) slight wavelength errors in measuring highly wavelength selective samples, (3) spectral stray light and/or geometrically scattered light, (4) beam shift across the non-uniform detector area, (5) unrecognized polarization of the light beam combined with dichroic samples, (6) spatially non-uniform samples, and (7) samples whose reflectance and/or transmittance is a strong function of angle, especially when measured in spectrophotometers of differing F-numbers.

On the whole, T measurements are routinely good to $\pm$ 0.5%, R measurements of specular samples good to $\pm$ 1%, or of diffuse samples $\pm$ 2 to 5%.

B. Impact

Commercial spectrophotometers are employed in an overwhelming majority of analytical laboratories or in any research program studying the optical properties of materials. In fact, the optical behavior of materials can be most readily characterized by their measured reflectance (R) and transmittance (T).

In the vast industrial field of optical thin films, reflectance and/or transmittance are used as the controlling parameters, and in many cases absolute (rather than relative) values of R and T are required.

In the field of temperature control by the absorptive and emissive properties of coated and uncoated surfaces, accurate spectral measurements of R and T are critical in evaluating the various possible materials. In the past intercomparison of the results among various laboratories has been hindered by a lack of suitable reflectance standards. Some examples of the uses of thermal coatings are artificial earth satellites, storage tanks of volatile fluids, and personal dwellings (housepaints).

In addition the lamp industry needs to have good integrating sphere coatings in order to measure the luminance of their sources.

C. Solutions

We need standards of specular transmittance covering the wavelength range 0.20 to 2.5 μm, transmitting 10% to 100% at intervals of $\sim$ 10%, with an accuracy of $\sim \pm$ 0.1%. These specifications would probably have reduced accuracy outside those regions where the sphere coatings used in the measurements are less efficient. These standards should be flat, spatially uniform, stable and durable, isotropic and preferably neutral. These standards would also serve as accurate attenuators. Metal films are probably best because they are most neutral and are more easily controlled during manufacture.

We also need standards of specular reflectance covering the wavelength range 0.2 to 2.5 μm, reflecting about 10%, 50% and 90%, with an accuracy of $\sim \pm$ 0.2%. These samples should also be flat, spatially uniform, stable and durable, isotropic and preferably neutral. Metal films are probably best for higher levels of R and dielectrics at the lower levels.

Again, as an overlap with attenuator requirements, there should be standards of high density transmittance, say 10^{-4} to 10^{-1}, with an accuracy of 1% relative.

In addition standards of diffuse transmittance and reflectance are desirable. However, it is more difficult to specify their behavior because of the broad ranges of angular characteristics that can be described.

One solution would be a standard of perfectly diffuse reflectance (a Lambertian surface) of well-defined total hemispherical reflectance for near-normal incidence, as a function of wavelength, accurate to $\pm$ 1%. The wavelength range would again be 0.20 to 2.5 μm. Finally, we need a well-defined, non-cumbersome procedure for producing integrating sphere walls of good diffuseness and high reflectance.

II. ATTENUATION

A. Problems

Many of the absolute radiometric and photometric parameters being measured today differ by orders of magnitude from the nominal values of the standards issued by NBS. Thus in order to make transfer calibrations of lower radiant or luminous power devices some form of attenuation must be employed. It is obvious that if high accuracy is to be obtained in calibrating these lower power working standards reliable and accurate techniques of attenuation must be utilized. The problem of attenuation is one of being able to determine both the absolute magnitude of the attenuation as well as the spectral perturbations introduced by the attenuator. A few examples may better illustrate the problem. Consider first the case of making an illumination calibration. Photometric standards of illumination are typically 500 watt lamps. At 150 centimeters distance these lamps yield on the order of 100 ft candles of illumination. Typical lamps which are calibrated from this standard might be 50 watt, 5 watt lamps etc. having illuminations at 150 centimeters of from .1 to 1 footcandles i.e. 3 orders of magnitude different from the standard. An extreme might be the calibration of low light level light sources commonly used to evaluate image intensifier devices. These devices are calibrated to operate as low as 10^{-7} footcandles, a 10^{9} order of magnitude difference between that of the standard! The problem is further complicated by the requirement that the spectral distribution of the light source be that of a black-body of a given color temperature (typically 2870 °K) over a spectral region of .4 μ to .9 μ.

Another use of attenuators is to determine linearity of precision measuring instruments, principally the detectors and systems that follow the detectors. Many texts, including Moon and Walsh roughly describe methods of attenuation but it is felt that the Bureau should take the lead in establishing and standardizingmore definitive techniques in attenuation. The current situation is one of each investigator or laboratory employing their own methods and thus giving rise to data correlation difficulties.

B. Impact

The result of not having standardized techniques for attenuation of high light level sources is disagreement in calibration values of low light level sources made by various secondary standards laboratories. The potential impact of disagreement between secondary standards laboratories, i.e. laboratories directly traceable to NBS, is tremendous. A contractor traceable to secondary laboratory A measures the performance of a device to meet specifications of a contractee. The contractee traceable to say laboratory B does acceptance testing of the device and finds it below his specifications and rejects the devices. Many manhours and delay of important developmental programs may be spent to resolve the discrepancy which in the end was found to result from laboratory A employing an attenuation method different from laboratory B.

The above situation is indeed a reality in many of the U.S. Army procurement programs for low light level intensifying devices and the problem is difficult to solve since it requires a significant expenditure of technological resources to determine which is the more theoretically valid method of attenuating a standard source. It is felt that this task more properly falls into the domain of the National Bureau of Standards.

C. Solutions

It is recommended that the Bureau attempt to collect, describe and analyze all methods of attenuation pertinent to photometry, radiometry, spectrophotometry. The Bureau should then make recommendations to industry suggesting which methods are pertinent to different areas of this technology. It is also recommended that these discussions from the Bureau be put in some form that can be distributed to the scientific community. A special NBS technical note or monograph along with the results of the other working groups could be made available to the public. Another recommendation would be to have the results of these analyses and working group discussions presented to the regular international CIE meetings and have international discussions of the results which may be also distributed to the public in the form of NBS technical notes or CIE notes or whatever. Another recommendation would be to periodically have round-robin measurement comparisons between laboratories similar to those which are held for measurements of luminous intensity. For example measurements of low level sources as opposed to sources which are of the magnitude of NBS standards may be compared. Another recommendation is to obviate the use of attenuators by providing to industry standards of luminous intensity and other photometric and radiometric standards which are themselves orders of magnitude lower than those which are currently provided. This relates back to the original discussion of this note: the reason that attenuators are used is that the phenomena being measured are very often different by many orders of magnitude from those of the standards obtained from the Bureau.

Appendix D

The objective of this group is to define and provide for the establishment of a national measurement system for relative and absolute spectral detector response measurements. This will include defining the NBS role in the measurement system and defining the needed accuracy and minimum detectable spectral irradiance as a function of wavelength.

SPECIFIC RECOMMENDATIONS

1.) Cavity receiver, electrically calibrated thermal detector capable of NEI on the order of 1 μ $watt/cm^2$ for use in relative spectral response calibrations.

2.) NBS should maintain a primary standard in the spectral response area coupled with recommendations for transfer standards and procedures for their use. NBS should encourage industry to go into the business of supplying these transfer standards with calibrations and to set up procedures (such as round-robins) to ensure these calibrations.

3.) A quantum detector should be the transfer standard going down to 0.2 μ. A transfer standard is also needed out to at least 25 μ. This standard need not be a quantum detector.

Studies of the linearity of these transfer standards or procedures for calibrating their linearity.

Studies of the stability of these transfer standards or procedures for calibrating their stability.

SPECIFIC PROBLEM AREAS

1.) Getting down to low irradiance levels.

2.) Correlation of pulsed and steady state measurements (integrated vs. peak). There are no pulse standards.

3.) Specification definitions are not well enough defined to really help the consumer

Areas not defined well enough for D* or responsivity specifications.

4.) Temperature dependence of silicon cells.

JUSTIFICATION

The lack of adequate detector spectral response standards, procedures, and definitions contributes to a disorderly marketplace. The user depends on the detector supplier for spectral response data which too many times is in dispute. Reliable spectral response data is needed for accurate data reduction of user's results. In the case of broad band detectors for example, spectral response is used to establish "effective radiance" characteristics which call for conversion of received radiation to equivalent blackbody temperature. All too often, without reliable spectral response standards the user is now forced to develop effective spectral response results by indirect means.

This group first moved to define its scope; namely, Flux (Luminous, Radiant and Spectral-radiant) needs in the area of measurements of luminous flux (lumens) and spectral-radiant flux (watts/nm) covering sources (incandescent, fluorescent, HID, etc.) of UV, visible and IR radiation.

Without particular discussion it was agreed that it was desirable for the Bureau to continue on programs now in progress, such as, the work now underway with Mrs. Burns on incandescent lamp standards, the fundamental definition of the candela, and the work on establishing and improving the derivation of the lumen from intensity, or even spectral irradiance standards goniometrically, then learning to transfer flux standards in spheres and understanding what is happening in spheres. Dr. Schaefer commented that this latter capability will be necessary in any event in order to measure spectral-radiant flux. He questioned if there is not, at least for now, still a necessity to be able to make photometric flux measurements directly with a well characterized detector.

Then came the question, are these needs best met by standards for each of the types of sources or by the development of means for attaining this end through the use of only a very limited number of standards? Up to the present time, photometric laboratories have been existing through the use of standards of luminous flux from NBS for incandescent and certain fluorescent lamps, and color standards for another group of fluorescent lamps. Measurements of luminous flux from lamp types and sizes outside the range of these standards or color assignments beyond the limited group have been made by each laboratory on the basis of its own methods or its own developed standards, usually without direct traceability to NBS.

The development of standardized procedures for the determination of spectral-radiant flux, with a limited number of standards for this characteristic available from NBS, would make it possible for laboratories to determine total luminous or total radiant flux from the results of the spectral-radiant flux measurements. A laboratory equipped to make this spectral determination then would be in a position to transfer flux assignments for a given type and size of lamp to other lamps of this same size and type for use as secondary standards in commercial assignments by substitution methods. A laboratory <u>not</u> equipped to make SED measurements would have to depend on an independent laboratory to supply these needs.

The development and use of the total spectral radiant flux as a means toward total luminous flux determinations has an added advantage in that color appearance and color rendering index both are computable from the results of this measurement. Thus, a standardized procedure for the determination of luminous flux would, at the same time, yield a standardized procedure for color appearance and color rendering index, where standardized procedures presently are available only for a small part of the lamp types and sizes being used.

What would be needed in the way of a range of standards? Lamp measurements now cover the range from 0.01 to 100,000 lumens. The 0.01 lumen is for sub-miniature incandescent lamps and the 100,000 lumens for some of the HID lamps.

If measurement were to be made by spectral-radiant flux determination, what range would be required? Bactericidal and ozone producing lamps would require special techniques for measurements down to 180 nm. It is, therefore, suggested that two sets of equipment and two measurements procedures be developed, one in the range from 180 to 320 nm and the other from 250 to 900 nm.

What is the justification for asking NBS to either furnish standards of all types and sizes or to develop measurements procedures to standardize the determination of spectral-radiant flux? Without lamp standards for the characterisitics or without standardized measurements procedures, determined values may vary from laboratory to laboratory by amounts up to 10 per cent or more. Further, since published performance data for various lamp types are based on the results of measurements in the various manufacturers' laboratories, catalog data will reflect these variations. As a result, there are influences on (a) business; domestic and foreign, (b) health and safety of the public, (c) legal liabilities, and (d) consumer protection.

In business, many purchases are made on the basis of promised performance. A difference of the order of one or more percentage points in promised performance will, therefore, determine the business to be done, either domestic or foreign, by a given manufacturer or even by an industry. This can run into millions of dollars.

In addition, to the unfair competition resulting from such comparative ratings, there is the influence of such catalog data on purchase specifications by state and local governments, GSA, OEM, DOT, FAA, etc.

People live in a radiation environment, natural or artificial. Just as too much sunlight may be harmful, certain elements in artificial light may be harmful. On the other hand, other elements may be beneficial. In other words, there is no doubt but that radiation may have influences on health. BRH no doubt is interested.

Light plays an important part in the safety of our people. Highway and traffic safety depend on light signals. DOT and FAA both are active in specifying performance.

Consumer protection is considered to be of such importance that an agency is set up in government in an effort to provide this protection. One facet of this protection is truth in advertising, facts and not fiction. FTC is interested in this. When a customer replaces a lamp, he expects a similar performance from the replacement. In other words, lamps similarly marked should be interchangeable. With all of this, the manufacturer is subject to possible legal action due to nonfulfillment of contract if lamps do not perform in service as the purchaser was led to believe from catalog data.

With the announced policy of NBS to limit the number of types and sizes of standards to be provided, this group strongly recommends that NBS proceed (1) to continue its present program of calibration of specific lamp types to provide to industry a baseline for these types, (2) to develop methods of extending the calibration of secondary standards from a limited number of standards for a given lamp type, and (3) to develop standard procedures for determining spectral-radiant flux for all types and sizes of lamps. This latter development should provide means for handling different lamp geometries -- bulb shapes, etc.

Appendix F

The working group listed the following items, in order of priority, as the most pressing needs in the area.

1) Provision by NBS of detailed, written descriptions of the methods and techniques through which NBS calibrates standards of spectral radiance, spectral irradiance, luminous intensity, color temperature, etc. Ideally, these descriptions would be duplicated in other laboratories with minimum chance of error.

2) When NBS is unable to provide full calibration services, they should provide some method of guaranteeing that commercial standards labs are providing measurement services on the NBS scale. Various methods of formal and informal certification are under discussion (e.g., NBS calibration reports might include a value predetermined by the customer in addition to the NBS determined value and uncertainty statement).

3) Small-scale, simple interlaboratory intercomparisons utilizing NBS techniques (item 1 above), with NBS acting as referee, would be desirable to determine the level of agreement between interested labs and NBS in selected areas (luminous intensity, total irradiance, color temperature, etc.).

4) NBS should take the steps necessary to provide easy access to existing written descriptions of techniques and methods through bibliographies, subscription information on periodicals, etc.

The committee recognizes a strong need to coordinate closely its future activities with the working group on techniques (working group VI). For the immediate future, the working group on dissemination will direct its efforts toward the preparation of a detailed outline of most useful material to be included in future NBS write ups of techniques and methods.

Appendix G

I. STATEMENT OF PROBLEM

The basic problem with laser energy and power measurement is the large scale discrepancy in calibration of the various energy and power meters that are commerically available. Although manufacturers of these instruments claim traceability to NBS within 5% of absolute, variations of as much as 30% have been seen on several different types of instruments.

The specific problems related to standarization and calibration of laser power and energy monitors are as follows:

1. Lack of standard laser sources stable enough to use as an equivalent to a standard lamp.

2. Lack of readily available standard thermopiles or calorimeters.

3. Unavailability of secondary standards labs to provide a traceable industry-wide calibration service for power and energy meters.

4. Lack of detailed information as to procedures and techniques for use of laser measurement instrumentation.

II. EXISTING STANDARDS AND PROCEDURES

Presently, NBS-Boulder is capable of achieving a 1% accuracy of laser energy measurement with the C-series calorimeter system. In general this is accurate enough for all current laser applications such that a new standard is not needed at this time.

Several NBS documents are available which treat some of the applications of power and energy meters in a standards laboratory setting; however, a generalized descriptive procedure in the form of a handbook is badly needed.

III. CONSENSUS ON NECESSARY NBS ACTION

By consensus of the Laser Committee, the following measures are listed in order of priority:

1. Specification of a generalized class of calorimeters or thermopiles which could be easily calibrated within a 2-3% uncertainty.

2. Appropriate software to support the above chosen class of calorimeters based on laboratory data and containing a broad based procedure and technique for accurate use.

3. Detailed applications note concerning the compounding of errors in laser power and energy measurements to be used as a guide in designing the measurement procedure.

4. Continuation of the calorimeter and thermopile calibration service at NBS with the possible future certification of secondary standards labs who could provide fast accurate calibrations.

IV. JUSTIFICATION FOR NBS ACTION

As previously stated, NBS can achieve a 1% accuracy in measurement of laser energy and power based on the electrical calibration of its C-series calorimeter. The measurement problem therefore exists in the calibration and use of the commercially available measurement devices. As much as 30% error may be found in some instruments due to calibration uncertainty, faulty application techniques and actual instrument instability.

There is a pressing need for increased accuracy by both laser manufacturers and laser users. Laser manufacturers must have accurate measuring instruments in order to guarantee product capability and performance. They must also be assured that their customer's power and energy meters are of the same absolute accuracy such that discrepancies in power level will not be due to the measurement system.

Laser users on the other hand have a significant number of applications which require highly accurate measuring instrumentation. Some of these applications are:

1. Laser damage threshold measurements.

2. Laser material and laser system research and development.

3. Raman scattering.

4. Laser radars and range finders.

5. Laser monitoring in conjunction with the new laser safety standards.

The laser industry is expanding in influence in a multitude of new produce areas. With each new development an increased demand is placed on laser power and energy measurements.

We must rely on NBS to develop new standards and insure that all industry can be supplied with accurate calibrations.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Serious measurement discrepancies universally plague quantitative measurement in the electro-optics industry. The impact of the resulting problems is reviewed and the role of NBS explored. The measurement discrepancies arise chiefly through the recent explosive expansion of this industry. The growth has precipitated a complex development in the variety and accuracy of measurements required. The impact of problems in optical radiation measurement falls in many areas. One is the increasing Federal responsibility for public life defined in recent legislation. Another is the influence of good optical radiation measurement on the technical development of the electro-optics industry. The impact of these measurements on a number of public issues is reviewed: public health, public safety, the energy crisis, meteorology, pollution, agriculture, crime prevention, and surveillance from air and space. The economic impact of improved measurement both on a fair domestic market and on the balance of payments operates through unit production cost, quality control, product improvement, and innovation. Leadership by NBS has been urged by the industry not only in fulfillment of its legislative responsibility but also to permit the focus of elaborate and impartial resources on the complex problem of optical radiation measurement. In keeping with its mission to help improve industrial technology and the competitiveness of American industry, NBS has an opportunity of major proportions in the electro-optics industry. Leaders of this industry are calling for NBS initiatives to resolve many of the measurement problems now hindering further progress.

17. KEY WORDS (Alphabetical order, separated by semicolons)
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Optical Radiation Measurements:

Stability and Temperature Characteristics of Some Silicon and Selenium Photodetectors

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Optical Radiation Measurements:

Stability and Temperature Characteristics of Some Silicon and Selenium Photodetectors

Kshitij Mohan, A. Russell Schaefer
and Edward F. Zalewski

Heat Division
Institute for Basic Standards
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Preface

This is the fifth issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series will consist primarily of reports of progress in or details of research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division and will appear about every six weeks.

The level of presentation in OPTICAL RADIATION MEASUREMENTS will be directed at a general technical audience. The equivalent of an undergraduate degree in engineering or physics plus familiarity with the basic concepts of radiometry and photometry [e.g., G. Bauer, Measurement of Optical Radiations (Focal Press, London, New York, 1965)] should be sufficient for understanding the vast majority of material in this series. Occasionally a more specialized background will be required. Even in such instances, however, a careful reading of the assumptions, approximations and final conclusions should permit the non-specialist to understand the gist of the argument if not the details.

At times, certain commercial materials and equipment will be identified in this series in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

Any suggestions readers may have to improve the utility of this series are welcome.

Henry J. Kostkowski, Chief
Optical Radiation Section
National Bureau of Standards

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STABILITY AND TEMPERATURE CHARACTERISTICS OF SOME SILICON AND SELENIUM PHOTODETECTORS

Kshitij Mohan, A. Russell Schaefer and Edward F. Zalewski*

This paper describes the comparison of some characteristics of selenium barrier layer photocells and silicon PIN and PN type photodiodes operated in the photovoltaic or non biased mode. The work was done to study the suitability of these detectors specifically for goniometric measurements of flux and possibly for other photometric (or radiometric) measurements. The characteristics studied were the stability of detector output over approximately twenty hours, fatigue or light memory effects over short periods of time, and the temperature dependence of detector output.

Key words: Fatigue; light memory; photocells; photodiodes, photometry; radiometry; selenium; silicon; stability; temperature dependence.

1. Introduction

Since the advent of physical photometry, barrier layer selenium photovoltaic cells have been used extensively in photometry at NBS. The selenium cells used were equipped with photopic filters that approximately corrected the response of the detector to match the CIE defined spectral luminous efficiency in photopic vision.

Selenium cells have been found [1,2,3][1] to exhibit certain characteristics, such as fatigue, that are undesirable in goniometric measurements of total flux. In the last decade solid state technology has made available several new kinds of photodetectors, some of which seem promising for photometric applications. In particular, silicon photodiodes appear to be a possible replacement for selenium barrier layer photocells.

We have examined and compared certain characteristics of two selenium detectors and several different types of silicon detectors to ascertain their suitability for use in our work. The study is by no means exhaustive or definitive and was initially meant to be an in-house guide for the selection of a specific detector for a specific purpose. It is being published because we are unaware of any other comparative study of these detectors and also because it may give potential photometric users of these devices a feel for the problems involved.

We have tested photodetectors for three characteristics: the long-term stability over periods of about 20 hours, light memory or fatigue effects over short time periods, and the sensitivity to changes

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*National Bureau of Standards research associate from the Electrical Testing Laboratories (acting on behalf of the Lamp Testing Engineers Conference).

[1]Figures in brackets indicate the literature references at the end of this paper.

in temperature. Not all the detectors were tested for all these characteristics. Appendix A is a list according to the type and manufacturer of the detectors that were tested. In this report we shall refer to each detector by the numbers assigned in Appendix A.

Among the silicon detectors, we have studied the PN type of photodiodes and the PIN type of both the Schottky and planar diffuse varieties. Descriptions of these devices are available in the manufacturers' literature, but for the sake of completeness and as an introduction we shall include descriptions of some typical devices here.

The PN type of photovoltaic cell consists essentially of a junction of two types of material, referred to as p-type and n-type respectively. The p-type is doped with impurities such that it is a "hole" conductor; i.e. there is a deficiency of electrons in the material. The n-type material has been doped to provide a surplus of electrons. At the interface of these two materials the surplus electrons and holes diffuse across the junction to combine with each other and form a depleted "barrier" region which is now free of holes and electrons. The p-type material near the junction, having lost holes, acquires a negative space charge and correspondingly the n-type material near the junction, having lost electrons, acquires a positive space charge. Thus an electric field is maintained across the depletion barrier. This electric field will then inhibit further diffusion of the electrons and holes so that a state of equilibrium is reached. Now, when a photon is incident on the junction it can excite an electron from the valence band to the conductance band. This will happen only if the incident photon has an amount of energy greater than the energy difference between the valence and the conductance bands. This difference is known as the "energy gap" for the material and is different for different kinds of material. The excitation of the electron makes it free to move in the material and a corresponding free "hole" is also created. The process is known as the creation of a hole-electron pair. Ordinarily, if other free holes or electrons are present there would be a recombination of the holes with the electrons or the pair could recombine itself. But if the electron-hole pair is created in the depleted region where there are no other free holes and electrons present then the electron will be accelerated to the positive space charge in the n-region and the hole to the negative space charge in the p-region. If there is a load resistor across the ohmic (external) contacts on the n-region and the p-region, there will be a flow of electrons from the n-region through the load to the p-region. Since by convention a current flow is said to be in the opposite direction of the electron flow, there will be a current flow from the p-region through the load to the n-region.

If every photon incident on the detector were to produce an electron-hole pair, and if all these electrons and holes were to migrate as predicted, the detector would be absolutely linear.

The PIN type of silicon photodiode derives its name from the fact that it consists of a p-type semiconductor and a n-type semiconductor with a layer of nearly intrinsic (i.e. almost pure, non-doped) region of silicon in between. This intrinsic layer acts as an extended depletion layer which can, under appropriate conditions, improve the linearity and response time of the photodiode. In the photovoltaic mode these PIN photodiodes operate in a manner similar to the PN photodiodes described above. In the photoconductive or biased mode, a voltage is externally applied across the electrodes such that there is an electric field completely across the photodiode and the intrinsic region is fully depleted. When a photon is absorbed in the silicon, an electron-hole pair is created and propelled by the external field to their respective electrodes, creating a current through an external load as before.

In the Schottky barrier PIN silicon photodiode, the p- and n-regions are created by depositing a thin gold layer on one side of a pure silicon wafer and an aluminum (or other metal) layer on the other side. The gold layer is transparent and forms the front side of the detector. In the planar diffuse type of silicon photodiodes, a layer of aluminum (or other metal) is evaporated on one side of a silicon wafer and on the other side silicon dioxide is formed. Then through an opening in the oxide, an impurity is diffused into the silicon to form a p-type layer. The spectral response of the detector depends not only on the energy gap of the pure silicon but also on the spectral transmittance of the material on the front surface of the detector.

All the detectors that we studied were operated in the unbiased or photovoltaic mode rather than the photoconductive mode. The advantages of the photoconductive mode are an improved linearity and a faster response time. These arise from the fact that the strong electric field applied externally to the junction fully depletes the intrinsic region and creates greater carrier acceleration. However, the application of an external voltage also leads to a leakage or dark current which is large compared to the signal being measured. This dark current is not constant in time and, therefore, makes the photoconductive mode of operation unsuitable for dc measurements. In the photovoltaic mode the dark current was usually quite small (less than 0.1% of our measurement signals).

2. Experiments and Results

2.1 Stability and Fatigue Effects

One important requirement for a detector that is used in goniometric photometry is that it should be stable; that is, it should maintain its calibration during the course of a set of measurements which could take up to several hours to complete. Another requirement is that the detector should achieve a stable output within seconds after a change of illumination.

We have studied the stability of detector output for periods of approximately twenty hours. We have also investigated the short term stability in a 10-15 minute interval by noting any fatigue effects or other kinds of instabilities that might result after a change in illumination level.

The experimental apparatus consisted of a 120 volt, 750 watt quartz-halogen EHF type lamp that was mounted on one end of a 3 meter optical bench. The lamp was operated at a constant current of 4.8300 ± 0.0001 amperes and the voltage was approximately 75 volts. Mounted at the other end of the optical bench was a detector holder that could hold two test detectors simultaneously. A third detector with an independent current-to-voltage converting amplifier was placed about 50 cm from the lamp and to one side of the optical axis. This detector was used to monitor the output of the lamp in each test.

One may question the stability of the lamp and monitor detector combination. However, previous work by one of the authors (E.F. Zalewski) that compared several lamps of the above type using detector No. 1 had shown this lamp and detector combination to be stable to less than 0.1%. Of the six runs in table 1 in which this detector and the monitor detector are compared, only one run shows a disagreement of more than 0.2% (run No. 3). This run, it should be noted, shows a larger change in the lamp voltage than was observed during any other run. We believe, therefore, that any detector drift that differs by more than 0.2% from the monitor detector is actually a change in detector response and not a change in lamp output.

When examining detectors which did not have built-in photopic filters, a set of infrared and ultraviolet cut-off filters was used to block radiation from all but the visible part of the spectrum. The ambient temperature near the detector holder was monitored by using thermocouples. Except in the case of detectors with built-in amplifiers, the outputs of all detectors were read by using either of the two current-to-voltage converters described in an earlier paper [4] and a digital voltmeter. Automatic data acquisition equipment was used to collect data.

For the long term stability measurements, the outputs of the test detectors and the monitoring detectors, the voltage and current of the lamp, and the temperature of the detector holder were noted at intervals of 20 minutes over approximately 20 hours. As mentioned earlier, all the test detectors were operated in the photovoltaic mode.

Table 1 summarizes the results of the long term stability measurements for the different detectors. The detectors are briefly distinguished in the following manner: Si-S, silicon Schottky; Si-D, silicon diffuse; and Se, selenium. The numbers for the range of noise are the short term fluctuations above and below a straight line approximation of the detector drift. The numbers for the amount of drift for individual detectors have not been adjusted for lamp drift as sensed by the monitor detector. Each row in table 1 represents a single run so that detector drifts appearing in the same row indicate that those detectors were used simultaneously to provide comparisons between them. Where a plus or a minus appears before the number for percent drift, it indicates that the increase or decrease in detector output was approximately monotonic. The cases where the detector output first drifted up then down or vice versa, are indicated in the table. The temperature of the test detector holder was monitored in several runs and found to be within ±0.5 °C. Except for Nos. 2, 4, 5, and 10, the detectors appear to be stable to within 0.02% per hour--a fact that should meet most photometric requirements for stability.

All the measurements had been taken after the lamp had been warmed up for about 20 minutes, during which time the detector was illuminated.

TABLE 1

PERCENT DRIFT IN DETECTOR OUTPUT OVER APPROXIMATELY TWENTY HOURS

Run No.	Lamp Volt. Drift	Temp. Changes	Monitor Detector Drift	Test Detector Drift (in percent)									
				DETECTOR 1 (Si-S)	DETECTOR 2 (Si-S)	DETECTOR 3 (Si-D)	DETECTOR 4 (Si-S)	DETECTOR 5 (Se)	DETECTOR 6 (Se)	DETECTOR 7 (Si-D)	DETECTOR 8 (Si-D)	DETECTOR 9 (Si-S)	DETECTOR 10(Si-D)
1	-0.04%		-0.15%	-0.15	+0.4/6 hrs level/5 hrs -0.15/4 hrs								
2	-0.025		-0.2	-0.25	+0.35/7 hrs then ±0.1								
3	-0.1	+0.25 °C	-0.26	+0.1	level								
4	-0.03	+0.1 -0.3	-0.22	-0.1				-0.7					
5	-0.02	±0.5	-0.25	-0.1					-0.2				
6	<0.01		<0.1			level/4 hrs -0.2/9 hrs +0.15/7 hrs							
7	<0.002		<0.1				+0.8						
8	-0.03		-0.25				-0.55						
9	<0.01	±0.1	-0.15	-0.2			-0.15/7 hrs +0.1/11 hrs						
10	<0.01		-0.05							-0.1			
11	<0.01		-0.1								-0.1		
12			<0.1									<0.1	
13		±0.3	<0.1				-2.0					<0.1	
14		+0.5	-0.2										-1.0
RANGE OF NOISE			0.05	0.05	0.1	0.06	0.05	0.1	0.05	0.1	0.1	0.05	0.3

TABLE 2

DETECTOR OUTPUT DRIFT DURING 10 MINUTES AFTER SHUTTERING FOR 20 MINUTES

DETECTOR	DRIFT	RANGE OF NOISE	
		Before	*After*
1 (Si-S)	less than noise	0.1%	0.1%
3 (Si-D)	less than noise	0.05	0.05
4 (Si-S)	less than noise	0.06	0.06
5 (Se)	-0.4%	0.06	0.20/2 min then 0.06
7 (Si-D)	less than noise	0.1	0.25
8 (Si-D)	less than noise	0.1	0.3
9 (Si-S)	less than noise	0.1	0.1

TABLE 3

TEMPERATURE DEPENDENCE OF DETECTOR OUTPUT IN THE INTERVAL 20 TO 30 °C

DETECTOR	BLOCK TEMPERATURE DEPENDENCE	REMARKS
1 (Si-S)	-0.06% per °C	
2 (Si-S)	-0.02	
3 (Si-D)	±0.07*	Minimum near 24 °C
4 (Si-S)	-0.12	
5 (Se)	+0.06	
7 (Si-D)	±0.07*	Maximum near 24 °C
9 (Si-S)	±0.08*	Maximum near 24 °C
11 (Si-D)	+0.12	

*These temperature dependences went through a minimum or a maximum. The numbers represent the slope on the steep part of the temperature dependence curve.

This was done to avoid any short term fatigue effects. These were studied separately.

Using the same experimental set-up described above, detectors were checked for any fatigue or light hysteresis effects by first warming up the lamp and illuminating the test detector and then shuttering the detector for a period of about 20 minutes. The shutter was then opened and the detector output and other parameters were read out at 20 second intervals for a period of 10 minutes. Table 2 summarizes the drift and noise that were observed after the shutter was opened. The numbers for range of noise *Before* and *After* refer to the noise ranges observed before the detector was shuttered for 20 minutes and after it was again illuminated. No drifts above the noise level were observed except for detector 5 which was a selenium photocell. This detector showed the expected fatigue effect [2,3]. A comparison plot of the output of this detector and detector 1 is shown in the figure. Detectors 7 and 8 did not show any drift, but the noise on both showed a large increase in the 10 minutes after the shutter was opened. It seems that a longer time period is required for them to achieve equilibrium.

2.2 Temperature Dependence

The temperature dependence of a set of detectors was studied over the range of approximately 20 °C to 30 °C. The experimental apparatus remained the same as in the stability studies except that the detectors were mounted in a metal block which was cooled or heated by two thermoelectric plates. The detectors were shielded from room temperature changes by a transparent plastic box surrounding the detector holder.

The temperature of the detector was changed by altering the amount of current passing through the thermoelectric plates. The current polarity determined whether the detector was being cooled or heated. Temperature was measured by two thermocouples, one of which was embedded in the metal block that held the detectors. The metal detector cases were in good thermal contact with this block. The other thermocouple measured the temperature of the air surrounding the detector in the plastic box.

Readings of the detector outputs and other monitoring parameters were taken when both the temperature of the block and the ambient temperature within the box had achieved equilibrium. Table 3 gives the changes in detector output per °C change of block temperature. Two detectors, No. 4 which is a Schottky type PIN device and No. 11 which is a diffuse PIN device, showed temperature dependences slightly greater than 0.1% per °C. Some of the detectors had a temperature coefficient which went to zero (minimum or maximum in the response curve) near room temperature. The maximum slope is, therefore indicated in table 3.

3. Conclusions

As mentioned in the introduction, this study was not meant to be a definitive or exhaustive study of all the different kinds of photodetectors available today, hence we can not draw any general conclusions of the relative merit of any manufacturer of these detectors. Detectors of the

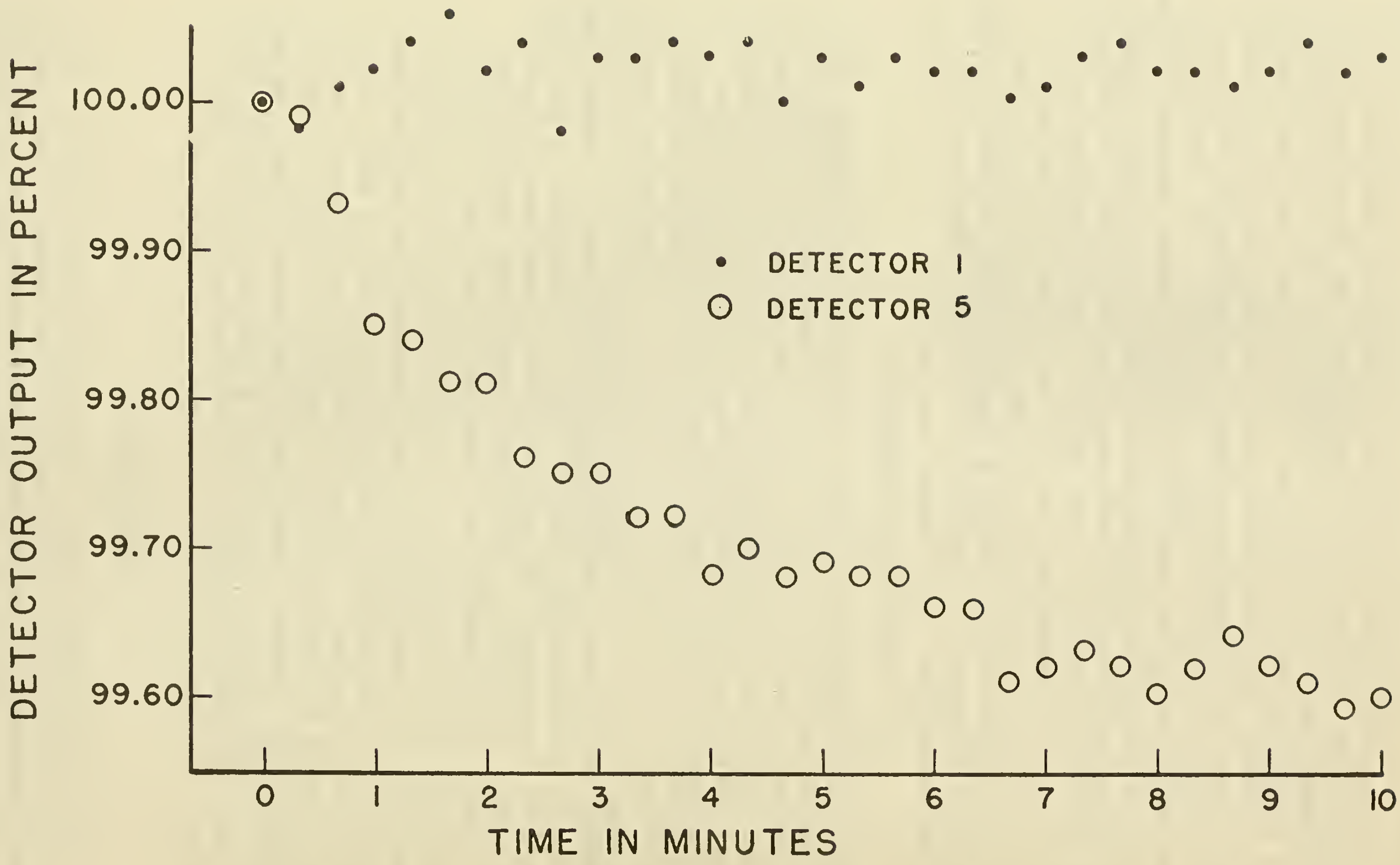

Fig. 1. Initial short term drift in detector output. Output normalized to initial reading.

same type and manufacturer may at times perform differently as is evidenced by the differences in the stabilities of detectors 1 and 2; both were of the same type, were made by the same manufacturer, and had the same model numbers.

We can, however, draw some conclusions and also get an indication of where problems *may* exist. The study also gives us estimates of a part of the uncertainty that should be taken into account when these detectors are used in specific applications.

1. In photometric applications (dc measurements) the silicon detectors of the kinds that we studied should be operated in the photovoltaic or non-biased mode.

2. Several of the silicon detectors studied proved to be sufficiently stable for applications in precise photometry: the instability of output was less than 0.02% per hour. However, some of the detectors were significantly less stable. Thus silicon detectors have to be individually tested and selected for optimum performance.

3. The silicon detectors did not show any identifiable fatigue or light memory effects, whereas the selenium photocells studied showed the expected fatigue. Some silicon detectors are very noisy when first illuminated and it sometimes can take several minutes before the noise decreases and the cells achieve equilibrium. In goniometric measurement of flux, effects due to changing levels in illumination are undesirable. One cannot therefore use the selenium detectors without some sort of arrangement to take account of these effects. However, there are some silicon detectors that can be used; again, the characterization of the specific detector is required.

4. All the detectors showed sensitivity to temperature changes and if they are to be used in photometric work at the few tenths of a percent level of precision, temperature control within ±0.5 °C or less is necessary. For precise photometric work the specific detector chosen should first be characterized for its temperature sensitivity and then the required amount of temperature control should be built into the detector holder.

Detectors 9 and 10 were silicon detectors that had a current-to-voltage converting amplifier built into the detector case. Detector 9 had stability and temperature dependence characteristics that were of the same order as the other silicon detectors. Detector 10, however, showed larger drift and noise. Since these detectors are used without external operational amplifiers, laboratories that do not now have such amplifiers may consider using them.

For goniometric measurements of flux the detectors should also be tested for linearity and spectral response. The linearity, however is more critical than spectral response for our purposes. Some preliminary linearity tests using the inverse square approximation have shown that silicon cells operated in the photovoltaic mode are linear within 0.1% over two decades. Future studies of these detectors will include more detailed linearity and spectral response measurements.

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Appendix A

List of Detectors Tested with Assigned Numbers

Assigned No.	Detector Type	Manufacturer
1	Silicon PIN Schottky, photopically corrected	A
2	Silicon PIN Schottky, photopically corrected	A
3	Silicon PIN diffuse	A
4	Silicon PIN Schottky	A
5	Selenium barrier-layer, photopically corrected	B
6	Selenium barrier-layer, photopically corrected	C
7	Silicon PIN diffuse	D
8	Silicon PIN diffuse	D
9	Silicon PIN Schottky with built in op amp, photopically corrected	A
10	Silicon PN diffuse with built in op amp, UV optimized	D
11	Silicon PIN diffuse	A

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This paper describes the comparison of some characteristics of selenium barrier layer photocells and silicon PIN and PN type photodiodes operated in the photovoltaic or non biased mode. The work was done to study the suitability of these detectors specifically for goniometric measurements of flux and possibly for other photometric (or radiometric) measurements. The characteristics studied were the stability of detector output over approximately twenty hours, fatigue or light memory effects over short periods of time, and the temperature dependence of detector output.

17. KEY WORDS (Alphabetical order, separated by semicolons) Fatigue; light memory; photocells; photodiodes; photometry; radiometry; selenium; silicon; stability; temperature dependence.

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NBS TECHNICAL NOTE 594-6

Optical Radiation Measurements:

The Present State of Radiometry and Photometry

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Optical Radiation Measurements:

The Present State of Radiometry and Photometry

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Preface

This is the sixth issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series consists primarily of reports of progress in or details of research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division. The current issue, however, is an exception. It attempts to characterize and analyze the radiometry and photometry portions of our National Measurement System. A basic knowledge of the operation of this system is essential in applying the resources of NBS and the technical community towards improving it. This document is included in the Optical Radiation Measurements series to further the understanding of the radiometry and photometry portions of the National Measurement System.

Henry J. Kostkowski
Optical Radiation Section
National Bureau of Standards

FOREWORD

The recent rapid expansion of the electro-optics industry has generated many new devices and a wide variety of new components. This industrial and scientific activity has led to the formation of new technical groups and whole new organizations.

This remarkable growth and the resulting size and scope of problems associated with it have been chronicled both by the technical journals and by popular journalism. A survey of related serious problems and their consequences has already appeared in this Technical Note series under the title "The Impact of Radiometry and Photometry and the Role of NBS" [1][1]. This review dealt with the relation between precise and accurate optical radiation measurement and areas of national concern. It identified prominent areas of impact.

By contrast, the present note identifies the origins and the extent of problems within optical radiation measurement. It focuses on the performance of the measurements themselves. The preceding Note identified the external motivation for specific levels of agreement among measurements. The present Note describes the internal state of, and interrelationships among, optical radiation measurements. It analyzes the components of the system comprising these measurements in the U.S. It identifies new trends in the flow of information within the system. And finally, it draws conclusions on the improvement of agreement among radiation measurements now causing wide concern.

Prominent issues and conclusions are reviewed in an executive summary at the end of the document.

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[1]Figures in brackets indicate the literature references at the end of this paper.

"Enormous sums are involved annually in electrical lighting contracts, lamps of certain candle-power being usually specified. Disputes between the consumer and the lighting company are an almost daily occurrence. It is not that the lighting company seeks to take advantage of suitable standards but rather that the company, which usually aims to furnish a satisfactory service, is handicapped by the lack of authoritative standards."

-- Samuel Wesley Stratton in
address advocating the estab-
lishment of a National
Standardizing Bureau, 1900.

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THE PRESENT STATE OF RADIOMETRY AND PHOTOMETRY

Bruce Steiner

The electro-optics industry and the public that depends on it are part of an informal but influential system for optical radiation measurement. The growth of this industry and of public concerns related technically to it have put severe new strains on this measurement system. The system itself must therefore be analyzed. The state of the art, on which the measurement system depends, is surveyed in terms of basic measurement parameters. The measurement system is analyzed in terms of its three basic components: the flow of physical standards, the generation of procedural standards, and the funding framework. The roles of the professional society and of the Council for Optical Radiation Measurement are reviewed. New requirements of the system are identified. Finally, the methodology of the study is reviewed in detail.

Key Words: Measurement system; photometry; professional societies; radiometry; standards.

CHAPTER I

Background

A. MOTIVATION

The Stratton quotation from 1900 on page v suggests several problems that industry and government, once more after seventy years, are again facing. Lack of agreement among light measurements is again a problem of severe commercial importance. But now the problem has public and social significance as well.

Moreover, this time not only the lamp industry is involved. The even larger photographic and television industries are concerned. Many new, small, but rapidly growing, industries involving a wide diversity of technologies are making light measurements that present difficulty and serious discrepancies. Examples are new solid state light detectors, image intensifiers, and a wide variety of information displays: light emitting diodes, films, electrophoretic devices, gas discharges, and liquid crystals [1-3].

One primary source of this resurgence of optical radiation measurement difficulty is novelty. Completely new and changed products, made possible with new rapidly advancing electro-optics technology, differ greatly from their predecessors and from one another. Moreover, the measurements involved are frequently new to those making them. Coupled with both types of novelty is the inherent complexity of the measurements. These factors interact to produce surprisingly large disagreements. "Gross errors, perhaps as high as ±30%, are now known to be occurring, and with disturbingly high frequency, in our particular field of optical sensing (photo-emissive detectors, visible and near UV/IR)" [4]. The sources of such problems are the subject of this Note.

B. THE DICHOTOMY BETWEEN PHOTOMETRY AND RADIOMETRY

A fundamental feature of the measurement of light is the existence of two separate, not-precisely-convertible, systems of quantities.

The physicist working with electromagnetic radiation typically needs to identify the *flux:*

$$\phi$$

that is the power or photon rate of flow, with which he is working. For radiation transfer problems and for the spectral-characterization of surfaces such as film or room illumination, the ratio of flux to area, or *irradiance:*

$$E = d\phi/dA$$

is a quantity of primary importance. Optical systems, because they conserve both flux and the geometrical throughput, $\cos\theta dA d\Omega$ (where θ is the angle between the normal to the surface and direction in question and Ω is the solid angle involved), conserve the ratio of flux to throughput, or *radiance:*

$$L = d^2\phi/\cos\theta \, dA d\Omega$$

This is the radiometric quantity of primary importance in imaging systems.

In principle photometric, that is luminous, quantities could be derived from the corresponding radiometric quantities by performance of an algorithm. Thus the spectral radiometric quantity of interest could be integrated with an agreed normalized eye-response curve, for example that of the CIE photopic observer, $\bar{Y}$ or $V(\lambda)$. The resulting integral could then be multiplied by the constant K_m, the ratio of the average eye sensitivity at its maximum in lumens to radiometric power in watts. For example, *luminance* L_v could in principle be calculated from spectral radiance,

$$L_\lambda = d^3\phi/(\cos\theta \, dA d\Omega \, d\lambda)$$

by means of the algorithm:

$$L_v = K_m \int V(\lambda) \, L_\lambda \, d\lambda$$

But in practice, a separate system of photometric quantities was required long before a complete radiometric foundation had been laid. As the Stratton quotation on page v suggests, the photometric system was already in wide use seventy years ago for the description of visible light sources. Initially there had been oil lamps and candles, which were not employed with fixtures or other optical systems. The primary interest was therefore in the comparison or prediction of illumination in a certain direction at various distances from a source. At distances large compared with the source dimensions, the concept of intensity, with dimensions of flux per unit solid angle,

$$I_v = \int L_v \cos\theta \, dA \approx d\phi/d\Omega$$

permitted such comparison of sources. This quantity, intensity, provided the practical utility that it could be identified with a source rather than with an arbitrary surface that must be specified in space at some distance from the source. Moreover, with the assistance of certain assumptions, the concept of intensity also facilitated the comparison of two different sources by means of the extremely important but highly non-linear and non-digital detector, the human eye. Given additional assumptions, the necessity for independent but unavailable radiometric data was avoided (or more accurately, obscured).

Initially, arbitrary candles were established as national units of luminous intensity. These units were then compared with, and defined according to, the intensity per unit area in the aperture of a platinum blackbody. This unit was incorporated into the SI system as a Base Unit. The present definition then (1) permits independent laboratory realization of the unit of luminous intensity, and (2) provides a loose coupling to radiometry via Planck's law and the melting point of platinum. Presently used values of the melting point of platinum vary from 2040.8 [5] to 2045 K [6]. These values lead to the values for the coupling constant, K_m: 690 lm/W and 673 lm/W respectively. Very recently, Blevin has shown that consideration of the index of refraction of air raises previously published measured melting points 0.3 K and lowers the corresponding K_m by 3 lm/W [7]. The 3% spread between 687 and 670 is comparable to the 2% spread in photometric measurements made in national laboratories, as described later in Appendix B. Few measurements are more certain than this. Most are substantially less certain.

Thus, although in principle photometric quantities could have been derived from radiometric quantities, in practice the corresponding unit systems have developed along independent paths. In radiometry the quantities realized are those just noted: spectral radiance, spectral irradiance, and irradiance. In photometry, the quantities realized are not the corresponding quantities, luminance and illuminance or illumination, but rather luminous intensity and luminous flux. The difference in the genesis and operation of the two unit systems reflects the contrasting nature of the measurements actually made in the two fields. These differences are of much more than academic interest with the recent growth of the electro-optics field and the consequent rapidly increasing desire for convertibility between the two systems of measurement in the characterization of a single object.

C. THE CONCEPTUAL MODEL

Measurements of optical radiation can be divided into three interrelated but distinct shells and each of these into radiometric and photometric components (Figure 1). In areas

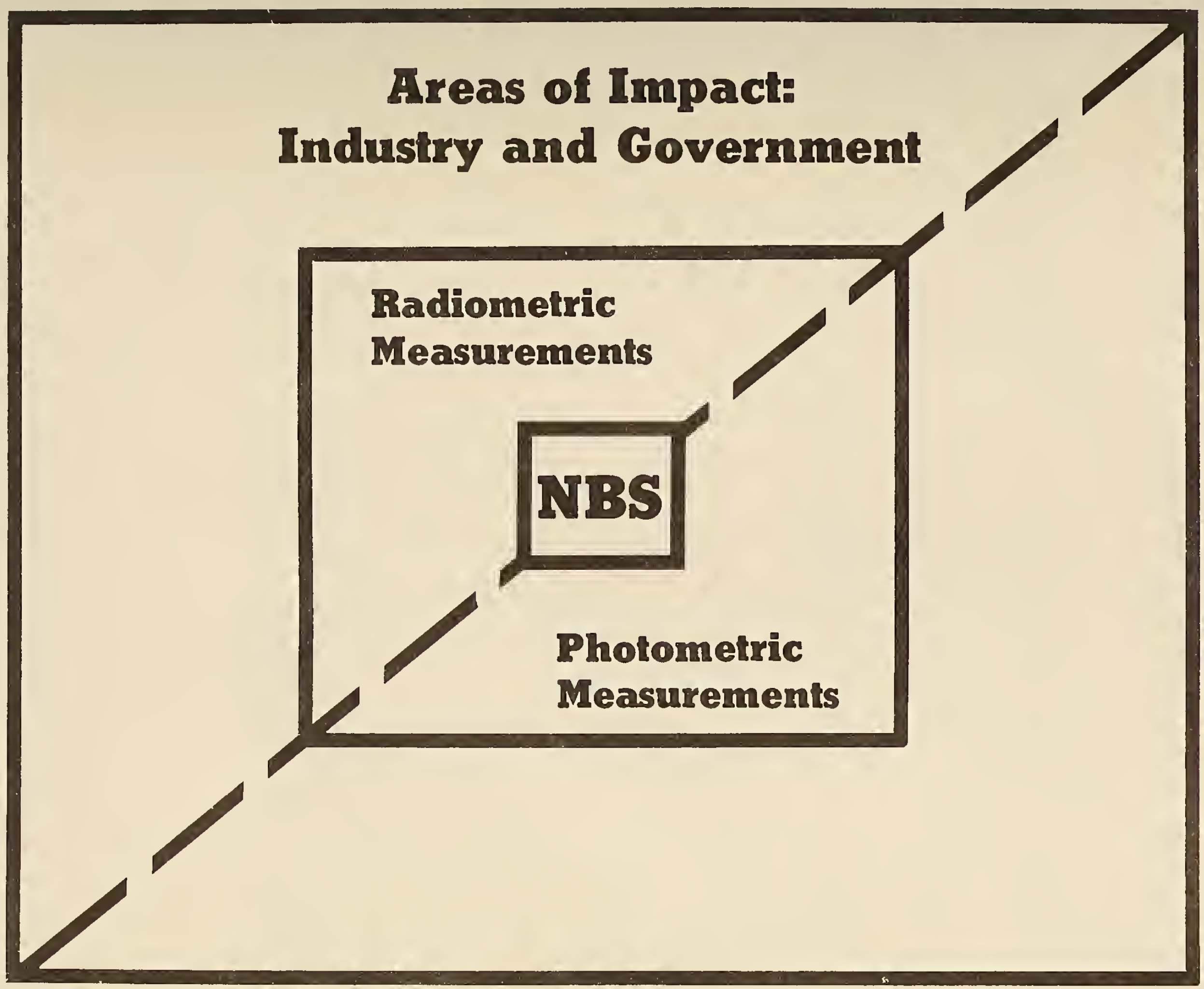

Figure 1. Relationship of areas of preceding study [1], outer box, to the area of present study, middle box, and to NBS, the inner box.

of impact the measurements made by a wide variety of industries, and increasingly by government agencies, are generally motivated by non-measurement considerations. For example, production, improvement in efficient energy utilization, and concern for public safety and health are issues of current concern. The specific rationale for improvement in optical radiation measurement, which is to be found in the outer box in Figure 1, thus comes from outside the system of measurements itself, the middle and inner boxes of Figure 1. The areas of impact comprising the outer box were reviewed in an earlier NBS Technical Note [1].

The optical radiation measurements themselves, the fields of radiometry and photometry, constitute an exceedingly informal but elaborate system. If this system performed satisfactorily for those who employ it, an analytical examination of this system would be of only academic, or metrologic, interest. But as the preceding Note indicated, the performance of the system is widely considered by those in the areas of impact to be severely inadequate to the demands made on it. If the system is in fact to be made more responsive to new and growing demands, it must be analyzed. This analysis forms the core of the present Note.

At the center of the informal system of optical radiation measurement in the U.S. is the National Bureau of Standards. The reasons that it should be involved in the analysis of the measurement system and in subsequent action to improve the system have been reviewed previously [1]. Programs designed to address the current problems are presently being developed by Dr. H. J. Kostkowski, Chief of the Optical Radiation Section, and his staff.

The looseness of the coupling between radiometry and photometry, as currently practiced, is also symbolized in Figure 1. The problems in the areas of impact that radiometry and photometry were designed to address also show a corresponding division. The influence of this historical division is still strong and must be acknowledged. But both parts must now be analyzed together as components of a larger system. This system is already being unified at NBS. Elsewhere it is rapidly becoming highly interrelated.

CHAPTER II

Present State of the Art

A. EXPLOSIVE GROWTH IN DEMAND

The feasibility of various solutions to the measurement problems will depend on their origin and extent. One source of desire for vastly improved radiometry and photometry can be found in two distinct types of growth: (1) rapid movement of the frontiers of electro-optics *technology* and (2) growing *public awareness* that technology must solve or ameliorate large scale problems that have important technical elements. In each of these cases the growth involved has two aspects. First is a rapid general expansion characteristic of the middle part of the growth curve for new fields. Second is a broad diversification in the technology, diversification involving expansion in multiple directions simultaneously.

A survey of the initial development in demand for sophisticated optical radiation measurement appeared in the preceding Note [1]. Prominent examples both of rapidly moving technology and of increasing public awareness were described there. Commercial as well as technical concern with the present status was cited in detail.

The rate of growth can perhaps most succinctly be summarized by a Table. It shows recent and projected dollar volume for several parts of American industry most directly affected by optical radiation measurement.

TABLE
(Source: Reference 8)

Millions of Dollars

	1967	1968	1969	1970	1971	1972	1975	1980
Lamp (bulbs)					943	1015	1243	1703
Lighting Fixtures					2254	2478	3301	5259
TV Tubes	823	680	580	464	500	520		
Optical Instruments	407	458	484	508	535	565	675	995
Photographic Equipment	3665	4009	4317	4403	4667	5040		

The parallel increase in diversification of the technology as well as its dramatic increase in efficiency is illustrated in Figure 2 [9-11]. By incorporating new technology the efficiency of space illumination increased more than twenty fold between 1905 and 1965. Even these recent data were rendered obsolete on 3 October 1973, while the current Note was in press, by the announcement of low pressure sodium lamps generating 183 lumens per watt [12], an increase in 74% over the highest value in Figure 2. Other specific examples of recent growth are reviewed in Appendix A.

B. NATURE OF THE MEASUREMENTS

1. Five-Fold Parameter Variation

Optical radiators and detectors typically differ from one another in five different parameters: the total power or photon flux level or sensitivity; spatial distribution of (or sensitivity to) this flux; spectral distribution (or sensitivity to) this flux; temporal distribution (or sensitivity to), this flux; and polarization.

a. Level

Differing power or photon flux levels are generally unavoidable in optical radiation measurement. With a gread deal of effort and cleverness, such differences can of course be minimized in the standards laboratories. But the field of optical radiation measurement in essence consists of the measurement of differences in level as a function of various parameters. In general, therefore, these differences are to be measured and not avoided.

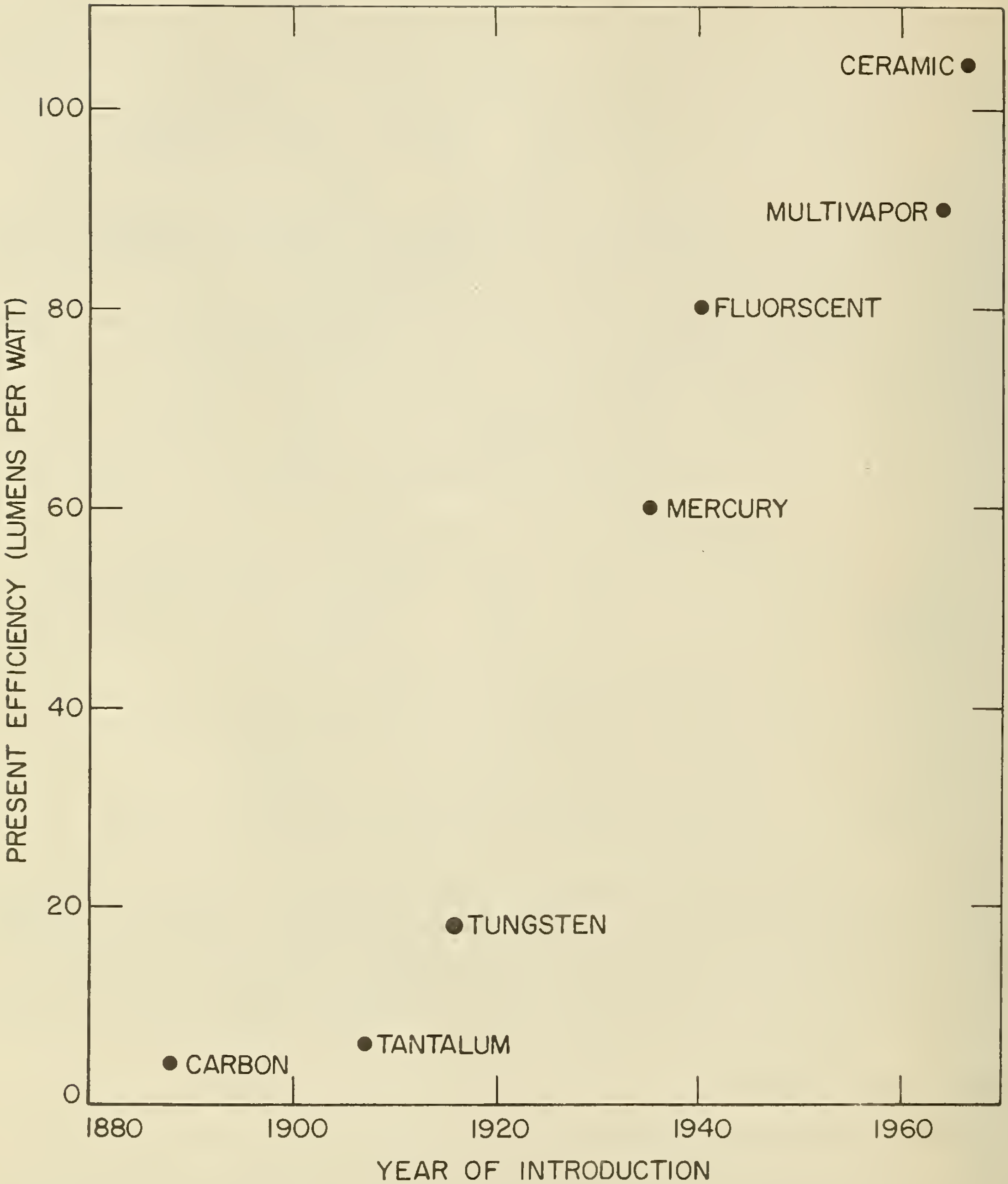

Figure 2. Growth curves of lamp efficiency for various types of lamps as a function of time of introduction (Source: References 9-11).

If detectors were generally linear, or if standards existed over the twelve decades of general measurement from one watt to 10^{-12} watts, then the measurement of different levels would not constitute a problem. But neither of these conditions obtains. Detectors are generally non-linear by unknown amounts, and standards do not exist at more than a few levels. The further one gets from the level of the standards [13], the lower the level of agreement. Many approaches to the determination of detector linearity have been used; they were reviewed recently by Sanders [14]. The various techniques provide differing combinations of accuracy, convenience, and freedom from interactions with the other parameters: directional, spectral, temporal, and polarization dependence. Thus, the choice of an optimum technique may thus be rather complex. Underestimation of this complexity is frequently associated with large disagreements among measurements.

b. Spatial distribution and sensitivity

With rare exceptions, the spatial distribution of commonly used sources and the spatial sensitivity of detectors are generally significantly non-uniform. The lack of uniformity in the flux distribution of lamps, for example, is sufficient to introduce question in the total flux produced by different types such as incandescent lamps and fluorescent lamps [15], and even among the various types of fluorescent lamps. Agreement among measurements of light emitting diodes is hindered by unpredictable variation with distance [16]. The orientation of standard lamps in the measurement of directional properties such as irradiance and intensity has contributed a major source of error [17-18].

Work with detectors frequently involves differences in image size, location, and angle of incidence. The non-uniformity of response of detectors is thus only rarely insignificant but is frequently ignored in actual measurements. New solid state detectors promise to be substantially more uniform than vacuum photodiodes and multipliers, whose response involves a complex integral of photocathode characteristics and electron optics. The solid state devices surely offer a simpler approach to some radiometric and photometric problems. But the extent of improvement in agreement among measurements remains to be determined.

c. Spectral distribution and sensitivity

The spectral distribution of the flux emitted by lamps now in common use varies widely [1]. Nevertheless, the photometric system has of past necessity been constructed on the assumption that the spectral distribution of lamps undergoing measurement either is identical or can be made so at the detector by appropriate filters. Fluorescent lamps have strained these assumptions to the point that arbitrary adjustments have had to be made in their comparison with incandescent lamps [19]. The measurement of flux emitted by high intensity discharge lamps indeed is so uncertain that few intercomparisons have been undertaken at all.

Similarly, spectral response differs greatly from one detector to another, perhaps even of the same type. To be sure, some new solid state detectors promise to be similar enough to each other to permit interchangeable handling for the first time. But such treatment is still to be performed only with great care [20].

The measurement of detector spectral response, although simple in principle is now performed commercially in the U.S. only with unacceptable levels of agreement, a factor of two. (Figure 3). Several representatives of the detector industry have turned to NBS with requests for assistance [21-22].

d. Temporal behavior

Both in radiometry and photometry the greatest emphasis has been placed on sources that are relatively stable. Although fluctuations can be observed in any source or detector, these fluctuations have frequently been of the order of percent or less over a time period of seconds or minutes. Such instability influences measurement enough that it is not to be neglected in precise measurement. But in the absence of wide fluctuation of sources, the frequency response of measurement systems has been a factor of secondary importance in their analysis.

There is however a considerable and growing number of fluctuating sources of interest. The most efficient light-producing media are arc discharges. These respond rapidly enough to 60 hertz alternating current to display considerable ripple in the emitted flux. Thus, for example, the mercury spectral lines in fluorescent lamp spectra display 60 hertz modulation, while the fluorescent continua in the same lamps do not. The spectra of high intensity discharge lamps also display this 60 hertz variation. Moreover, with increasingly accurate requirements for photography, the measurement of singly and repetitively pulsed

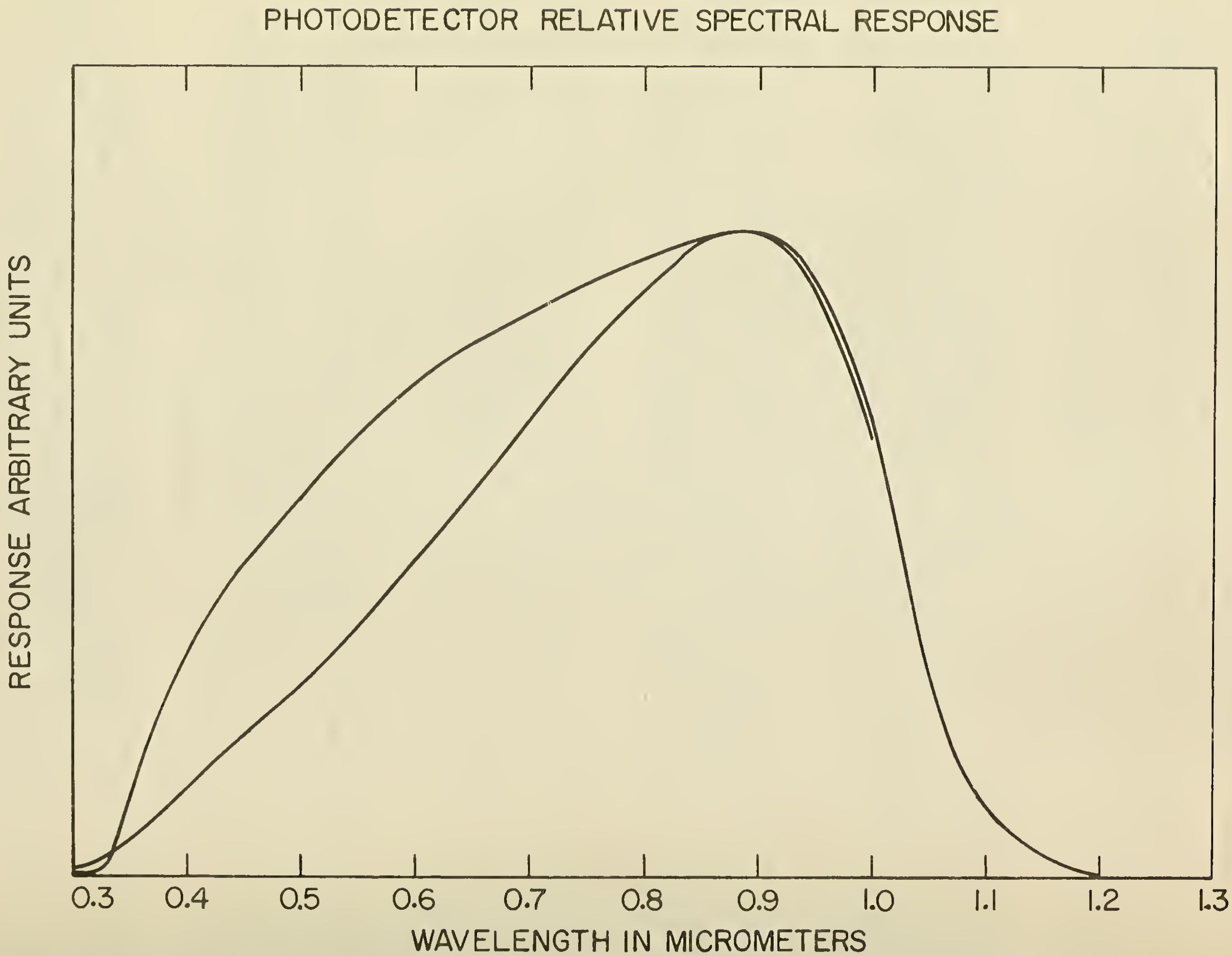

Figure 3. Commercial spectral response measurements on a silicon photodiode.

sources becomes progressively more important. These rapidly varying sources must be compared at some point with relatively unvarying sources, a comparison that requires new techniques as well as the re-evaluation of old ones.

e. Polarization

Polarization is an aspect of optical radiation measurement that is frequently ignored. In some careful work polarization either has been demonstrated to be negligible or has been reduced by the incorporation of diffusing elements into the optical system. Nevertheless, polarization is a significant problem in other areas of optical radiation measurement [23-25]. Polarization is becoming more important both because sources are increasingly remote from blackbodies in character and because optical systems, especially spectrally dispersive systems, are increasingly complex. Each reflection and dispersion can introduce a substantial amount of polarization and increase the sensitivity of the transmission of the optical system to the character of the polarization of the source.

2. Common Measurement Elements

A complete measurement will require not only an evaluation of these parameters, but also of their fundamental dependence on the environment and its fluctuation. Effects of variation in temperature, pressure, and humidity, must be determined. The temporal behavior of standards over an extended period of time must be also be learned. Earth satellite measurements in particular require an estimate of temporal stability over months or even years.

The relative importance of these various factors and their environmental dependence will depend upon the particular measurement being made and the degree of similarity of the object being measured to the measurement standards involved. In general one starts a measurement with no prior information. He must now characterize his source, detector, and optical system to the extent necessary for the particular measurement of interest. Since similar information will be desired for most standards and system components, generally available information of this type has been requested in order to save substantial duplication of effort. The detailed description of successful techniques would save similar widespread duplication in development effort by all laboratories making comparable measurements.

3. Uncertainty: A Question of a Point of View

The uncertainty of a measurement, like its beauty, is in the eye of the beholder. This is not to say, like beauty, uncertainty cannot be estimated on an objective basis. Rather the basis itself is a parameter to be assigned in context.

Several uncertainty bases are used in optical radiation measurement, for example, an uncertainty with respect to the International System (SI) will differ in general from that with respect to units maintained by NBS, or from that with respect to another group of comparable measurements. That is, uncertainty implies fidelity to a system. This system in question must be either specified or directly implied before the term "uncertainty" has meaning.

For measurements designed for severely limited reference, the point of reference must always be specified. For example, if a given measurement is intended for reference only to other measurements made in the same manner, the precision of the measurement will frequently act as a valid predictor of agreement, and might be designated the uncertainty of the measurement. If the measurement in question is destined for comparison exclusively with other measurements made in one of only a few different ways, then the precision of the result from all such measurements conceivably could be taken as a measure of uncertainty, provided that the results are sufficiently homogeneous. Figure 4 represents data similar enough to be compared in this manner. The measurement of the luminous flux produced by incandescent lamps is shown as a function of production year. In such a system incorporating only a few measurement methods, even heterogeneous data can still be reconciled by correction factors allowing for systematic differences. The application of such correction factors *de facto* defines a reference to which the uncertainty is related by the size of the factors involved.

In the most general case of assessment of uncertainty, where each potentially important comparison with other measurements cannot be anticipated, an estimate of the limits of all systematic effects must be made in order to arrive at an estimate of the overall uncertainty. Figure 2 illustrates data too dissimilar to be compared reliably without taking into account systematic effects. The spectral differences of differing lamp types are large

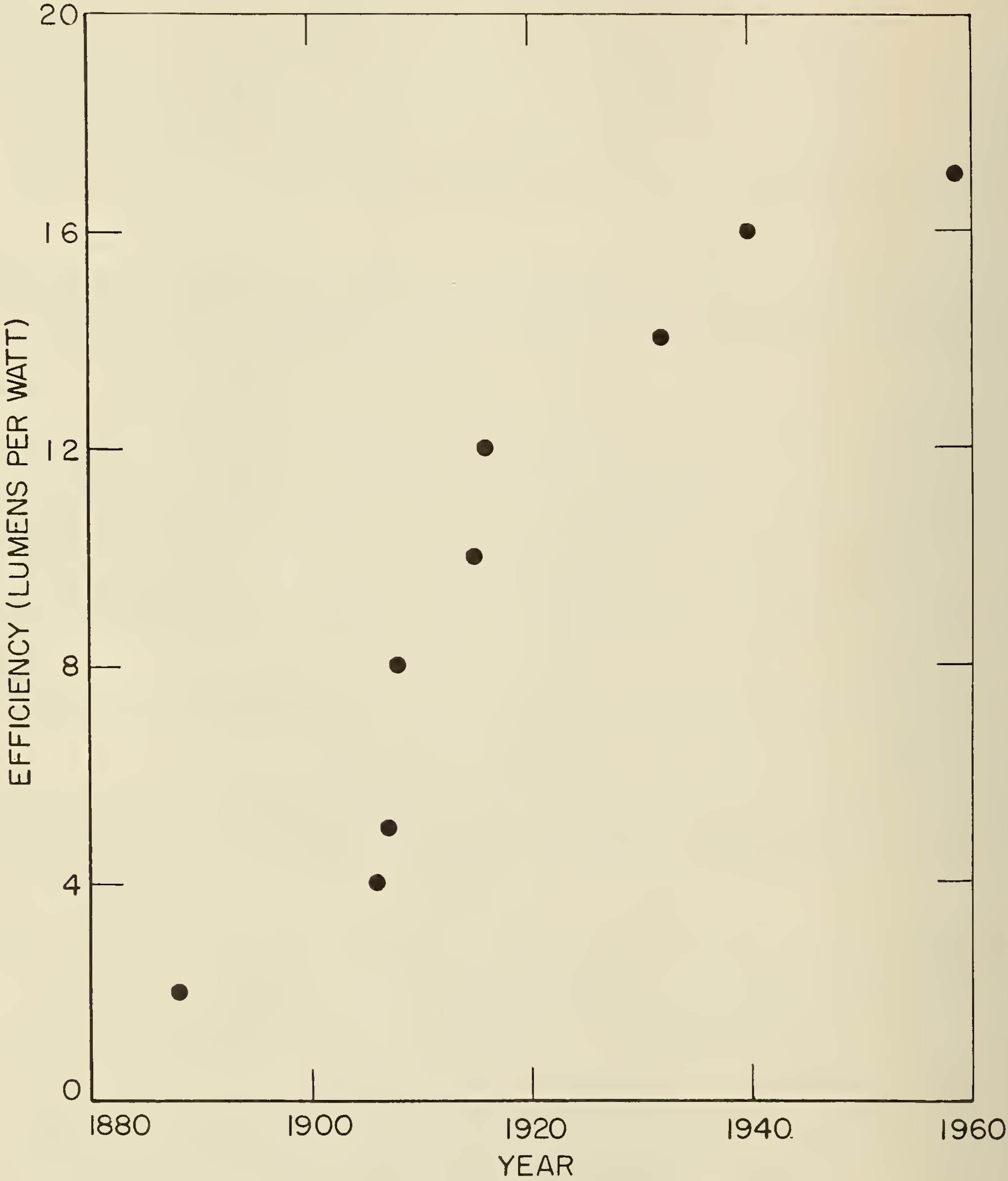

Figure 4. Increase in incandescent lamp efficiency as a function of time (Source: Reference 10).

compared with the precision of the measurements. Uncertainty here refers implicitly to international units, the SI. This is the uncertainty that conservative estimators will want to use. Because of the increasingly wide variety of measurement that are to be compared, it is the uncertainty with respect to SI that increasingly must be used to provide a reliable predictor of agreement among measurements. There is relatively little of such information presently for optical radiation measurement.

Certain consequences of the availability of systematic information can be grouped in the following manner. Progress in any field depends on two types of advance: breakthroughs provided by a new technology, and gradual but steady improvement in existing technology. For the former type of progress to take place with assurance, major systematic errors (with respect to SI) must be avoided so that the comparison of different technologies is not obscured by systematic errors comparable in size to the effects being observed. Since new technologies are particularly prone to unexamined systematic errors, critical attention must be paid to the various parts of the system. One example in classical photometry is the evaluation of the flux emitted in all directions through use of detectors with a photopic response. Since the spectral distribution of most new lamps differs so greatly from that of the incandescent lamps with which they are to be compared, the photometric detector employed in such measurements must correspond much more closely to the defined visibility curve than must a detector used simply for intercomparing different incandescent lamps of relatively similar spectral distribution.

Slow gradual progress also becomes exceedingly important in aggregate. Figure 4 shows such progress in the efficiency of incandescent lamps. The improvement of about 50% in fluorescent lamp efficiency over the last twenty years has already been cited [1]. Such gradual progress (Figure 5) will depend both on the precision of the given measurement and on the stability of a relatively arbitrary "base line". Precision is exceedingly important here because of the small size of individual increments that accumulate to an impressive size over an extended period of time.

4. Factors Associated with Automation

The automatic control of measurement presents not only new opportunities but also new requirements for optical radiation measurement. Automation offers the possibility of such voluminous data collection that much more precise information can now be obtained for a given measurement than was previously possible. To realize the advantage of this complete information, radiometric measurements must be redesigned with two factors in mind. First, smaller systematic effects will become more obvious and thus must be included in experimental investigations. The increasing visibility of measurement differences among increasingly precise numbers is leading to great commercial pressure for a better understanding of these measurements. Second, measurements must therefore be conceived with automation in mind at the planning stage.

5. Conclusion

Thus for much work in optical radiation measurement, the SI uncertainty is of growing importance. It is the required information on systematic errors that is most conspicuously lacking throughout the measurement system. Dramatically increasing precision is making this void increasingly felt.

C. TRAINING

Radiometry and photometry draw extensively from two relatively independent fields: optics and radiant heat transfer. Those with experience in one of these areas usually have little background in the other. Formal training specifically in radiometry and photometry is not widely available. Many enter from peripheral fields that employ photons as tools, such as spectroscopy or collision physics, or from the even more distant electrical engineering.

This lack of a single focus for training has important general consequences. As we shall see, the field is generally fragmented into many different schools of experience and thought. Technical papers appear in widely scattered journals. No coherent body of practice or literature has developed.

Specific technical consequences of these heterogeneous roots also can be identified. One example is the differing development and position of the concept of intensity in radiometry and photometry [18]. While the concepts of intensity and a point source have been

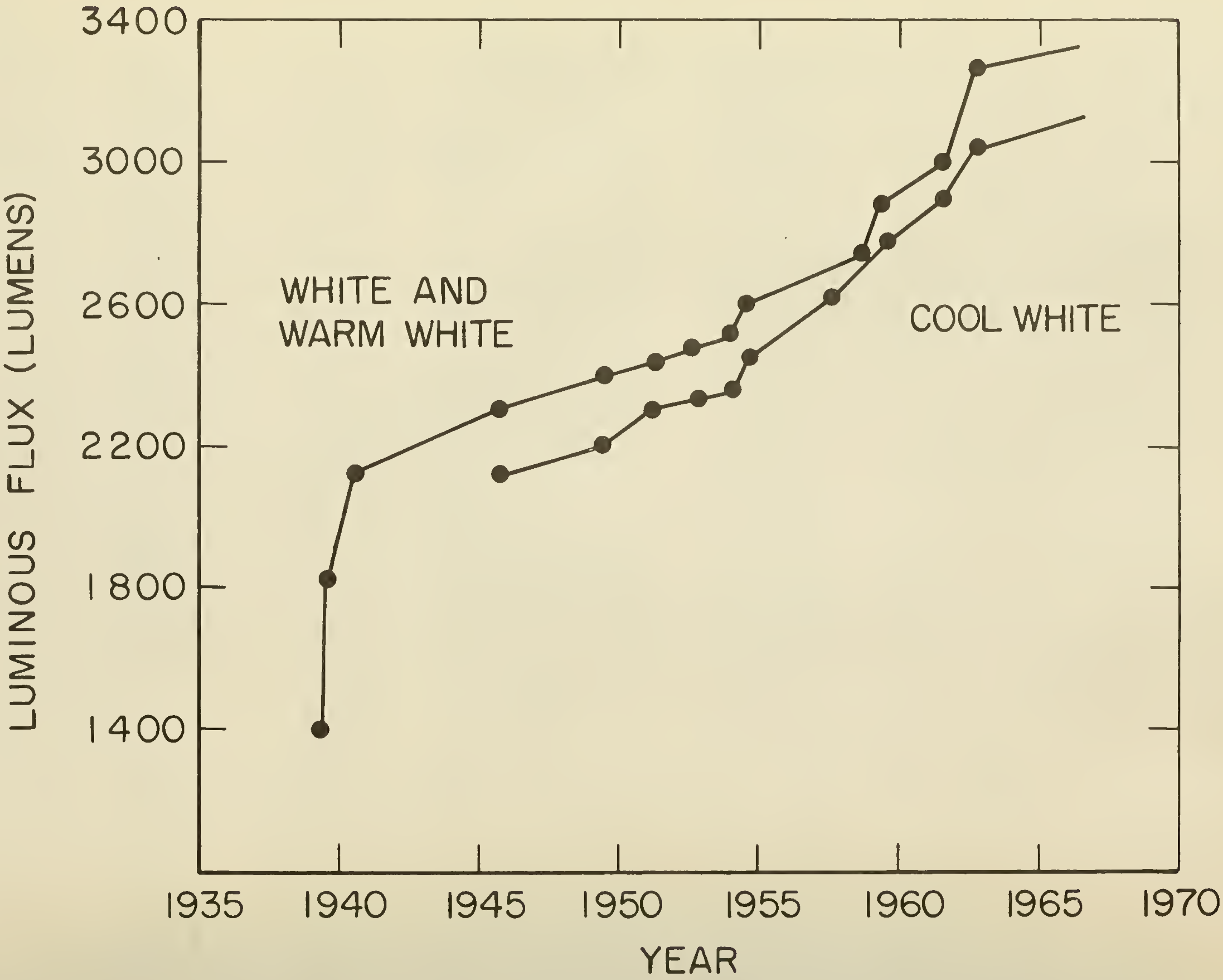

Figure 5. Increase in the luminous flux of commercial fluorescent lamps as a function of year of production.

central to the development of the photometric unit system, radiometry makes use of these concepts primarily in engineering applications. In photometry, intensity is used as the point of departure for other photometric quantities; while in radiometry, the point of departure is either radiance or flux. The distinction is not merely an academic one. Zalewski has shown that subtleties in the use of intensity can lead to practical difficulty in the realization of the unit system [18].

Another example of the fragmentation of the field of radiometry is the use of widely varying types of nomenclature for given concepts. The situation is so serious that indeed some radiometrists spend a substantial fraction of their time attempting to sort out what their colleagues are doing on an elementary level. A comprehensive radiometric dictionary is now under development by one of the most respected radiometrists, Fred Nicodemus. This dictionary should constitute a major milestone in the field. In an exactly parallel manner, experimentalists are being called upon to identify what precisely has been determined in various measurements. Only in this way can various results now be intercompared in a satisfactory manner with predictable levels of agreement.

Because it has been neglected so long, training is very badly needed. But before appropriate training is to become widely available, appropriate materials must be developed. This material requires in turn the development of a firm systematic data base so that appropriate generalizations can be drawn.

CHAPTER III

The Present Optical Radiation Measurement System

A. THE MODEL

Optical radiation measurements in the United States are not performed within a completely formalized system of measurement. The typical measurement is made by comparison to one of a variety of standards in a manner dictated by tradition, by an agreed procedure, or by reference to the laws of physics as perceived by the experimenter.

Nevertheless, the system is not completely formless. It consists of three distinct aspects: the flow of physical standards (hardware), the flow of procedural standards (software), and the flow of funding (administrative structure). The structure of each of these "subsystems" differs from the others, but all are interrelated. The rates of change of each also differ. These three system components will now be examined. Then the role of the professional society will be reviewed. Finally, the effort to identify, strengthen, and extend the structure through the formation of the Council for Optical Radiation Measurement will be described in some detail.

One general feature of the entire system was outlined in Chapter I: the dichotomy between radiometry and photometry. The division is the natural consequence of the historical development of each, which was sketched. The periods of greatest activity have taken place at different times. Separate standards and procedures have been developed. Funding has been along rather different administrative lines.

Two years ago NBS took the initiative by combining its activity in the two areas into one administrative unit. Since then, the committees on photometry both of the Comité Internationale des Poids et Mesures and the Commission Internationale de l'Eclairage have added "radiometry" to their names. The change in these committees is already more than nominal. The maintenance of two separate systems is now being actively questioned, particularly by those entering these fields for the first time. NBS has recognized that the technical effort to build bridges between the two systems, however, must be based on a firm awareness of the situation as it actually exists at present, as well as on anticipation of future modifications in the system.

B. PHYSICAL STANDARDS (HARDWARE)

The general flow of physical standards in the U.S. takes place within a framework shown in Fig. 6. A measurement occurring in any one of the areas indicated is related to other measurements by a series of operations that is referred to as a calibration chain. In general, this chain will have one link in each of the areas indicated; but such a long chain is not always involved. Another general feature of the flow of standards is a much more explicit definition near the origin of the national system, close to NBS, than at more distant points. The individual links in this chain are described in Appendix B along with data on their performance.

C. PROCEDURAL STANDARDS (SOFTWARE)

The complexity and variety of the measurements noted in the previous chapter, coupled with the existence of relatively few physical standards, has led to uncomfortably large disagreement among these measurements. The situation would nevertheless be even worse if it were not for the development of various formal procedural standards by workers in various fields. Since the systematic errors contributing to a given measurement are not in general understood quantitatively, the present levels of agreement have been achieved only through formal concurrence to perform various measurements in given ways. Because of the diversity of the fields involved, a wide variety of organizations has developed to generate and codify the required procedural accords in each field. The boundary line between the procedural-standards organizations and the professional societies is sometimes indistinct. These groups are listed and described in Appendix C.

The dominant impression left by a survey of the various organizations related to optical radiation standards is one of diversity. Various organizations have been established or utilized to deal with restricted problems. Identification of specific activity and its coordination are serious problems.

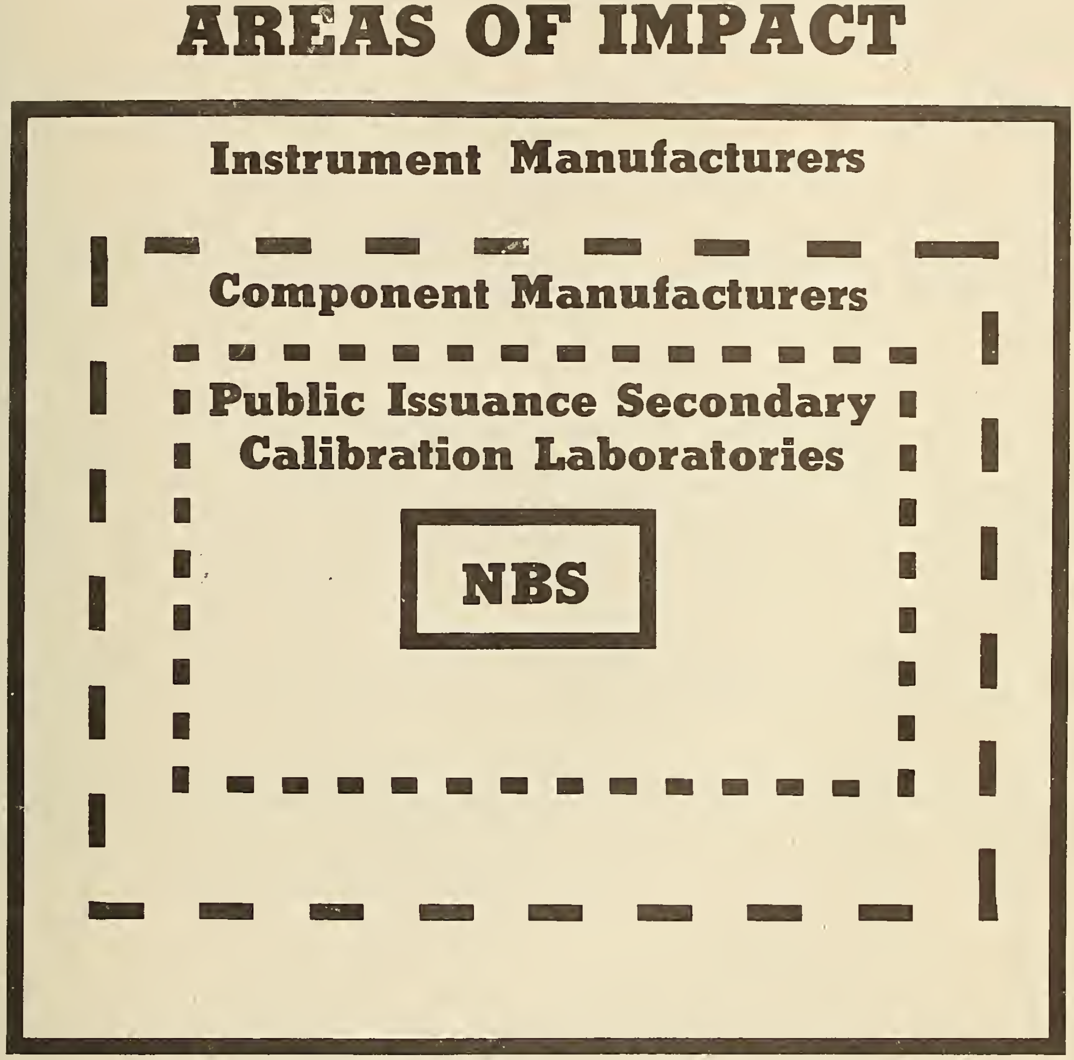

Figure 6. Physical standard measurement system.

However, an even more immediate problem has been identified by Robert D. Compton, editor of Electro-Optical Systems Design [26]. He writes "One of the beauties of the transistor and tube industry is that some semblance of order has resulted through the standardization of products through the EIA component registration process. What old timer in the electronic industry has not heard of the 2N174 transistor or the 6L6 tube? By contrast, it is a very sad commentary on the optoelectronic industry that so few devices have been registered and that, without exception, only one company makes each of those devices that have been registered. How can we expect the general usage of the phototransistors, photodiodes, LED's, and other optoelectronic devices to grow when we discourage usage of these products through the strict use of house numbers to identify products?" Mr. Compton has certainly identified a serious problem. It is even more serious than its mere statement might suggest. The radiometrist suspects that, in spite of an elaborate superstructure of standards groups, the agreements called for could not be reliably formulated at this time. If an attempt were made to do so, it would not really ameliorate the situation. Measurement agreement is not sufficiently precise, not to mention accurate, to support an identification system similar to that of the electronics industry. There is no serious question that a reliable registration procedure would be desirable. But we must advance in measurement capability to make such a system feasible. At a crucial time in the development of the new optoelectronic industry, the physical measurement system is so seriously inadequate that the procedural standards groups cannot perform important tasks.

D. FUNDING FRAMEWORK

The nature of NBS funding of work in the areas of radiometry and photometry is related strongly to the development and the status of each. Radiometry has been funded, both in the system as a whole and within NBS, substantially by other agencies of the Federal government. The primary agencies involved have been the Department of Defense and the National Aeronautics and Space Administration. This funding provided a certain slow but steady and firm development of basic measurement standards not available anywhere else in the world. Recently however, this "other agency" funding has decreased markedly, while at the same time commercial and public factors have been receiving increased attention.

Photometry, on the other hand, has until recently largely operated on a pay-as-you-go basis. Research funds have been devoted largely to the subsidization of the replication of standards and consultation among users rather than to the development of superior standards. The research base remained correspondingly weak.

The flow of funding in both areas has been far more important than the value of money involved. In radiometry, the agencies involved provided explicitly a set of priorities and implicitly a program framework for NBS. In photometry, the lower level of outside research funding has been paralleled by the absence of an external structure for the establishment of priorities. The current shift in NBS program emphasis from the relatively well-focused "other agency" interest to far more diffuse commercial needs and those of less well-established government agencies have left the field without its program formulation structure. NBS has responded to this situation by a consolidation of its effort. But how are the diffuse new needs to be correlated and priorities established apart from NBS? The sheer number of standards groups in the field seems to preclude their presenting a coherent approach to this fundamental organization problem. Two approaches present themselves. The first is coordination by the relatively small group of professional societies; the second is the establishment of a new organization for the necessary coordination. These two approaches will now be addressed in turn.

E. ROLE OF THE PROFESSIONAL SOCIETY

Many individual members of the professional societies have certainly been aware of the growing technical problems in optical radiation measurement. Nevertheless, for several good reasons the attention of the professional societies has been directed elsewhere. It will prove worthwhile to examine these reasons now before examining alternative approaches.

The primary purpose of a technical society is the advancement of the field, typically through conferences and journal publications. The professional societies tend to represent the research-oriented, most rapidly moving parts of technology. Lack of agreement among such workers is not only expected, it is really a way of life. What sets the electro-optics industry apart perhaps from others is that, even after the first wave of rapid development has passed, agreement has not followed as it has elsewhere. The man at the bench who has had to face severe measurement problems over an extended period of time is typically not active in the professional societies. He has been more active in the standards groups. The professional society member has looked at the serious measurement situation as one to which *others* should address themselves and not one involving the professional societies.

Closely correlated with these underlying factors within the professional societies has been the lack of a mechanism to provide for action. These societies are typically "presentation" societies and "debating" societies but not "action" societies. Valuable action has been undertaken on occasion. An example is the Committee on Color of the Optical Society of America. But a more typical role is represented by other activity of the Optical Society. Recent experiments are described in Appendix D.

F. THE COUNCIL FOR OPTICAL RADIATION MEASUREMENT

An outstanding characteristic of the present measurement system as defined in the preceding sections of this chapter is an absence of overall coordination of activity and a focus for cooperative effort. The reasons that NBS alone cannot fulfill this function are discussed in Appendix E. As described in that Appendix, a new cooperative venture was called for and established last year: The Council for Optical Radiation Measurement. By means of a series of meetings, the Council developed the document, "Pressing Problems in Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS" [21]. More recently, the Council has completed the formulation of a detailed "Program for Action" [27].

The Council has elected to operate as an activity of US TC 1.2 on Photometry and Radiometry of the CIE. It has done so for several reasons. In the first place, an increase in the number of independent groups in the field seems to be undesirable if avoidable. More specifically, the international impact of the technical problems dictates an approach that provides for ready expansion into international effort. And finally, the existing international CIE technical committee projects already provide a basis for an international technical effort that it would be unfortunate to duplicate in a parallel organization.

Four types of activity are called for. In the first place, dissemination of useful information and debate on suitable approaches to specific problems through professional and quasi-professional meetings seem essential. In the second place, technical activity through cooperative technical projects such as those already underway within international TC 1.2 provides an essential foundation. In the third place, communication of information on priorities throughout the field to NBS for its use in the formulation of its program is an important step to optimum expansion of the availability of physical standards. And finally, greater coordination of information about and among the procedural standards groups is a widely recognized area of concern. Separate groups have been established within the Council for the achievement of each of these four objectives.

CHAPTER IV

Challenges Facing the National Measurement System

A. SYSTEMATIC FACTORS

1. Flow of Physical Standards

In the preceding chapter the chain of calibration between two typical measurements was shown to consist of a number of links. Both the length of this chain and its weak nature are causing very serious concern among those making measurements. If the performance of the entire system is to be improved this measurement chain must be evaluated quantitatively. Since NBS is located in a calibration chain typically roughly half-way between two measurements, NBS may be in a position to exert great influence. Already by a recent change in its calibration policy in order to provide certain standards to anyone who asks, NBS has shortened some of the chains involved. In many cases a reformation of the individual links may be called for.

2. Flow of Procedural Standards

The flow of procedural standards is much less clearly defined than is the flow of physical standards. Many different organizations have addressed themselves to agreement on procedures and practices in limited measurement areas. The cooperative industry-NBS role in the formation of the Council for Optical Radiation Measurement offers some hope for additional coordination in this important area in this country. The job of coordination is an enormous one. It remains to be seen whether the CIE will rise to this challenge.

3. Flow of Information for the Establishment of Priorities

The transfer of responsibility from the Department of Defense and other relatively centralized Federal agencies to decentralized communities has left an administrative vacuum and a new and expanding need for leadership and coordination. The Council for Optical Radiation Measurement and NBS have a challenge in the fulfillment of this role.

B. TECHNICAL FACTORS

The extremely complex nature of optical radiation measurement was reviewed in Chapter II. The existence of only 25 standards [13] on which to base a wide variety of measurements is crucial. If the system were more restricted in size and if the technical nature of the problems were less complex, then perhaps it would be feasible to establish physical standards similar to every type of object that one wanted ultimately to measure. But such an approach is not feasible for so complex a system. And even if it were adequate now, it would not prove viable in the long run for a technology so rapidly advancing.

Thus, in addition to the diversity, there is the rapid growth of the field. If one were "merely" to strive to solve today's problems as completely as possible and as rapidly as possible, the resulting hasty solutions would very likely be inappropriate to the problem that actually existed upon completion of such a crash program.

Approaches must be designed to address these two technical characteristics: complexity and growth. Dr. Kostkowski, Chief of the Optical Radiation Section at NBS has noted "a standard itself does not solve your measurement problem" [28]. NBS has thus recognized the necessity for a broad approach to the solution of optical radiation measurement problems.

C. COMMERCIAL FACTORS

1. Cost

The technical constraints just described imply in addition some economic constraints. First, the complexity of the measurement means that, without substantial outside assistance, institutions making reliable measurements face very high measurement costs. Not only will highly trained people be involved, but at present a great deal of time for research will be required. The exceedingly high costs thus involved are simply not feasible for a large part of this fragmented industry. It is much cheaper to argue a case of disagreement in court, if it comes to that, rather than to set up a research laboratory to solve the problems on an individual basis.

Another cost factor involved is the size of the effort in quality control. Thousands of lamps must be measured by a large number of people in the lamp industry. Large numbers of measurements on film and cameras must be made. If the costs of sufficiently reliable measurements are to become compatible with production costs, then work must be designed to facilitate convenience, rapidity, and reproducibility. Much more effort in this direction is required.

2. Aggregation of Resources

We have seen that a great variety of technical problems must be solved in order to produce one reliable measurement of optical radiation. At the same time, similar problems must be solved for a wide variety of different measurements. It has just been noted that it is not economically feasible for most institutions involved in relatively isolated parts of the entire electro-optics field to solve individually all of the requisite problems. If the system is to be optimized only in a given plant or laboratory, the solutions will necessarily be short range solutions not generally applicable. Only by successfully addressing the entire set of technical problems can one justify a general, across-the-board approach. One basic role of the national laboratory is to analyze various specific requests received and to establish a program geared to optimizing the performance of the entire system, not of a particular segment. When the entire measurement system is brought into better agreement, intralaboratory performance will also improve dramatically and indicate to the individual company or agency that more reliable measurements have been achieved.

D. BROADENED FEDERAL CONCERN

In view of the recently increased public concern for technological answers to national questions, the Federal government is reviewing its role. Optical radiation measurement plays a part in all of the issues included in one recent outline reviewed in Appendix F.

E. CONCLUSIONS

A measurement system can be based on conclusions drawn implicitly from the various factors just described. Before defining one such system (Appendix G), it may prove useful to draw these conclusions explicitly.

1. Coordination of Activities

The complexity both of the measurement system and the administrative arrangements related to it imply the need for strong leadership. "NBS is being asked to help--to supply technical leadership and the know how in this measurement area" [29]. Nevertheless, even with a greatly expanded budget, it is clearly impossible for NBS *single handedly* either to define the problems comprehensively in detail or to bring about their solution. It was this observation that led NBS to contribute to the establishment of the Council for Optical Radiation Measurement. The question of such leadership is explored in Appendix E.

2. Source Characterization

Dr. Kostkowski has already noted that "we plan to characterize radiometric components" [28]. The necessity for such characterization is thus already recognized as part of the NBS program. Indeed until the system as a whole can perform such characterization on a broad basis, it will continue to perform unsatisfactorily. Source characterization is important not only to the lamp industry but to anyone making radiometric measurements.

3. Detector Characterization

The growing importance and stability of detectors require a parallel effort in detector characterization [22]. One can indeed anticipate that some of the burden for standards now carried by sources will be assumed in the foreseeable future by detectors [30]. Some are quite stable and easy to use. Indeed, although photometric units are defined in terms of a source, the photometric system is built *in principle* on a detector, albeit a very complex one, the human eye. Thus the use of calibrated detectors may now offer both theoretical and practical advantages over the more traditional photometric hardware.

4. Technique Building Blocks

Optical systems typically consist of more than sources and detectors. The intermediate components must be characterized not only optically but also radiometrically, that is, in their effect on the transmission of photons. In addition to the characterization of the physical components, various physical phenomena must be better understood if their influence is not to disturb serious optical radiation measurement. Examples of such effects are diffraction, polarization, and partial coherence [29].

5. System Performance Evaluation

Although some intercomparisons have been performed, as cited, there is a general paucity of precise information on operational levels of agreement. Where exactly are the problems, and the real needs? And how severe are they? The quantitative measurement of system performance by intercomparisons in a substantial variety of areas would facilitate the establishment of priorities for close attention in the measurement system [27].

6. Measurement Assurance

In the long run, the only way to guarantee that measurements in a system will agree to a desired level is to provide a program for measurement assurance. Such a program can have a variety of emphases, but it will necessarily involve periodic realistic sampling of the entire radiometric and photometric measurement system [31].

7. Types of Transfer

In addition to providing the capability to make various measurements, the system must engender communication of this capability to assure the transfer of the new technology as it is developed to the places where it is needed most. A technical paper in the literature that contains solutions to measurement problems but that goes ignored is clearly not influential. Indeed, until a system of transfer is perfected there will probably be little evidence of improvement in the measurement system as a whole.

8. Setting Priorities

That the problems described are urgent is beyond dispute. The measurement system must be coordinated in such a way that improvement is apparent to participants as early as possible. *Early attention must thus be paid to the most serious problems.* Relative urgencies must be periodically reassessed. Attention must also be paid to elements that have a *future* impact as well as an immediate one. The technical growth of the industry should be anticipated in such a way that solutions to the most severe problems are generated by the time the latter become crucial, rather than years afterward. These two priorities may appear to conflict, but in fact they need not do so. The second factor may define the elements of the program, whereas the first factor may define the weighting system attached to the various elements.

Acknowledgements

The furnishing of background data by Joseph Fones is gratefully acknowledged. Extensive conversation, cooperation, and advice from all of the Council for Optical Radiation Measurement participants and especially its leaders on CIE TC 1.2 are also very gratefully acknowledged. Contributions of the four Council coordinators should be mentioned in particular: The Council's founder, Robert Watson, the Council's present Secretary, E. S. Steeb, the Council's Coordinator with NBS, Franc Grum, and the Council's Coordinator for Technical Projects, Richard Becherer. Extensive conversations with Jon Geist are also gratefully acknowledged.

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APPENDIX A

Examples of Recent Requirements for Improved Measurement

1. ORIGINS OF DEMAND

a. New Technology

Light emitting diodes (LED's) are a visible manifestation of the new electro-optics technology. As was the case with lasers, much of the activity concerning LED's has centered around coaxing them to produce light at shorter wavelengths: first in the red, then down into the green, and ultimately into the ultraviolet. Red diodes are now common [32]; undoubtedly other colors will be appearing shortly in commercial quantities [33].

The entire history of space illumination for the past hundred years shows rapidly developing successive technologies (Figure 2) [9-11]. The most efficient lamps, both fluorescent and high intensity discharge lamps, are characterized not by a single spectral distribution but by a dozen or so that differ greatly from each other [34,9-11]. A diversity in geometrical shapes of lamps as technology progresses is another prominent feature of this development which leads to measurement difficulty. In addition, differences in the extent and type of fluctuating emission among these lamps add to the sophistication required for comparisons among different types of sources.

A parallel development has taken place in photon detector technology. Selenium solid state detectors are being replaced by silicon diodes, which have different characteristics. Relatively slow thermal infrared detectors are being replaced by a variety of quantum detectors and by a new type of thermal detector, the pyroelectric (capacitor) detector. Vacuum photodiodes and multipliers have been widely used for some time, but new photoemissive materials endow them with unfamiliar properties. Thus, the photometric measurement system, which in the U.S. and elsewhere was built largely on selenium photodiodes, is having to adjust itself to diversification not only in the types of sources measured but also in the detectors used to make the measurements. The measurement system is thus not only being improved, but technically modified in unquantified ways (with quantum detectors).

New complex instrumentation, which employs both new detectors and sophisticated low noise, solid state electronics is undergoing rapid development. New lines of equipment are either becoming available [35] or are about to be introduced shortly [36]. Established electronics firms are entering the promising new field of electro-optical measurements, e.g., Hewlett-Packard and Tektronix.

Another aspect of the growth in instrumentation derives from new applications, for example the observation of and from space. The field of remote sensing [37] is growing so rapidly that major measurement problems are just beginning to be uncovered and explored in detail [38].

b. New Public Interest

Increased public concern for safety, health, and the quality of the environment have led a number of new, surprisingly broad, Federal responsibilities. Since the review last year [1] of many of these, still others have emerged. Transportation in an area of Federal activity previously limited to state government [39-41]. In this case, a change in focus for governmental responsibility is complicated further by the introduction of new technology, entirely new types of lighting materials that render obsolete former measurement techniques [42]. In still another area of growing interest, safety, new technology in the form of very intense lights for movie production is leading Underwriters Laboratories to develop new specifications for safer handling of these lamps [43]. No standards exist at, or even close to, the irradiance levels involved.

The hazards of ultraviolet radiation are a rapidly developing field of public concern. First, the future of the protection of the earth's surface from solar ultraviolet radiation by the atmosphere is causing wide debate among scientists [44-45]. The ultraviolet output of lamps has also raised considerable concern in an area of technology where safety has not been the subject of activity in the past. Technical questions have been raised in this area by the National Academy of Engineering [46]. In addition, several pieces of legislative action embody new Federal responsibility with implications for all ultraviolet measurement: The Federal Hazardous Substances Act, the Radiation Safety and Health Act of 1968, and the Occupational Safety and Health Act of 1970 [1].

Public health issues involving optical radiation measurement arise in two clinical areas [1], phototherapy and clinical analysis. Phototherapy is being studied now by a panel of National Academy of Sciences and Engineering as a result of the widespread employment of this treatment, with little control or understanding of the dosages involved. Clinical analytical procedures operate with a similar, but not such an extreme, lack of information.

Public concern for the environment has led to activity in areas that depend on optical radiation measurement. One of these is the energy crisis, which has many other causes and implications [47-48]. There is growing public sensitivity both to power conversion and to the efficient utilization of energy. A review article summarized the situation with respect to energy conversion recently: "Whatever method is being pursued, the electro-optics community is very firmly entrenched in the search for new energy sources. The long- and short-term goals discussed in these pages seem destined to keep a great many of us diligently at work for a good many years to come" [49]. With respect to another promising type of energy conversion, "the laser reaction idea is the newest one on the fusion scene and the simplest conceptually" [50]. The efficient utilization of power is also receiving attention. Since lighting takes 25% of the electric power generated, measurement of efficiency in lighting becomes important to improving the efficiency of power utilization as a whole [1].

Pollution of the environment must be monitored if it is to be controlled in a realistic fashion. Control of pollution at some level is widely considered a desirable goal. Remote sensing approaches are being explored [51]. Problems in pollution are coupled with the energy problems through the wide availability of hydrocarbon fuels that contain relatively large amounts of sulphur, a serious pollutant. Another specific interest in monitoring attempts to control pollution is connected with substantial changes in the earth's atmosphere. Serious climatic changes may follow increased pollution as a long term effect. In the short term, as just noted, the amount of ultraviolet light, which is controlled by ozone in the upper atmosphere, may be affected. Meteorology in fact is providing some of the tightest requirements in radiometry [52].

2. CHARACTER OF THE GROWTH

a. Rapid Pace

The growth rate of dollar volume in key segments of the US electro-optics industry over the decade 1958-1967 [1] has been generally maintained since then [8]. It is now expected to continue into the forseeable future, to 1980 [8]. (See Table in main text) But cause for some U.S. concern can be found in the sudden change in the fraction of world photographic equipment and supplies represented by U.S. production. This fell from 68% in 1968 to 63% in 1970. The original U.S. market lead in electro-optics is now being followed quickly by other countries. For example, "Tokyo Electric Co. (Toshiba), Tokyo, Japan, has announced plans to open, in June, two plants to produce LED's and power transistors" [53].

The production quantities of the electro-optics industry have increasingly required the incorporation of automated measurement. This automation in turn has caused a widespread re-examination of the optical radiation measurements involved with a view toward providing both increased comparability among different measurements and greater reproducibility of a given type.

b. Wide Diversity

Some of the diversity of the growth in the electro-optics industry has been indicated in the preceding description of new technology involved in sources, detectors, and general purpose instruments.

This new technology involves a wide diversity of technical parameters. One example is a variety in the spectral range of new widely used light sources. Differences in spectral distribution and sensitivity characterize new detectors and lamps. Combined with the increasing variety of spectral characteristics are widely differing flux levels. For example, light emitting diodes are characterized both by an unconventional spectral distribution and by a substantially lower flux level than that previously involved in widely disseminated standards. At the other end of the scale is the measurement of high intensity discharge lamps, sources not only consisting for the first time primarily of spectral lines but also much more intense than those traditionally measured in the past. New flashlamps have both a different spectral distribution and higher intensity than most standards, while at the same time they furnish a very different temporal behavior from that of the standards with which they are compared.

Diversity is a characteristic also of new applications. Transportation and satellite remote sending [54] are examples of rapidly growing areas. Meteorology is a newly prominent area [55]. Photobiology and astronomy represent more historic areas of interest [56-57]. The varied authority for enforcement of new Federal regulation is increasingly important. The Departments of Health, Education and Welfare, Labor, and Commerce are involved. The Environmental Pollution Agency is responsible for an area of rapidly expanding concern.

APPENDIX B

The Flow of Physical Standards

1. NBS AND OTHER NATIONAL LABORATORIES

The central position in the U.S. of NBS radiometric standards is derived from the responsibility of the Secretary of Commerce, defined in 15 US Code 272, to undertake "the custody, maintenance, and development of the national standards of measurement, *and the provision of means and methods for making measurements consistent with those standards, including the comparison of standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government*". Although photometric standards also are covered implicitly by this legislation, the responsibility of the Secretary of Commerce for photometric standards has been made even more explicit. 15 US Code 224 identifies as the specific duty of the Secretary of Commerce "to establish the values of the primary electric and photometric units in absolute measure, and the legal values for these standards shall be those represented by, or derived from, national reference standards maintained by the Department of Commerce".

NBS authority is thus far-reaching. In practice however it is not possible for NBS or indeed for the entire Department of Commerce to provide substitution standards for all types of sources and detectors used in the country. NBS has calibrated a number of incandescent lamps that are used by public issuance laboratories to calibrate radiometers and photometers. These instruments are used, in turn, to measure sources and other detectors of direct interest to industry, other agencies, and universities. However, these latter groups also receive standards directly from NBS rather than from the public issuance laboratories.

Before beginning to trace the U.S. calibration chain away from NBS, the observer should note that other countries have systems similar in principle to the one described here for the U.S. The various national systems in the past have been quite independent. But as the need for new standards grows, foreign standards will probably impinge increasingly upon the U.S. measurement system. The seldom employed chain of American standards to foreign standards typically has as an essential link intercomparisons between NBS and foreign national laboratories. In radiometry, few of these intercomparisons have in fact taken place. Indeed the only one within memory involved lamps that were so unstable as to make the results essentially useless [58]. By striking contrast, international photometric intercomparisons have taken place over many years at remarkable frequency. One of the earliest on record, in 1907, displayed a spread of approximately 2% in the measurement of luminous intensity [59]. The most recent international intercomparison, one that took place in 1969, showed a similar spread of 2% in the measurement of luminous intensity at two different color temperatures and of luminous flux at a third color temperature [60]. In the intervening years the national laboratories have repeatedly demonstrated the ability to perform photometric measurements on certain incandescent lamps with an agreement to roughly 2%. Radiometric measurements can probably be performed to a similar level of precision. Therefore, unless very special circumstances are predicated, agreement among new measurements in various countries cannot be expected routinely to agree better than about 2%. If several steps are involved in international measurements, the spread will undoubtedly be somewhat greater than this [61].

2. PUBLIC ISSUANCE SECONDARY CALIBRATION LABORATORIES

The American photometrist or radiometrist will get his reference standard typically not from NBS but from a secondary calibration laboratory. A civilian will approach one of a number of commercial calibration laboratories, which typically furnish either radiometric or photometric standards, but usually not both. Defense Department radiometrists or photometrists will generally obtain standards from a designated service laboratory. There have been few formal intercomparisons performed among any of these publis issuance secondary calibration laboratories. Customers who have obtained standards from more than one laboratory have reported differences almost routinely of the order of 10% among standards from various public issuance laboratories.

3. COMPONENT MANUFACTURERS

Until recently most photon detectors were usually found to be less stable than the most stable lamps. Those that were sufficiently stable were too insensitive to permit the filtering required for photometers. For this reason, because sources were frequently of ultimate interest, and because primary reference has been made to blackbody sources, optical radiation measurement has been largely "source-oriented" in this country. Standard sources have been furnished, but not standard detectors. In other countries, particularly England, Netherlands, Japan, Germany, and Australia, important radiometric measurements have been based on electrically calibrated radiometers, that is those for which electrical heating can be substituted for radiant heating. But even abroad, reference to electrically calibrated radiometers has been restricted largely to the national laboratories.

One exception to these generalizations, the large photographic meter industry, has operated relatively independently of the rest of the systems. Complaints about the level of agreement of such instruments have not been widespread. This is perhaps an example of a sub-system that has operated fairly readily as a gauge system decoupled from other measurements. Film does not typically have a standard CIE sensitivity. When one finds that his light meter readings are consistently too high or too low, he can allow for this bias in setting his camera. These meters are typically not recalibrated by NBS after sale.

In contrast to the detector industry, the lamp industry has always depended heavily on the availability of the standards both from NBS and from the secondary calibration laboratories. Because of the central position of these measurements to the industry, informal intercomparisons of luminous flux and closely related quantities have been arranged through an industry organization, the Lamp Testing Engineers Conference (LTEC). The results of only one of these intercomparisons have been published [62]. Through such intercomparisons, because of the availability of incandescent standards, and because of the similarity of the lamps measured, agreement among incandescent lamp measurements is not presently a serious problem. This agreement is generally comparable to that of the national laboratories in their intercomparisons: a spread of 2%.

The single most widely selling type of lamp however is the 40 watt "cool white" fluorescent lamp. This lamp differs sufficiently from other lamps [34,9-11] that an unsatisfactory spread occurs in their measurement: 2.0% when comparing with a similar fluorescent standard; 3.6% when comparing with a fluorescent standard with a different spectral distribution; 5.1% when comparing with an incandescent standard utilizing the same photometric detector used in the comparison with fluorescent lamps, and 22.6% when comparing with an incandescent standard by spectroradiometric techniques [62].

High intensity discharge lamps were compared internationally ten years ago with a spread of 7% [63]. There is the feeling in the industry that different companies may be using standards differing at least by 6% in establishing advertised values for such discharge lamps. This situation is considered to be a serious problem.

Light emitting diode manufacturers have found spreads of the order of 40% among measurements [16]. Such differences are clearly visible and intolerable commercially.

4. INSTRUMENT MANUFACTURERS

With the development of relatively stable and sensitive silicon photodiodes over the last few years, the development of convenient radiometers and photometers has blossomed. These instruments are calibrated against standards either from one of the component manufacturers, as suggested by Figure 6, or directly from one of the public issuance secondary calibration laboratories or NBS as suggested above in Section 1. Instrument manufacturers have not yet formally intercompared their instruments inasmuch as this is a new and very rapidly developing field. But those who use these instruments for measurements find substantial disagreements. The level of agreement is very likely correlated with the fact that, while the instruments may be calibrated with one type of standard source, the chain between measurements by users of two different instruments is typically coupled through NBS by way of a number of links [c.f. 61,64]. Large disagreements among commercial photometers and radiometers have led the electro-optics industry to express formal concern [1,21].

In the past it has not been unusual for different parts of a large company to be getting separate sets of optical radiation standards from NBS. This practice has now fortunately been reduced by the designation of centralized responsibility within such companies. For some time the indirect results of these previous unnecessarily long chains of calibration may continue to be felt however.

5. AREAS OF IMPACT

The ultimate user falls generally within one of four major categories: industry, government, the academic community, and the general public. The photographic industry and related enterprises are the single largest component of industrial users: 5 billion dollars. The lamp industry is comparable in size: 1 billion dollars. The aerospace and transportation industries are other substantial users. The television, theater, and movie industries use of lighting is obvious. Increasingly the computer industry and office equipment manufacturers are using new types of light source displays that are leading to new requirements.

The Federal government is rapidly increasing its concern with optical radiation measurement. Some of the federal agencies involved are:

Department of Transportation
Department of Health, Education and Welfare
Department of Labor
Department of Commerce
Department of Defense
Environmental Pollution Agency
National Aeronautics and Space Administration
General Services Administration

Academic, as well as Federal, science involves measurements of optical radiation in a wide variety of technical areas: plasma physics, atomic physics, solid state physics, and astronomy, and the science of optics itself.

Because the user community is so diverse, formal intercomparisons of optical radiation measurements have not been carried out. The existence of substantial disagreement, however, is shown by the founding and growth of the Council for Optical Radiation Measurement [21,27]. All segments of the user community are represented. Indeed, one of its most active projects is the inauguration of a series of intercomparisons [27].

APPENDIX C

Organizations Associated with Procedural Standards

In order to ascertain the role and status of these organizations as seen by participants, a questionnaire was sent to participants in the Council for Optical Radiation Measurement. Most respondents feel that the standards groups fulfill an essential function, although sometimes with less than desirable efficiency and alacrity.

A cursory review of the various organizations involved directly and indirectly in the generation of procedural standards follows. This description is based primarily on the response to the Council questionnaire: approximately 40 questionnaires were returned from the original mailing of about 200 in January, 1973. In some cases the following accounts have been modified by official spokesman. But in all cases the brevity permits only a severely limited perspective of the activities of these organizations. The serious reader will want to get a fuller picture directly from the organizations themselves.

1. AMERICAN INSTITUTE FOR AERONAUTICS AND ASTRONAUTICS (AIAA)

This professional society has concerned itself with heat balance radiometric requirements in air and space science and engineering. Its Thermophysics Committee, ASTM E-21 Committee, and IES jointly sponsor annual space simulation conferences.

2. AMERICAN METEOROLOGICAL SOCIETY (AMS)

This professional society has concerned itself largely with professional seminars. Its relationship to the generation of procedural standards has been indirect.

3. AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

ANSI coordinates the development of national consensus standards by other voluntary standards organizations. It is perhaps better known for its procedure for formal recognition of these standards once they have been developed by these other organizations. Committee Z-36 deals with laser safety.

4. AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM has two primary functions: the development of voluntary standards and the sponsorship of symposia for the exchange of information. Committee F-1.2 deals with lasers. Committee E-12 deals with the appearance of materials. Committee E-21 deals with space simulation. The AIAA Thermophysics Committee and IES cooperate and have overlapping membership with ASTM Committee E-21 (c.f. AIAA).

5. COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE (CIE)

This is one of the most prominent international organizations dealing with light measurement. Its Action Committee, whose chairman is currently Sylvester Guth of GE Nela Park, guides the technical committees. Technical Committee 1.2 on Photometry and Radiometry prepares both technical studies and procedural recommendations for the measurement of illumination in its broadest sense. These are sometimes based on intercomparisons organized by the committee. Technical Committee 1.4 on Photopic, Mesopic, and Scotopic Vision coordinates the study of, and measurement practice in, these fields. Technical Committee 2.3 on the Photometric Characteristics of Materials is now completing a comprehensive report on these characteristics and their measurement. Other recent reports deal with polarization and fluorescence.

In this country CIE consists of a U.S. National Committee made up of the U.S. representatives to the international technical committees, who are also chairmen of the US technical committees, and a number of others. Its Executive Committee appoints the U.S. technical committee chairman and the membership of the technical committee with the advice of the respective chairman. US TC 1.2 in the last 2 years has broadened the scope of traditional activity by its organization of the Council for Optical Radiation Measurement (q.v.).

6. COMITÉ CONSULTATIF DE PHOTOMÉTRIE ET RADIOMÉTRIE (CCPR)

This committee is advisory to the Comité Internationale des Poids et Mesures (CIPM; International Committee on Weights and Measures), the technical body responsible for the provisions of the Treaty of the Meter, which established the basis for the International System of Units. Recommendations of the CCPR, after review by the CIPM, are considered by the Conférence Générale des Poids et Mesures (CGPM; General Conference on Weights and Measures), which has ultimate responsibility for carrying out the provisions of the Treaty.

The CCPR consists of representatives of the national laboratories and a few designated experts. It provides a forum for discussion of, and ultimately for international agreement with respect to, the photometric unit system. To provide a quantitative background for its decisions, it arranges international comparisons of the various national standards among the national laboratories. Its most recent international intercomparison, in 1968, involved national standards of the candela, both those at the platinum point and those at CIE illuminant A (approximately 2856 K on the International Practical Temperature Scale of 1968) and of the lumen at approximately 2788 K on IPTS 1968. Thus the CCPR provides both general coordination and evidence of measurement agreement among a few international photometric standards. The application of these standards to a wider variety of photometric and radiometric measurements is left to the CIE.

7. COUNCIL FOR OPTICAL RADIATION MEASUREMENT (CORM)

The Council is an activity of US TC 1.2 of CIE. It has been formed to "fill in the cracks" between the activities of other standards groups and professional societies. It is described below in Chapter III and in detail in Appendix E.

8. ELECTRONIC INDUSTRIES ASSOCIATION (EIA)

This group represents manufacturers of electronic products. Among many other activities it provides for registration and standardization of specifications for new products, including those connected with optical radiation.

9. ILLUMINATING ENGINEERING SOCIETY (IES)

IES (not to be confused with 12 below) has been a primary vehicle for the establishment of agreement on measurement practices and procedures in the lamp and affiliated industries. Formal IES recommendations are also used as a basis for illumination practice in fields such as architecture and transportation. Meetings, written reports, and its journal deal with applications of illumination and technical background, as well as testing and measurement.

10. INFRARED INFORMATION SYMPOSIA (IRIS)

These annual symposia engage government and industrial representatives in a continuing information exchange on infrared technology largely for defense applications. Associated with these symposia are IRIS Specialty Groups. The Infrared Standards Group has provided a forum for technical review of measurement problems and, in particular, has been a useful focus for interaction with NBS on physical standards in the infrared.

11. INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)

The Institute acts both as a professional society and as a standards-writing group. For example, IEEE has become a particularly important professional society for laser technology. It is also involved in formulating agreement both on nomenclature and on procedural standards for light emitting diodes.

12. INSTITUTE OF ENVIRONMENTAL SCIENCES (IES)

This IES (not to be confused with 9 above), along with the AIAA Thermophysics Committee and ASTM Committee E-21, (c.f. AIAA and ASTM) has taken the lead in trying to arrive at agreements on the best value to be used for the solar radiation constant.

13. INTERSOCIETY COLOR COUNCIL (ISCC)

This is a council consisting of delegates from 29 national societies, plus individual members, with a common interest in color. Its major technical activities include symposia at annual meetings and special conferences, and the activity of 14 (currently) problems subcommittees. The ISCC does not issue standards, but occasionally a problems subcommittee may publish a recommended practice with the endorsement of the Council.

14. JOINT ELECTRON DEVICES ENGINEERING COUNCIL (JEDEC)

This council has provided agreement on standard measurement conditions for characterizing photodetectors. Committee JC-23 on solid state opto-electronics devices is now beginning to establish procedures for measuring light emitting diodes.

15. LAMP TESTING ENGINEERS CONFERENCE (LTEC)

This conference meets twice a year primarily to exchange lamp measurement information among various companies in the lamp industry. The conference has carried out several intercomparisons, most notably one in cooperation with NBS published as NBS Tech. Note 559 [62]. Within the framework of this Conference, upon occasion the lamp companies have agreed to base certain measurements on particular standards in order to provide as consistent a set of nominal luminous flux values as possible throughout the industry.

16. MANUFACTURERS COUNCIL ON COLOR AND APPEARANCE (MCCA)

This is a trade association composed primarily of manufacturers of color and appearance instrumentation. One of its major objectives is to arrive at agreements on standards and techniques in order to provide greater uniformity in the measurements made with these instruments. A Collaborative Reference Program for color and gloss is being carried out on a continuing basis under the co-sponsorship of the Institute of Applied Technology of NBS.

17. OPTICAL SOCIETY OF AMERICA (OSA)

This professional society, both as a whole and in its Technical Group on Radiometry and Photometry, has been predominantly occupied with the exchange of technical information. It has published the monograph, "The Science of Color". Its Committee on Colorimetry is addressing the problem of defining scales of uniform color difference. The Society is represented in many standards organizations. (See Appendix D)

18. SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)

The Society has been the primary organ for the formation of industry agreement on aircraft and spacecraft lighting as well as automobile lighting. The resulting documents formed the basis for American practice until the recent increase in Federal responsibility for highway safety standards. The SAE work was not designed for rigid enforcement, but rather as more flexible, "designed to conform to", specifications. These specifications therefore require review before Federal adoption as strictly enforced standards.

19. THE SOCIETY OF MOTION PICTURE AND TELEVISION ENGINEERS (SMPTE)

This group provides for the coordination of practice in the motion picture and television industries.

20. SOCIETY OF PHOTO-OPTICAL INSTRUMENTATION ENGINEERS (SPIE)

This professional society roughly complements in function the Optical Society of America. As the name implies, it emphasizes instrumentation and engineering. Its meetings are primarily professional in nature, frequently topical seminars.

21. WORLD METEOROLOGICAL ORGANIZATION (WMO)

This organization's Committee on Instruments and Methods of Observation (CIMO) concerns itself with the design of physical standards and measurement techniqeus for the determination of parameters characterizing solar radiation in the vicinity of the earth. The Committee has held a number of international intercomparisons of pyrheliometers, instruments for measuring the direct solar irradiance at the surface of the earth. Until very recently these measurements were not directly coupled to national radiometric standards. A general renaissance in interest in detector radiometry stated in this field before its more general appearance in this country as a solution to broader radiometric problems.

22. UNDERWRITERS LABORATORIES (UL)

These private laboratories have not been widely known for dealing with optical radiation standards. However, recently they have displayed interest in establishing limits for irradiance in close proximity to high intensity movie lights. Provision of contemplated standards would require measurements at a much higher level than that for which standards currently exist.

APPENDIX D

Expansion of the Role of Professional Societies

The professional societies are undergoing a self re-examination of their role. Experimentation is a part of this process. For example, at a recent Optical Society meeting, the Technical Group on Radiometry and Photometry held two panel discussions. The first of these discussions was entitled "New Stringent Meteorological Demands on Radiometry". Experts in the field of meteorology were invited to summarize the meteorological needs for superior radiometry. A quantitative review of some of the most sophisticated radiometric measurements on satellites was also presented as a measure of present capability. A substantial gap between needs and performance was identified but described in too cursory a fashion to be clear to everyone participating in the discussion. Nevertheless, this discussion will lead to a more ambitious symposium at a future Optical Society meeting.

At this same meeting a second panel discussion was held on a developing fundamental problem with practical consequences, the looseness in the coupling between radiometry and photometry. This discussion was entitled "Re-examination of the Photometric Unit System". A number of weaknesses in the present system were described and proposals for redefinition examined [65]. This meeting was designed to lead to a formal proposal by a US technical committee of the CIE to a meeting of the international Technical Committee this past summer. It is significant that direct action, if it is to occur, will take place outside of the framework of the Optical Society but perhaps within the framework of the CIE.

APPENDIX E

Methodology of Study

Because of the novelty of technology assessment in general and in particular of the analyses carried out in this Technical Note and in the preceding one on the impact of radiometry and photometry [1], a review both of the critical factors that have been perceived and of the responses to these factors that have been developed and tools that have evolved may find application in other areas. But *caveat emptor:* any transfer of this "technology" to other areas should follow a preliminary investigation to ascertain whether the contemplated application is indeed suitable or not.

1. GENERAL FACTORS

a. Size and Complexity

The size of the analytical job involved is far more than one person, working full time, can carry out by himself. The time factor will be explored in detail in the next section. There is the sheer volume of the potential data that must be collected, correlated, and evaluated. In addition to the enormous quantity and complexity of data, the necessity for a critical approach is crucial. And this critical approach requires technical expertise in a wide variety of technical fields. Evaluation of a broad measurement area must rely on many experts in relatively narrow technical fields.

b. Desirability of Interaction Apart from NBS

A more fundamental reason, also, exists for the desirability for the involvement of non-NBS people in key roles of the interaction. The structuring of the data collected involves critical thought and is part of a useful *educational* process. The organizational complexity of radiometry and photometry is shown by the number of different organizations involved. Key members of the community are desirous of achieving a less parochial approach to these problems, and this requires an interaction apart from NBS. The synthesis performed on the variety of needs throughout the field will be far more practicable if those who must live with the results are involved in the synthesis itself. This is not to say that NBS should not exercise strong leadership; indeed it has been asked to do so. But others must be involved in key roles as well and must share this leadership with NBS.

c. Necessity for Interaction Between NBS and Other Elements of the System

Just as it is desirable for the analysis of a system to involve participants in that system, it is also extremely important to have strong interaction between NBS and the rest of the system. At times NBS leadership may be required, as just noted. At other times, pressure by the rest of the system on NBS may be involved. But still more generally, a partnership must be established if optimum solutions are to be achieved. Before drawing conclusions from these background factors, it is useful to review critical requirements for continuity.

2. SPECIFIC CHALLENGES REQUIRING CONTINUITY

a. Novelty

The serious analysis of the national measurement system is new, although the concept of the system itself is not. A methodology must be evolved, and this takes time. The present Appendix is one contribution toward evolution of such a methodology. Technology assessment is indeed nowhere an exact science yet. Until this methodology becomes fully developed, time will be required for trial and error, re-analysis, and further trial.

b. Second-Order Interaction

It was noted in the Chapter III that the chain between NBS and the ultimate user typically has a number of links. Thus NBS has not been highly coupled to the ultimate user. Channels of direct communication must be established. This process requires time and continuity.

c. Commercial Factors

The preceding impact study [1] noted that individual companies were not strongly motivated to solve basic optical radiation measurement problems on their own. This is partly because consistency with other measurements is a far more important commercial consideration than is the strength of the tie to absolute truth in itself. Indeed, if a choice must be made, business constraints require a common measurement basis with others, rather than fidelity to physical truth. To be sure, the only way that wide agreement in a *complex* physical field can be achieved is by resort to fundamental physics. Nevertheless, a complex cooperative effort is required. This cooperation involves time, participation in a multi-faceted effort, and continuity. Agreements, either tacit or explicit, must ultimately be reached among those most directly involved; and these agreements require time and coordination.

d. Personal Confidence

Because of the commercial impact of information in this area, the flow of information requires the establishment of personal confidence. The development of personal confidence requires both time and substantial continuity.

e. Location of Right People

Because of the diversity in the field of optical radiation measurement and the variety of industries involved, substantial time is required to locate the right person in each institution. Two factors define the right person, his experience and his inquisitiveness. Those at the top of a corporate structure cannot always be expected to have at their finger tips, ready for immediate judgement, an analysis of technical factors limiting the performance of their institution. On the other hand the man at the bench in one part of a company may not have the breadth of experience to speak authoritatively even for his own company, much less for the industry as a whole. At an early stage of the coordination of analysis, basis technical factors must be identified and placed within a coherent structure. Institutional representatives must thus display not only experience but inquisitive minds and must also be prepared to do some hard work. Imaginative analysis is required of those involved at the pioneering stage.

f. Identification of Crucial Questions

When the proper person is located in an institution, or indeed even before he is located, crucial questions must be identified. The nature of these questions of course varies with the individual field. Questions on foreign trade may be important in one area and irrelevant in another. The training of staff involved in the laboratory may be a vital question in one area and relatively unimportant in another. On the one hand, critical factors in the structure of the field must be identified and their relationship to measurement problems established; on the other hand, tractable specific questions must be formulated. The crucial interaction is one of "development" and not "location" of the right questions.

g. Phrasing the Right Question

Because of the diversity of this field, phraseology itself becomes an important factor. The propensity of radiometrists and photometrists for developing nomenclature is well known. But in a deeper sense, the establishment of a suitable background may be required before questions can be properly interpreted. Without continuity this background must be continually re-established.

h. "Induction Period"

Even with the right question phrased in the proper manner, the answer may nevertheless not be immediately forthcoming. Because of the novelty of this analysis both to NBS staff and those with whom they otherwise never deal, answers, although they may already exist, may not be specifically identified in the minds of the people initially involved. Weeks or months after a question has been raised the answer may well come in an unexpected context to the novice who has been asked. More indirectly, our postulated novice may recognize, long after the original posing of a question, another person who knows the answer to the question. This analog of the "induction period" to a chemical reaction is applicable even to those experienced in such analysis. One finds relevant data in unexpected places, fertilizing the "prepared mind". These data that will not come from a crash search at the time a question is posed later may provide extremely important leads.

i. "Other Guy" Symdrome

Since the problem in the measurement system is basically one of agreement, and since scientists and technicians in general are not aware of all systematic effects on measurements being made, estimates of uncertainties will frequently not provide a reliable prediction of the level of agreement actually achieved. Because systematic errors are inadvertently ignored, the tendency is to assume that it is the other person who is in error by more than his stated uncertainty. Because the other fellow is the one presumably in error, the person making this evaluation will not be strongly motivated to search for the source of the error. It is only after considerable interaction with one's colleagues, a result of substantial continuity, that one builds up sufficient confidence in one's colleagues to motivate a serious re-examination of one's own measurement problems.

j. "Emily Post" Syndrome

Another problem, more psychological then technical in nature, but nevertheless severe, is a general reluctance to discuss measurement errors. Even in a completely objective, scientific atmosphere, it is the *possibilities* that receive primary attention, not the *difficulties*. Until a sufficiently firm relationship is established, many will not discuss in detail their measurement difficulties. "It just isn't done".

k. "State-of-the-Art" Syndrome

Even though levels of agreement are typically worse than anticipated because of the neglect of unknown systematic errors, rough levels of agreement ultimately become established in a crude fashion and recognized among experienced workers. This "effective-state-of-the-art" becomes an excuse that is used to justify the absence of better performance. If one *doesn't* do any better, then many will assume that one *can't* do any better. In established fields with long traditions such as those of radiometry and photometry, this complacency has become a barrier recently to rapid movement of the state-of-the-art. With the introduction of new people and new technical constraints such barriers to improvement can be readily removed. A "new continuity" is required to replace the old.

l. Efficiency

And finally, the determination of an efficient response to serious measurement disagreement here, as in basic research, may await a new synthesis of previously unrelated factors. Efficiency demands the identification of new techniques for current problems. This efficiency requires continuity and time for analysis.

3. PERMANENT STRUCTURES

a. Professional Societies

All of the preceding characteristics indicate the desirability of a permanent organizational structure within which appropriate individuals can be identified and their effort to improve the national measurement system coordinated. Information coordination has occurred traditionally through the various technical groups in professional societies. The question is sometimes asked, "Why not strengthen these technical groups to provide the requisite continuity and coordination?" Such an approach cannot be excluded. Indeed it offers some attractive opportunities that have not been exploited. We shall see later that these societies very likely do not offer the total answer.

(1) Technical discussion

The strongest feature of the professional societies has been the provision of a forum for technical discussions and technical papers. These are a *sine qua non* for progress in the measurement system. Without a firm technical foundation, agreement can not be achieved on a widespread scale. Nevertheless, this is only the first step; it must be followed by analysis, coordination of information, and response to specific proposals. The technical groups of these societies can indeed be used to provide for keen interaction among people in addressing specific questions. One example is the recent use of the Standards Specialty Group of the Infrared Information Symposia, which operate primarily as a technical society, to provide tentative answers to specific questions posed by NBS in its re-evaluation of needs for infrared standards and services. Other examples are given in Appendix D.

(2) Difficulties with systematic action

In spite of their great strengths, professional societies face two problems in serving as the *primary* progenitors of solutions to measurement system problems. In the first place, they offer no formal structure for systematic synthesis and the resolution of difficulties. These are societies for thought, not typically societies for action, although they may be changing in this respect. Second, participation in the professional societies typically is not fully international in scope. But the technical problems know no national boundaries and must be solved on an international scale if international problems such as trade are to be ameliorated. Cooperation, then, with an international organization is essential as a long-term solution to the measurement system analysis problem.

b. Council for Optical Radiation Measurement

(1) Origin

Early in an intensive effort by NBS to determine the status of, and needs for, the measurement of optical radiation, a parallel restlessness became evident within industry. Robert Watson, whose professional activity in industry led him to face severe measurement problems in an area where few answers were available, suggested that a group of industrial and NBS scientists in this area get together to discuss a coordinated approach to these measurement problems. Those who were known to share this mutual restlessness with the situation were invited to a meeting at NBS that took place on 28 October 1971 under the title "Conference on the Definition of Pressing Problems and Projected National Needs in Radiometry and Photometry". Representatives from twelve industrial companies, one military agency, and NBS both in Boulder and Gaithersburg took part. Two themes developed during the meeting. The first was industrial desire for more vigorous NBS action in this area and recognition that such an increase in activity would require justification from industry. The second theme was the recognition that a permanent organization ought to be formed in order to provide industrial and other-agency information for NBS and to coordinate future activity. Participants agreed as a first step to submit statements of need to NBS and then, as a second step, to gather to consider these statements together.

(2) Requirements

On 10 February 1972 a second conference was held as a follow-up to the first. It agreed to establish itself on a permanent basis as the Council for Optical Radiation Measurement and to operate as an activity of the Commission Internationale de l'Eclairage (CIE). Action was directed to the following ends:

(a) Leverage on NBS

Uppermost in the minds of participants was the desire for NBS to increase its service in the field of optical radiation measurement. The bulk of the first Council meeting was dedicated to establishment of working groups to provide a consensus on the detailed requirements and a justification for these requests. This concern with NBS activity has remained a primary focus of the Council. It resulted in the lengthy formal report to NBS described below [21].

(b) Coordination of other activities

As noted earlier in this Appendix, three types of activity were to be coordinated. In the first place, an exchange of information throughout the electro-optics industry and government agencies working in the field is vital in order to optimize progress. In the second place, the coordination of technical activities with those of the CIE is called for. And finally, the coordination of activity of the many procedural standards groups described in Appendix C is a problem that must be addressed.

(3) Operation

Because of the magnitude of the work involved and the relatively limited resources of the new organization, it was clear that effort ought to be employed with maximum efficiency. It was this consideration that led to incorporation of the activity within the program of the CIE. This act provided: (1) the coordination with existing technical projects and (2) the international interface that would be a primary requirement of long term work in the field.

The Council thus has become a full-fledged, indeed the primary, effort of Technical Committee 1.2 on Photometry and Radiometry of the US National Committee of the CIE. The most actively interested participants in the Council meetings were invited to join this US CIE Technical Committee, which then proceeded to function as the executive committee of the Council. The following statement of purpose was adopted at a September 1972 meeting of TC 1.2, and with it, a statement of operation:

> The Council for Optical Radiation Measurement (CORM) is a body of American industrial, governmental, and university scientists and engineers organized to facilitate the development of reliable standards and procedures for the measurement of optical radiation.

The Council is an activity of Technical Committee 1.2 on Photometry and Radiometry of the United States National Committee of the CIE (Commission Internationale de l'Éclairage).

(4) Initial goal

The first formal Council meeting, in February 1972, and the following meeting, in May 1972, were devoted to the preparation of a formal report to NBS "Pressing Problems and Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS" [21]. Authors for various sections were designated, and the reports of various working groups were condensed into a common format. Common elements in the requests were identified and brought together so that a unified series of proposals for new standards and techniques was developed. Key ideas were extracted for the introduction. The entire Technical Committee 1.2 met in June 1972 to review the document in detail. The resulting document was then sent to all CORM participants for comment, which would then be incorporated by a meeting of the authors into a final document presented to NBS in the fall of 1972.

(5) Permanent goals

With the report published and well received, the US Technical Committee 1.2 met in September to adopt the preceding statements of operations and purpose and a set of objectives. These were grouped into four sets of goals, as noted, grouped around four distinct sets of participants.

I. COUNCIL MEETINGS

To establish and maintain a dialogue throughout the American electro-optics industry on problems of optical radiation measurement; to use this dialogue to establish priorities and to investigate alternative solutions.

II. COUNCIL-INTERNATIONAL TC 1.2 TECHNICAL PROJECTS

To coordinate study of specific optical radiation problems and recommend solutions to them in cooperation with the international effort organized through the CIE.

III. COUNCIL-NBS INTERFACE

To establish and maintain a dialogue with NBS; to use this dialogue to inform NBS on industrial priorities; and to suggest feasible approaches to these problems.

IV. COUNCIL-STANDARDS GROUPS INTERFACE

To coordinate the dissemination of commercial standards and procedures developed by American and international standards organizations.

Communication throughout the field was to be maintained by a series of general meetings. Technical activity was to take place via ten specific projects, the first six of which were already activities of the international Technical Committee 1.2. Information for NBS was to be coordinated through establishment of a group for this purpose. And finally, the coordination of information on the various standards groups was to be coordinated by a fourth activity. Detailed programs in each of these areas have just been issued [27].

(6) Prospects for the future

Comparison of the Council program with the factors necessary for a coordinated attack on measurement problems identified in the preceding section indicates that a mechanism for continuity has now been established to carry out the various functions analyzed. Since the industry and its organizational structure are very much in a state of flux, the future is hard to predict. The degree of cooperation throughout the field achieved already leads one to be optimistic about future achievement. CORM leaders were invited to an international conference on Photometry and Colorimetry this summer in eastern Europe to describe this activity. The problems that the Council is addressing are apparently not localized, and interest is high. Whether or not the challenges are successfully met remains to be seen.

Relation of Improved Optical Radiation Measurement to Broadened Federal Concern

1. PROMOTING ACCURATE, MEANINGFUL, AND COMPATIBLE SCIENTIFIC AND TECHNICAL MEASUREMENTS

A traditional central role for NBS has been widely recognized to be: "promoting accurate, meaningful, and compatible scientific and technical measurements". Paralleling the expanded public interest in coordinated approaches to various public and national problems, NBS is re-examining its role in cooperating in this endeavor. One example of a broadened view of the NBS role in "promoting" such measurements is the present study.

2. PROMOTING MORE EFFECTIVE USE OF SCIENCE AND TECHNOLOGY

The recent rapid development of photon sources and photon detectors has been described. Opportunities to use these new tools in a more effective manner have also been noted. Appropriate strengthening of the measurement system will be required if these new tools are to be utilized to fulfill their promise.

3. PROMOTING STRENGTH IN THE ECONOMY AND EQUITY FOR BUYER AND SELLER IN TRADE

The economic impact of improved measurement technology for optical radiation falls in two broad areas identified in the earlier Technical Note [1]. Within this country, if the buyer is to make intelligent decisions, whether he be an individual buyer in a supermarket or the economically more important large scale commercial purchaser, he requires such data as the luminous flux provided by various manufacturers. This data must be of sufficient accuracy for reliable comparison of dissimilar objects designed to meet a given performance criterion.

Abroad, the growth of international trade in the rapidly growing electro-optics industry has been widely recognized. "I have travelled through every country that sells our products and talked to each of our representatives, and their story is the same. We must have improved light measurement traceability to the National Bureau of Standards" [22].

And finally, in the development both of domestic and of international agreements, authoritative participation is highly desirable if the U.S. is to respond to the coordinated approach displayed by other countries. We are being asked to achieve a higher degree of coordination than that which has characterized our activity in the past [21,27].

4. STANDARDS AND TEST METHODS FOR PROTECTION OF THE PUBLIC FROM SPECIFIC HAZARDS

In the preceding Technical Note [1], several pieces of relatively new legislation were cited. Three of these bear directly on hazards. The first is the Federal Hazardous Substances Act, 15 US Code Chapter 30. More recently has come the Radiation Health and Safety Act of 1968, Public Law 90-602. And finally there is the Occupational Safety and Health Act of 1970, Public Law 91-596. These establish very broad powers for the Secretary of Health, Education and Welfare and the Secretary of Labor. Emphasis will naturally be placed in certain spectral regions and at specific levels. It is in anticipation of increased activity in these areas that the national measurement system must be designed.

5. TECHNICAL INFORMATION SERVICE

Because of the state-of-the-art nature of most measurements in this area, information resulting from radiometric research is awaited with keen anticipation throughout the industry. In areas where commercial factors may influence technical objectivity, users require access to relatively unbiased information.

6. EXPERIMENTAL TECHNOLOGY INCENTIVES PROGRAM

Because of the technical complexity and vast extent of the effort of required for improvement in the measurements, symbiotic approaches by government and industry might be explored. One path is the NBS Experimental Technology Incentives Program. Both because of the rapid march of technology in electro-optics and because of a heavy defense orientation in the past, a number of new commercial opportunities exist that have not been fully realized in this area. The civilian application of highly advanced, and previously classified, areas of technology presents an opportunity for the solution of national problems, both social and economic. This challenge may lead to a very new and complex interaction with industry.

APPENDIX G

A Comprehensive Approach to the Measurement System

A reliable measurement system consists of two parts: (1) research and (2) the interaction between this research and routine measurement.

1. THE RESEARCH REQUIRED

Since radiometry and photometry consist of the measurement of electromagnetic radiation generated, transmitted, and detected by optical system components, the system can readily be approached in terms of these elementary functions.

a. Source Characterization

The characterization of a source by a system user typically involves three separate elements: the realization of a scale, its transfer to secondary standards, and the development of techniques for extension of these standards to the generally dissimilar object to be measured. For the characterization of a source in the U.S., a second source typically embodies the scale and a third source the secondary standard. But detectors may well be used increasingly for these purposes.

(1) Realization of the scale

The realization of radiometric scales by sources for the characterization of other sources has been a widely recognized accomplishment of the NBS program in radiometry. NBS leadership in source blackbodies is acknowledged. One important area remains to be developed within the system as a whole however: the characterization of large area blackbodies. Both space and ground requirements have led to a need for the full characterization of sources with an area of many square centimeters. A number of designs have been proposed and used under a variety of conditions. A full analysis remains to be performed however.

(2) Transfer of scales to secondary standards

The transfer of blackbody scales to secondary standards is another area where NBS has already provided acknowledged leadership. Comparable standards of spectral radiance are available nowhere else. A major fraction of the emphasis of the present NBS program is still in this area. Substantial NBS work is being directed to the transfer of scales to particular standards in a definitive way at the 1-2% level: standards of spectral irradiance, luminous intensity, and luminous flux.

A fundamental question remains to be examined. For important new standards is it preferable for the system to operate with additional secondary standards, or rather to generate the additional measurement capability by the establishment of reliable techniques for the extension of present standards. The second approach is considered by many to be preferable for large systems. Three system elements can be defined in the area of secondary standards:

(a) Characterization of present standards

Because of the complexity of the measurements, some NBS standards and most others remain to be fully characterized. More complete characterization of its standards has a high priority now at NBS. Particularly as other countries develop similar standards it will be important for NBS standards to receive full, documented quantitative characterization.

(b) Improvement of present standards

The best U.S. secondary standards are spectral radiance standards, to which is ascribed an uncertainty of between 1 and 3%. Requests are already being received for radiometric accuracy better than 1%, and planning should start, at least, for the generation of new standards better by at least by a factor of 2. But in view of the requirements in other areas, this area probably will not receive high priority at the moment. Areas receiving primary attention at NBS now are spectral irradiance and luminous flux.

(c) Description of procedures for present standards

The utilization of present standards has been hampered in the field by lack of a complete description of procedures recommended for their use. Such description ideally consists of two parts. A complete characterization of the standards involves a description of the variation of the measured output with respect to the various parameters of the lamp. One example important for some lamps is the variation with orientation. A second set of parameters deals with the influence of the environment, such as temperature and humidity. Until such descriptions are supplied with the lamps, the user will still be left with an unnecessarily large job to do and one whose performance would be redundant if performed in a large number of laboratories.

(3) Extension of present standards

The major thesis of Chapter II was that many different types of measurements were to be made. These can be made either by substitution or by extension, as just noted in Section 2. For example, most source standards are incandescent lamps, whereas a major fraction of radiometric and photometric measurements are made on non-incandescent sources. One approach would be to generate an enormous series of non-incandescent standards so that all field measurements can ultimately be made by substitution with similar standards. Alternatively, one could generate a set of techniques whereby present standards could be used reliably to calibrate a wide variety of lamps. If the system were relatively small, the former approach would inevitably be economical. But for a large system with great diversity of measurements there are probably fewer *aspects* that need to be characterized than there are different lamp types to be measured. Lamp production is so varied that even a subset, for example, fluorescent lamps, are probably more economically standardized against incandescent standards then by direct substitution standards for each type of fluorescent lamp.

This general approach may also be advisable even for smaller systems where work is destined ultimately for comparison with that on dissimilar objects. Such is increasingly the case for artificial illumination and its comparison with natural daylight. If two dissimilar measurements are to be made on a comparable basis then one must understand in detail the nature of the measurements. With proper attention to design, it is to be expected that measurements providing for extension of given standards to dissimilar areas can be made sufficiently convenient that economic procedures can be developed. Such a system has the further advantage that it can be extended with minimal effort as the field grows.

The optimum system may involve the establishment of a few additional secondary standards in areas where a large number of measurements are relatively similar to each other but very dissimilar from the secondary standards presently available. But such a conclusion must be drawn with extreme care. Two dominant factors in such an evaluation will be the stability of the contemplated new standards and their similarity to the various objects that they are to serve as standards. These questions both arise, for example, with respect to proposed LED standards.

b. Detector Characterization

(1) Realization of scales

Work in a number of national laboratories on electrically calibrated radiometers is demonstrating that this approach to the realization of radiometric scales is perhaps the most certain, particularly where spectral information is secondary in importance. One extremely promising approach to absolute detector radiometry arises in the development of pyroelectric detector technology. Several vigorous programs in the development of this technology are already underway at NBS [66].

(2) Transfer of scales to secondary standards

Several new detectors seem to promise the stability required of secondary standards. Pyroelectric detectors are already under active investigation. Several solid state quantum detectors are also extremely promising, primarily silicon in the visible region. Although experience on the stability of, and environmental effects on, these detectors remains to be accumulated, preliminary indications are extremely encouraging. The high sensitivity of new detectors is especially important in permitting detailed spectral response information to be obtained. Both photometry and radiometry can be expected to undergo a revolution through this new technology.

(3) Extension of present standards

Vacuum diodes and multipliers have traditionally been considered to be too unstable to act as primary or secondary standards. Their response must be characterized however and techniques must be developed for doing so reliably. The National Research Council of Canada has a strong program in this area. There is a renewed interest in photomultipliers now that photocathodes composed of elements from the third and fifth periods of the periodic table (III-V compounds) have been shown to display a remarkably flat response throughout the visible and into the near ultraviolet and infrared spectral regions.

c. Techniques

There is wide agreement that the proper generation and use of physical standards require close attention to specific measurement techniques. Similar attention to the extension of present standards to dissimilar measurement objects is greatly needed.

One conspicuous example is the detailed characterization of attenuation. In a recent poll of members of the CIE international Subcommittee on Detectors, for example, the dominant concern expressed was for linearity [20]. Although a review article has appeared [14], the field is so extensive that an even more detailed review of various techniques with high precision has been requested.

A second general problem, particularly in photometry, is the characterization of spectral techniques, especially as applied to spectral lines. With increasing interest in spectral information, small, convenient, and reliable instrumentation is desired. Fourier interferometric techniques offer a number of attractive advantages for dealing with such spectral problems. They have been exploited for spectroscopy, where wavelength information is the quantity of primary interest. Their radiometric suitability remains to be determined.

A third general area is that of pulsed measurement. The measurements are so heavily dependent on the particular time scale of the pulses in question that a general approach may not be feasible.

A fourth area of concern is polariation. Interest in this area will probably continue to be focused on the characterization of specific components, rather than a general approach. Although some good reviews have been prepared [23-24], the sheer extent of the effect leaves much still to be done.

A fifth general area of optical radiation measurement is spatial distribution. Although the description of inhomogeneities is of greatest significance with respect to sources and detectors (q.v.), general techniques for determination of inhomogeneities would be useful for the system.

Diffraction is a sixth area of concern. Since the quantitative importance of diffraction can be determined meaningfully only with respect to an entire system, individual components clearly cannot be so characterized. Their degree of coherence is important though. The significance of diffraction is beginning to be recognized [67], and further work will be appearing. A full understanding of diffraction will be coupled with some basic questions of coherence in radiometry.

2. SYSTEM COORDINATION

Unless research continues to be based on up-to-date input from the measurement system on the one hand and, on the other hand, unless the results of the research are effectively coupled into the system, the research may be remote and its value, questionable. Thus interaction with the measurement system is of importance comparable to that of the research itself. Two types of interaction are involved. First, there is conceptual communication, either oral or written. Equally important is experimental assessment of measurement performance, a measurement assurance program, and dissemination of standards. Both conceptual and measurement communication are essential to a smoothly functioning system.

a. Coordination of Information

The importance of strong interaction between the NBS program management and the community that it serves is widely recognized. In addition to individual bilateral interaction, a number of more systematic channels must be employed. The professional societies provide facilities for communication of the type already described in Chapter III. These must be utilized. A more structured format providing for the achievement for coordination of effort is also extremely important. The organization of the Council for Optical Radiation Measurement for this purpose has been described and is analyzed in detail in Appendix E.

There is an additional type of important interaction. This is the normal initiative taken by those outside of NBS who would like to have various services performed by NBS, either routine or special. Many call on NBS for specific services. Some continuing compilation and evaluation of the kinds of service they are asking for would be highly desirable. Although some of these contacts occur at a non-technical level, attempts will be made to generate specific information on the use and utility of standards being requested.

b. Coordination of Measurements

The specific coupling of optical radiation measurements to NBS standards is achieved in one of two ways. Traditionally, calibrated objects have been disseminated by NBS. This is the simplest and the cheapest form for the provision of this interaction. It also provides the least information.

Either alternative or complementary to this calibration service is the establishment of intercomparison programs in which NBS can play a role. If NBS calibrates one of the objects used in the intercomparison, then this object can fulfill the function of a calibration. But in addition it can play a more rounded role. If the object is carefully chosen, its intercomparison can also assist in the determination of the performance of the measurement system and thereby provide a firmer basis for the prediction of system performance than can a calibrated object in itself. Such an approach essentially constitutes the performance of research in a parallel fashion in a number of laboratories. The great effort required must be balanced on a case-by-case basis against the expected benefits. Because of the extensive requirement for resources in such a program, critical planning must play a strong role in this work. Goals must be clearly established and articulated in advance. The intercomparisons must be carefully designed to achieve their goals with close attention to costs both at NBS and in cooperating laboratories. By means of such intercomparisons, one can both provide the basis for the measurement system and demonstrate that it is indeed performing satisfactorily. Moreover, the impact of system improvements can be clearly demonstrated. The immediate effect both of research and individual services can thus be measured in quantitative fashion. NBS is developing such an intercomparison program, but because of budgeting restrictions its realization will be very slow.

EXECUTIVE SUMMARY

The ultimate users of the optical radiation measurement system fall into four major categories: industry, government, the academic community, and the general public. All are facing severe problems.

Light emitting diode manufacturers, for example, have found spreads of the order of 40% among measurements. Such differences are clearly visible and intolerable commercially. But the complexity of the measurement means that, without outside assistance, companies making reliable measurements face very high measurement costs. Not only will highly trained people be involved, but at present a great deal of time for research will be required. The exceedingly high costs thus involved are simply not feasible for this fragmented industry. It is currently much cheaper to argue a case of disagreement in court, if it comes to that, rather than to set up a research laboratory to solve the problems on an individual basis.

The varied authority for enforcement of new Federal regulation is increasingly important. First was the Federal Hazardous Substances Act, 15 U.S. Code Chapter 30. More recently has come the Radiation Health and Safety Act of 1968, Public Law 90-602. And finally there is the Occupational Safety and Health Act of 1970, Public Law 91-596. The Departments of Health, Education, and Welfare, Labor, and Commerce are involved. Furthermore, the Environmental Protection Agency is responsible for an area of rapidly expanding concern.

In the past, the measurement systems of the various countries have been quite independent. But as international commerce in electro optics grows, foreign standards will probably impinge increasingly upon the U.S. measurement system.

Public concern for energy has led to activity in areas that depend on optical radiation measurement. There is growing public sensitivity both to power conversion and to the efficient utilization of energy. A review article summarized the situation with respect to energy conversion recently: "Whatever method is being pursued, the electro-optics community is very firmly entrenched in the search for new energy sources. The long- and short-term goals discussed in these pages seem destined to keep a great many of us diligently at work for a good many years to come." The efficient utilization of power is also receiving attention. Since lighting takes 25% of the electric power generated, measurement of efficiency in lighting becomes important to improving the efficiency of power utilization as a whole.

Pollution of the environment must be monitored if it is to be controlled in a realistic fashion. Remote sensing approaches are being explored. Problems of pollution are coupled with energy problems through the wide availability of hydrocarbon fuels that contain relatively large amounts of sulphur, a serious pollutant. Another specific interest in monitoring attempts to control pollution is connected with substantial changes in the earth's atmosphere. Serious climatic changes may follow increased pollution as a long term effect. In the short term, the amount of ultraviolet light, which is controlled by ozone in the upper atmosphere, may be affected. Meteorology in fact is providing some of the tightest requirements in radiometry.

The study of the measurement system leads to a number of conclusions. The first is the grave need for coordination of activity. What channels for concerted action can be utilized? In addition to bilateral interaction between NBS and the various other institutions already involved, a number of more elaborate systematic channels must be employed. The professional societies provide facilities for communication of a type described. These must be utilized. A more structured format providing for this coordination of effort is also extremely important. The establishment of the Council for Optical Radiation Measurement for this purpose has been described and analyzed in detail. Coordination in the dissemination of commercial standards and procedures developed by American and international standards organizations remains to be tackled.

A number of technical conclusions are also drawn. Source and detector characterization are called for as well as greater attention to technique building blocks. Monitoring of the performance of the entire system and of its basic measurements are called for. Improved methods of transfer of measurement technology must be developed. And last, a mechanism for the establishment of priorities in the development of an extremely complex technology is urgently needed.

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The electro-optics industry and the public that depends on it are part of an informal but influential system for optical radiation measurement. The growth of this undustry and of public concerns related technically to it have put severe new strains on this measurement system. The system itself must therefore be analyzed. The state of the art, on which the measurement system depends, is surveyed in terms of basic measurement parameters. The measurement system is analyzed in terms of its three basic components: the flow of physical standards, the generation of procedural standards, and the funding framework. The roles of the professional society and of the Council for Optical Radiation Measurement are reviewed. New requirements of the system are identified. Finally, the methodology of the study is reviewed in detail.

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Optical Radiation Measurements:

Approximate Theory of the Photometric Integrating Sphere

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Optical Radiation Measurements:

Approximate Theory of the Photometric Integrating Sphere

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Preface

This is the seventh issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series will consist primarily of reports of progress in, or details of, research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division.

The level of presentation in OPTICAL RADIATION MEASUREMENTS will be directed at a general technical audience. The equivalent of an undergraduate degree in engineering or physics, plus familiarity with the basic concepts of radiometry and photometry [e.g., G. Bauer, Measurement of Optical Radiations (Focal Press, London, New York, 1965)], should be sufficient for understanding the vast majority of material in this series. Occasionally a more specialized background will be required. Even in such instances, however, a careful reading of the assumptions, approximations, and final conclusions should permit the non-specialist to understand the gist of the argument if not the details.

At times, certain commercial materials and equipment will be identified in this series in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

Any suggestions readers may have to improve the utility of this series are welcome.

Henry J. Kostkowski, Chief
Optical Radiation Section
National Bureau of Standards

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Approximate Theory of the Photometric Integrating Sphere

W. B. Fussell

An approximate mathematical theory of the photometric integrating sphere is developed. The analysis is accurate to the first order in the ratio of the baffle area to the sphere wall area. The sphere is assumed to be occupied by a circular baffle and a spherical lamp; the centers of the baffle and the lamp lie on a diameter of the sphere. The surfaces of the sphere and the baffle are assumed to reflect in a uniformly diffuse manner. The lamp is assumed to absorb a fraction of the radiation incident upon it, and to transmit (or specularly reflect) the remainder. The luminance distribution at the sphere window is derived for a general source input at any point of the sphere wall. A model lamp illuminance distribution is assumed, and a formula for the fractional error in comparing the total luminous fluxes of two lamps in the integrating sphere, is derived. The physical significance of the formula is described.

Keywords: Illuminance distribution; integrating sphere; lamp comparisons; photometric accuracy; photometry; total luminous flux.

1. Introduction

The photometric integrating sphere was invented by R. Ulbricht, who made the first sphere in 1900 [1][1]. The usefulness of the integrating sphere for comparing the total luminous fluxes[2] of lamps was quickly recognized, and many large spheres were soon constructed [3].

In 1915 a large integrating sphere of 2.2-meter (88-inch) diameter was constructed at NBS by Rosa and Taylor [4]. They compared total luminous flux values obtained with this sphere for several incandescent

[1]Figures in square brackets are literature references at the end of the text.

[2]The nomenclature of this paper is that of the International Lighting Vocabulary (1970) [2].

lamp-reflector combinations, against corresponding values obtained by distribution photometry, and found differences ranging from 0 to 1.6% in magnitude. These differences are within acceptable limits for NBS values of total luminous flux, even today. (The current NBS goal is an accuracy of $2\frac{1}{2}$% for reported values of total luminous flux, for incandescent lamps.)

Integrating spheres are now universally used in photometric laboratories to compare the total luminous fluxes of lamps of all types. NBS for example, uses at present two 2-meter (79-inch) diameter spheres, one 76-cm (30-inch) sphere, and one 30-cm (12-inch) sphere, to compare the total luminous fluxes of incandescent lamps emitting from 10,000 lumens to 6 lumens.

The purpose of the analysis presented in this paper is: (1), to pinpoint the major sources of error in comparing the total luminous fluxes of lamps with the integrating sphere; (2), to estimate the magnitude of the errors in the present NBS techniques for comparing the total luminous fluxes of incandescent lamps with the integrating sphere; (3), to show how the errors described in (1) and (2) may be minimized.

2. Current NBS Techniques for Comparing the Total Luminous Fluxes of Lamps with the Integrating Sphere

Figure 1 shows the cross section of a typical integrating sphere with the baffle and a lamp inside the sphere. The lamp (whose total luminous flux is to be compared with that of another lamp) is located at the center of the sphere; the baffle is placed between the sphere window and the lamp so that it completely screens the lamp from the window. The baffle is usually placed roughly 1/3 the sphere radius from the lamp, since calculations have shown that this distance will approximately minimize the error in comparing the total luminous fluxes of two lamps [4]. Usually, the substitution technique is employed; that is, if the total flux of lamp A is to be compared with that of lamp B, the detector output is measured with <u>only</u> lamp A in the sphere, and then with only lamp B in the sphere.

The correction for the difference between the absorptances of lamps A and B is found approximately by Helwig's method [5], which uses an auxiliary lamp placed in the sphere near the wall. Lamps A and B are successively placed in the sphere with the auxiliary lamp (which is shielded so that none of its flux strikes either the sphere window, or A or B, directly). The lamps A and B are <u>unlit</u>, and the correction for the difference between the absorptances of A and B is approximately the <u>ratio</u> of the detector outputs produced by the auxiliary lamp when first A, and then B, is placed in the sphere.

The diameter of the integrating sphere used to measure the total luminous flux of a lamp, depends upon the magnitude of the lamp's flux output. As will be shown later, if the sphere is too large, the detector signal will be too small, if the sphere is too small, the sphere error will be too large. At NBS, lamps emitting between 270 and 10,000 lumens are measured in a 2-meter diameter sphere; lamps of smaller flux output are measured in either the 76-cm or the 30-cm sphere.

At present, only tungsten-filament incandescent lamps are calibrated for total luminous flux on a regular basis at NBS [6].

The internal surfaces of the NBS integrating spheres (and the surfaces of the baffles) are coated with paints of high reflectance which reflect in an approximately uniformly diffuse manner. (A surface which reflects - or emits - in a uniformly diffuse manner is defined as a surface which has the same luminance in all directions.) One 2-meter diameter sphere is painted with a thick coating of barium sulfate; the other 2-meter sphere - and the 76-cm and 30-cm spheres - is coated with Burch sphere paint (Burch Paint Mfg. Co., 10609 Briggs Road, Cleveland, Ohio 44111). The spectral reflectance of Burch sphere paint varies with wavelength, falling off towards the blue end of the visible spectrum [7]. (The spectral reflectance of barium sulfate is more uniform over the visible spectrum than that of Burch sphere paint [8].) The net effect of this varying spectral reflectance is to reduce the color temperature of the illumination at the detector from that of the lamp in the sphere, by a large amount. (For example, the color temperature of the illumination at the detector, produced by a 2856 K lamp in the sphere, is reduced by 700 K - including the effect of the sphere window [9].)

This reduction in the color temperature of the illumination at the detector from that of the lamp, due to the decreasing spectral reflectance of Burch sphere paint towards the blue end of the visible spectrum, produces an error in comparing the total luminous fluxes of two lamps with <ins>different</ins> color temperatures. To compensate for this effect, a blue filter (Corning 5900 glass; Corning Glass Works, Corning, N.Y. 14830) is used to make the net spectral transmittance of the sphere (from the lamp to the detector) approximately independent of wavelength. Calculations show that the spectral reflectance of an integrating sphere coated with Burch sphere paint can be neutralized sufficiently by this technique, to reduce the error due to this cause, in comparing lamps having color temperatures of 2360 K and 3000 K, to less than 0.2%.

3. Elementary Sphere Analysis

Elementary integrating sphere analysis has been presented in the literature [10]. The first step is to compute the luminance distribution in an empty sphere.

3.1. Empty Sphere Luminance Distribution

Refer to figure 2 and let α be the colatitude angle of a source point $P(\alpha)$ on the sphere wall; let θ be the colatitude angle of a detection point on the sphere wall. (The azimuth angles of the source point and the detection point are ignored, since the sphere wall reflectance is assumed to be spatially uniform, and hence the sphere is symmetric about the polar axis.)

It is assumed throughout this paper that the sphere wall and the baffle surfaces reflect in a uniformly diffuse manner. This means that the luminance of an element of surface area is independent of the direction from which it is viewed.

(The luminance, in a given direction, of an element of surface area, is defined to be the quotient of the luminous flux leaving the surface through an element of solid angle in the given direction, divided by the product of the element of solid angle and the projection of the element of surface area in the given direction. Symbolically, the luminance L is defined as

$$L = \lim_{\substack{\delta\sigma \to 0 \\ \delta A \to 0}} \left[(\delta^2\phi)/(\delta\sigma \cdot \delta A \cos\theta)\right],$$

where $\delta^2\phi$ is the element of luminous flux leaving the element of surface area δA, through the element of solid angle $\delta\sigma$, in a direction inclined at angle θ to the normal to the element of surface area.)

Let the reflectance of the sphere wall be r, and let the luminance of the sphere wall at $D(\theta)$, produced by a 1 lumen source input at $P(\alpha)$, be denoted $L(\alpha,\theta)$. The 1 lumen source input at $P(\alpha)$ produces a secondary source of luminous intensity r/π candelas at $P(\alpha)$; this secondary source illuminates the wall of the sphere with a <u>uniform</u> illuminance of $r/(4\pi R^2)$ lux (neglecting multiple reflections). To demonstrate that this illuminance <u>is</u> uniform, refer to figure 2 and consider the chord PD. The length of PD, denoted $\overline{PD}$, is $2R\sin(\beta/2)$; the angle between the normal to the sphere at $P(\alpha)$ and the chord PD is $\Sigma = \pi/2 - \beta/2$; this is also the angle between the normal to the sphere at $D(\theta)$ and the chord PD. Thus the illuminance at $D(\theta)$ produced by the 1 lumen source input at $P(\alpha)$, denoted $E(\alpha,\theta)$, is given by

$$E(\alpha,\theta) = (r/\pi)(\overline{PD})^{-2}\cos^2\Sigma;$$

since

$$\overline{PD}^2 = 4R^2\cos^2\Sigma,$$

the equation for $E(\alpha,\theta)$ becomes

$$E(\alpha,\theta) = r(4\pi R^2)^{-1},$$

and so it is seen that $E(\alpha,\theta)$ is indpendent of the positions of $P(\alpha)$ and $D(\theta)$, as desired.

Thus the illuminance at any point on the sphere wall, produced by a source input at any other point on the wall, is independent of the positions of the source point and the detection point, when the reflectance of the sphere wall is spatially uniform and uniformly diffuse. Stated in another way, the viewfactor of unit area on the sphere, as viewed from any point on the sphere, is constant and equal to $1/(4\pi R^2)$. (The viewfactor of a surface A_1, as viewed from surface A_2, is defined as the fraction of the total flux emitted by A_2 which is incident upon A_1, assuming that A_2 radiates in a uniformly diffuse manner. The concept of viewfactor is also useful in radiometry and heat exchange.)

The constant viewfactor of any area of the sphere, as viewed from any point of the sphere, is the <u>basic property</u> which makes the empty sphere, with walls of spatially uniform and uniformly diffuse reflectance, a perfect flux integrator.

Now it is necessary to consider the interreflections in the sphere. It is seen that the uniform illuminance over the wall of the sphere, E (dropping the functional dependence notation), produced by the 1 lumen source input at $P(\alpha)$, in turn produces a luminance distribution L' which is also uniform. It is clear that

$$L' = rE/\pi = r^2/(4\pi^2R^2).$$

The uniform luminance distribution L' in turn produces a uniform illuminance over the sphere wall, E', which is given by

$$E' = 2\pi(4R^2)^{-1}\int_0^\pi d\theta' \sin\theta' L' R^2;$$

this reduces to

$$E' = r^2/(4\pi R^2),$$

which is equivalent to

$$E' = rE.$$

Thus it is seen that the uniform illuminance in the sphere produced by the n-th reflection from the wall, E_n, is related to the initial illuminance from the source point, E, by the equation,

$$E_n = r^n E.$$

Therefore the total illuminance in the sphere, E_{TOT}, is also uniform and is given by

$$E_{TOT} = E\sum_{n=0}^{\infty} r^n,$$

which reduces to

$$E_{TOT} = E/(1-r).$$

Consider now instead of a point source input, the input illuminance distribution $E_{IN}(\alpha)$. The total input flux, ϕ^*_{IN}, is

$$\phi^*_{IN} = 2\pi R^2 \int_0^{\pi} d\alpha' \sin\alpha' E_{IN}(\alpha').$$

The total illuminance over the sphere wall produced by $E_{IN}(\alpha)$ is therefore (excluding the input illuminance)

$$E_{TOT} = r(1-r)^{-1}\int_0^{\pi} d\alpha' \sin\alpha' E_{IN}(\alpha')2^{-1}.$$

In terms of ϕ^*_{IN}, it is seen from the preceding two equations that

$$E_{TOT} = \phi^*_{IN} r/[4\pi R^2(1-r)].$$

This is the basic integrating sphere equation; it states that the illuminance inside an empty sphere, with walls whose reflectance is spatially uniform and uniformly diffuse, is proportional to the <u>total source luminous flux</u> in any region of the sphere which is <u>not directly illuminated</u> by the <u>source</u>.

Note that in this simple model, E_{TOT} becomes very large as the wall reflectance r approaches 1; note also that E_{TOT} decreases rapidly with increasing sphere radius R.

A necessary condition on E_{TOT} is that it satisfy flux conservation; that is, the total flux absorbed at the wall of the sphere, ϕ^*_{OUT}, must equal the source input flux, ϕ^*_{IN}. To show that E_{TOT} satisfies flux conservation, note that

$$\phi^*_{OUT} = E_{TOT} 4\pi R^2 (1-r)/r = \phi^*_{IN}.$$

3.2. Introduction of the Baffle

Consider a source point $P(\alpha)$ which is screened from a detection point $D(\theta')$ by an infinitesimal baffle. The effect of such a baffle is to eliminate the initial illuminance due to the source point $P(\alpha)$ at $D(\theta')$. Thus the total illuminance distribution in the sphere is no longer uniform, and it is now a function of θ as well as α. It is seen that, at a detection point $D(\theta)$ which is <u>not</u> screened from the source point by the baffle, the total illuminance (now denoted $E(\theta)_{TOT}$ since it is a function of θ) for a 1 lumen source input, is

$$E(\theta)_{TOT} = r/[4\pi R^2(1-r)],$$

identical to the illuminance equation for the empty sphere given above. However, for the <u>screened</u> detection point $D(\theta')$, it is clear that the total illuminance, $E(\theta')_{TOT}$, for a 1 lumen source input, is

$$E(\theta')_{TOT} = E(\theta)_{TOT} - r/(4\pi R^2),$$

since the illuminance from the source point which is screened by the baffle from the detection point is $r/(4\pi R^2)$. Thus one arrives at the result,

$$E(\theta')_{TOT} = r^2/[4\pi R^2(1-r)].$$

The basic effect, therefore, of even an infinitesimal baffle is to screen every point on the sphere from another point on the sphere; if a detection point is screened from a source point, the total illuminance at the detection point due to the screened source point, is equal to the total <u>unscreened</u> illuminance due to the source point <u>multiplied</u> by the sphere-wall reflectance r.

Consider now the effect of a baffle of finite size. The baffle clearly screens an area of the sphere wall from each point on the wall; the screened area associated with each point is defined by the projection of the baffle boundary from the point to the sphere wall. For a source point $P(\alpha)$ and a detection point $D(\theta')$ screened by the baffle, the major effect of the baffle is the screening of the initial illuminance from $P(\alpha)$ at $D(\theta')$. This effect is termed a "zero-order" effect, since it is independent of the baffle area. For an accurate "first order" analysis ("first order" as used in this paper means the ratio of the baffle area to the total sphere-wall area, a quantity assumed to be much less than 1), several other effects must be considered (such as the flux reflected from baffle surfaces, and the screening of sphere-wall areas which are not source areas). These effects, however, vary as the baffle area and thus are excluded from the elementary analysis of this section.

3.3. Effects of Absorbing Objects

The effects of introducing absorbing objects into the sphere are of two types: first, the screening effect which was treated in an elementary fashion above, and second, the absorption effect. This effect depends upon the area of the absorbing object, and the absorptance of the object. An elementary expression for the absorption effect can be derived from the flux conservation requirement discussed in section 3.1.

Consider a source point $P(\alpha)$ in an empty sphere which generates the uniform illuminance E_{TOT} over the wall of the sphere. If an absorbing object of area A and absorptance $\underline{\lambda}$ is introduced into the sphere, then the illuminance in the sphere is no longer uniform, due to the screening effect of the object. If the object is assumed to be opaque, with reflecting surfaces of absorptance $\underline{\lambda}$ (at any angle of incidence), then the illuminance at the detection point $D(\theta)$, denoted $E_{TOT}(\alpha,\theta,\underline{\lambda})$, is given approximately by

$$E_{TOT}(\alpha,\theta,\underline{\lambda}) = E_{TOT}\frac{[1-(1-r)S(\alpha,\theta)]}{[1+\underline{\lambda}A/(4\pi R^2(1-r))]},$$

where $S(\alpha,\theta)$ is the screening function of the object. This function is defined to be 1 if the object intercepts the line connecting the source point $P(\alpha)$ and the detection point $D(\theta)$, and 0 otherwise.

If the object is assumed to be transparent, with non-reflecting surfaces, and to absorb the fraction $\underline{\lambda}$ of the incident flux which strikes it from any direction, then the illuminance at the detection point is given approximately by

$$E_{TOT}(\alpha,\theta,\underline{\lambda}) = \frac{[1-\underline{\lambda}(1-r)S(\alpha,\theta)]}{[1+\underline{\lambda}A/(4\pi R^2(1-r))]}.$$

4. Analysis: Sphere with Coaxial Disc Baffle

4.1. First Order Luminance at the Sphere Window as a Function of Source Point Coordinates

In figure 3, a is the radius of the disc baffle B; the baffle axis goes through the centers of the sphere and the lamp L; the plane of the baffle is a distance h from the center of the sphere; the center of the lamp is a distance l from the center of the sphere (l is measured in the opposite sense from h); the radius of the lamp is b, and R is the radius of the sphere. The position of the source point $P(\alpha)$ is defined by the colatitude angle α; α'' is the colatitude angle of the projection on the sphere wall of the center of the lamp, from $P(\alpha)$; $\underline{\alpha}$ is the colatitude angle of the projection on the sphere wall of the center of the baffle, from $P(\alpha)$. The detection point is now taken to be the sphere window W at the south pole of the sphere (that is, at $\theta=\pi$). The luminance of the sphere wall at the window, produced by a 1 lumen source input at $P(\alpha)$, is denoted $L_1(\alpha,\pi,\underline{\lambda})$; $\underline{\lambda}$ is the absorptance of the lamp. The surface of the baffle visible from the lamp is labeled the "north" surface, and has reflectance r_N. The surface of the baffle visible from the sphere window is labeled the "south" surface, and has reflectance r_S. The lamp is assumed to be transparent and non-reflecting, and to absorb the fraction $\underline{\lambda}$ of radiation incident upon it from any direction.

The viewfactor of the baffle from the point $P(\alpha)$ is defined as the fraction of the luminous flux reflected from $P(\alpha)$ which strikes the baffle; this viewfactor is denoted $F_{BP}(\alpha)$. Similarly, the viewfactor of the lamp from $P(\alpha)$ is denoted $F_{LP}(\alpha)$. The viewfactors of the baffle and the lamp from the detection point at the sphere window, are denoted

$F_{BD}(\pi)$ and $F_{LD}(\pi)$, respectively.

At this point it is assumed (as suggested by Safwat [11]) that the baffle radius $\underline{a}$ is much less than the sphere radius R; it is also assumed that the radius of the lamp $\underline{b}$ is sufficiently small to ensure that no luminous flux from the lamp reaches the sphere window directly (this is the "screening condition"); thus the lamp radius $\underline{b}$ is also much less than the sphere radius R. On the basis of these assumptions, therefore, it is reasonable to compute the luminance produced at the sphere window by a 1 lumen source input at $P(\alpha)$, $L_1(\alpha,\pi,\underline{\lambda})$, to terms of the <u>first order</u> in the ratio of the area of the baffle to the sphere-wall area, and to neglect terms of higher order in this ratio. Thus the first order luminance at the sphere window produced by a 1 lumen source input at $P(\alpha)$ is found to be (note that this is the luminance <u>within</u> the sphere at the window):

$\underline{0 < \alpha < 2\delta}$,

$$L_1(\alpha,\pi,\underline{\lambda}) = r^2(4\pi^2R^2G)^{-1}$$

$$\times[1-(1-r_S)F_{BD}(\pi)-(1-r_N)F_{BP}(\alpha)-\underline{\lambda}F_{LP}(\alpha)]; \tag{1}$$

$\underline{2\delta < \alpha < \gamma}$,

$$L_1(\alpha,\pi,\underline{\lambda}) = r(4\pi^2R^2G)^{-1}$$

$$\times[1-r(1-r_S)F_{BD}(\pi)-r(1-r_N)F_{BP}(\alpha)$$

$$+r(2-r_S-r_N)\underline{a}'^2 4^{-1}+r\underline{\lambda}(\underline{b}'^2-F_{LP}(\alpha))]; \tag{2}$$

$\underline{\gamma < \alpha < \pi}$,

$$L_1(\alpha,\pi,\underline{\lambda}) = r(4\pi^2R^2G)^{-1}$$

$$\times\Big[1-r(1-r_S)F_{BD}(\pi)-r(1-r_S)F_{BP}(\alpha)$$

$$+r(2-r_S-r_N)\underline{a}'^2 4^{-1}+r\underline{\lambda}(\underline{b}'^2-F_{LP}(\alpha))$$

$$+4(1-r)r_S F_{BD}(\pi)F_{BP}(\alpha)\underline{a}'^{-2}\Big]. \qquad (3)$$

In eqs (1)-(3), the quantity G is

$$G = \big[(1-r)+r(2-r_S-r_N)\underline{a}'^2 4^{-1}+r\underline{\lambda}\underline{b}'^2\big],$$

and

$$\underline{a}' = \underline{a}/R, \ \underline{b}' = \underline{b}/R;$$

in addition, referring again to figure 3, it is seen that δ is the half angle subtended by the baffle at the sphere window W, while γ is the colatitude angle of the baffle plane.

The physical significance of the various terms in eqs (1)-(3) is as follows:

a. The term "$+rr_NF_{BP}(\alpha)$" represents luminous flux from the source point which strikes the north surface of the baffle, is reflected to the sphere wall, and then is reflected to the sphere window.

b. The term "$-rF_{BD}(\pi)$" represents luminous flux from the sphere wall (excluding the direct flux from the source point) which is screened from the sphere window by the baffle.

c. The term "$-rF_{BP}(\alpha)$" represents luminous flux from the source point which is screened from the sphere wall by the baffle, and is thus screened <u>indirectly</u> from the sphere window. (Note that the terms "a." and "c." represent positive and negative effects, at the window, of the <u>same</u> flux; for example, if $r_N=1$, then term "a." <u>cancels</u> term "c.".)

d. The term "$-r(r_S+r_N)\underline{a}'^2 4^{-1}$", together with the <u>same term</u> in the quantity G in the denominator, represents the luminous flux from the sphere wall (excluding the direct flux from the source point) which strikes the north and the south surfaces of the baffle, is reflected to the sphere wall, and then is reflected to the sphere window.

(Note that the <u>net</u> effect of the terms "$-r(r_S+r_N)\underline{a}'^2 4^{-1}$" in the numerator <u>and</u> the denominator is <u>positive</u>. For example, if the quantity $(1-r)$ is much larger than the magnitude of the remaining terms in G, then G^{-1} may be written to first order accuracy as

$$G^{-1} \approx (1-r)^{-1}[1-r(2-r_S-r_N)\underline{a}'^2 4^{-1}(1-r)^{-1}-r\lambda\underline{b}'^2(1-r)^{-1}].$$

When this expansion of G^{-1} is multiplied the numerator, the term "$-r(r_S+r_N)\underline{a}'^2 4^{-1}$" in the numerator combines with the term "$+r(r_S+r_N)\underline{a}'^2 4^{-1}(1-r)^{-1}$" in the expansion of G^{-1} to yield the <u>net</u> term "$+r^2(r_S+r_N)\underline{a}'^2 4^{-1}(1-r)^{-1}$" in the first order expansion of the product.)

e. The term "$+r\underline{a}'^2 2^{-1}$", together with the same term in the quantity G in the denominator, represents the luminous flux from the sphere wall (excluding the direct flux from the source point) which is screened from the sphere wall by the baffle, and is thus screened <u>indirectly</u> from the sphere window.

f. The term "$+r\lambda\underline{b}'^2$", together with the same term in the quantity G in the denominator, represents the luminous flux from the sphere wall (excluding the direct flux from the source point) which is partly screened (since the lamp absorptance $\underline{\lambda}$ is less than 1) from the sphere wall by the lamp, and is thus screened indirectly from the sphere window.

g. The term "$-r\underline{\lambda}F_{LP}(\alpha)$" represents luminous flux from the source point which is partly screened from the sphere wall by the lamp, and is thus screened indirectly from the sphere window.

h. The term "$+rr_S F_{BD}(\pi)$" represents luminous flux from the sphere wall (excluding the direct flux from the source point) which strikes the south surface of the baffle, and is reflected directly to the sphere window.

i. The term "$+rr_S F_{BP}(\alpha)$" has the same physical significance as term "a.", "$+rr_N F_{BP}(\alpha)$", except that the source point now illuminates the south surface of the baffle.

j. The term "$+4(1-r)r_S F_{BD}(\pi)F_{BP}(\alpha)\underline{a}'^{-2}$" represents luminous flux from the source point which strikes the south surface of the baffle, and then is reflected directly to the sphere window.

Referring again to figure 3, it is convenient to denote the intersections of the baffle axis with the sphere as the "north" and "south" poles; the north pole is marked N in figure 3, the south pole is marked W, since the sphere window is located at this point. The photometric detector D (in the typical photometric integrating sphere) is located at the sphere window, but is placed outside the sphere; the detector views the luminous flux transmitted through the translucent (diffusely transmitting and reflecting) window. (Filters required to match the spectral responsivity of the sphere-detector system to the C.I.E. photopic luminosity function [12], are placed between the detector and the sphere window.)

4.2. Lamp Flux Reflected from the Baffle

In figure 3, it is seen that if 1 lumen is incident upon the north surface of the baffle, the resulting luminance at the sphere window, denoted L_{1B}, is

$$L_{1B} = r_N 2\int_0^{\gamma} d\theta' \sin\theta' F_{BD}(\theta') L_1(\theta',\pi,\underline{\lambda})\underline{a}'^{-2} - \underline{\lambda} r_N F_{LB} \bar{L}_1(0,\pi,\underline{\lambda}).$$

In this equation, F_{LB} is the viewfactor of the lamp as viewed from the baffle, $L_1(\theta',\pi,\underline{\lambda})$ is the luminance produced at the sphere window by a 1 lumen source input to the sphere wall at a point whose colatitude angle is θ', and $\bar{L}_1(0,\pi,\underline{\lambda})$ is the average luminance produced at the sphere window, by a 1 lumen source input which illuminates uniformly the area of the sphere wall defined by the projection of the lamp from the center of the baffle, onto the sphere wall. (The preceding equation for L_{1B} is approximate, and valid to first order only. Note that F_{LB} is of first order in $\underline{a}'^2$, and that for an extended source distribution, the fraction of the total source flux emitted by the baffle can reasonably be assumed to be also of first order; thus for an extended source distribution, the term involving F_{LB} becomes of second order and hence may be discarded in a first order analysis.)

4.3. Extended Source Distributions

If the source illuminance on the sphere wall is denoted $E(\alpha)$, the total lamp flux ϕ_L^* (lumens) is given by the equation,

$$\phi_L^* = 2\pi R^2 \int_0^{\pi} d\theta' \sin\theta' E(\theta') + \phi_{LB}^*(1-r_N), \tag{4}$$

where ϕ_{LB}^* is the lamp flux which strikes the baffle. The luminance L_T

produced at the sphere window by this lamp flux is therefore

$$L_T = 2\pi R^2 \int_0^\pi d\theta' \sin\theta' E(\theta') L_1(\theta',\pi,\underline{\lambda}).$$

It is useful to define the ratio of the luminance at the sphere window to the lamp flux which produces that luminance; denote this ratio k, so that

$$k = L_T/\phi_L^*.$$

It is seen from the preceding equations that k is given in terms of $E(\alpha)$ by the equation,

$$k = \frac{2\pi R^2 \int_0^\pi d\theta' \sin\theta' E(\theta') L_1(\theta',\pi,\underline{\lambda})}{2\pi R^2 \int_0^\pi d\theta' \sin\theta' E(\theta') + \phi_{LB}^*(1-r_N)}. \tag{5}$$

It is convenient now to normalize the lamp flux to 1 lumen, for comparing lamps of different illuminance distributions. Then eq (5) becomes,

$$k = 2\pi R^2 \int_0^\pi d\theta' \sin\theta' E'(\theta') L_1(\theta',\pi,\underline{\lambda}),$$

where $E'(\theta')$ is the normalized source illuminance distribution on the wall of the sphere.

Consider now two different lamps, A and B, whose total luminous flux ratio is desired. The the fractional error $\delta k'$ in the ratio of the sphere-window luminances, L_{TB}/L_{TA}, compared with the true total luminous flux ratio, ϕ_{LB}^*/ϕ_{LA}^*, is defined,

$$\delta k' = (k_B - k_A)/k_A.$$

If the normalized illuminance distribution of lamp A is $E'_A(\theta')$, and that of lamp B is $E'_B(\theta')$, then it is seen that

$$\delta k' = \frac{\int_0^\pi d\theta' \sin\theta' \left[E'_B(\theta')L_{1B}(\theta',\pi,\underline{\lambda}_B) - E'_A(\theta')L_{1A}(\theta',\pi,\underline{\lambda}_A)\right]}{\int_0^\pi d\theta' \sin\theta' E'_A(\theta')L_{1A}(\theta',\pi,\underline{\lambda}_A)}. \tag{6}$$

4.4. Extended Source Distributions: Approximate Model

To compute the fractional error in the ratio of the sphere-window luminances of two different lamps, with respect to the ratio of the total luminous fluxes of the lamps, one may of course use experimental lamp-illuminance distribution data, if these are available. Another approach is to use a model distribution to approximate the true lamp illuminance distribution. A useful one-parameter model distribution is the cardioid,

$$E'(\theta) = (1+g(\theta)\cos\theta)/(4\pi R^2);$$

the parameter $g(\theta)$ is assumed to be a random variable such that

$$\int_0^\pi d\theta' \sin\theta' g(\theta')\cos\theta' = 0. \tag{7}$$

If the above cardioid lamp illuminance distribution is substituted into eq (4) for the total lamp flux ϕ^*_L, then it is seen that the total lamp flux is <u>independent</u> of $g(\theta)$, provided it satisfies eq (7) and that the lamp flux which strikes the baffle, ϕ^*_{LB}, is also independent of $g(\theta)$.

Assume now that the two different lamps, A and B, have the following parameters: lamp A is characterized by $\underline{\lambda}_A$, $\underline{b}_A$, and $g_A(\theta)$; lamp B is characterized by $\underline{\lambda}_B$, $\underline{b}_B$, and $g_B(\theta)$. Now substitute these values into eq (6) for $\delta k'$, refer to eqs (1)-(3) for $L_1(\theta,\pi,\underline{\lambda})$, and use the normalization condition (that is, the total flux from both lamp A and lamp B is 1 lumen) to obtain the approximation,

$$\delta k' \approx G_B^{-1}\left[r(\underline{\lambda}_A\underline{b}_A'^2-\underline{\lambda}_B\underline{b}_B'^2)+(1-r)^2\int_0^{2\delta}d\theta'\sin\theta'\cos\theta'(g_A(\theta')-g_B(\theta'))2^{-1}\right], \quad (8)$$

where

$$G_B = \left[(1-r)+r(2-r_S-r_N)\underline{a}'^2 4^{-1}+r\underline{\lambda}_B\underline{b}_B'^2\right],$$

and it has been assumed further that lamps A and B have similar illuminance distributions in the sense that the average value of the difference between their normalized fluxes, over any area of the sphere, is never larger in magnitude than a first order quantity.

It is helpful to consider the physical significance of the terms in eq (8) at this point. The first term,

$$r(\underline{\lambda}_A\underline{b}_A'^2-\underline{\lambda}_B\underline{b}_B'^2)/G_B,$$

represents the difference between the fraction of its total luminous flux absorbed by lamp A, and the fraction of its total luminous flux absorbed by lamp B. This is seen from the fact that the flux absorbed by the sphere wall is proportional to $4\pi R^2(1-r)$, the flux absorbed by lamp A is proportional to $4\pi r\underline{\lambda}_A\underline{b}_A^2$, the flux absorbed by lamp B is proportional to $4\pi r\underline{\lambda}_B\underline{b}_B^2$, and the flux absorbed by the baffle is proportional to $\pi r\underline{a}^2(2-r_S-r_N)$.

The second term,

$$(1-r)^2 G_B^{-1}\int_0^{2\delta}d\theta'\sin\theta'\cos\theta'(g_A(\theta')-g_B(\theta'))2^{-1},$$

represents the difference between the fraction of its total luminous flux absorbed by the screened region of the sphere wall for lamp A, and the fraction of its total luminous flux absorbed by the screened region of the sphere wall for lamp B.

It should be noted that this analysis of the physical significance of $\delta k'$ (for sources of similar illuminance distributions) is <u>independent</u> of the positions of the lamps and the baffles within the sphere, provided that the first order approximation is valid; that is, the lamps and the baffles may have any position within the sphere for which the lamps are screened from the sphere window and from each other, and for which all the interaction viewfactors (the viewfactors of the baffles and the lamps as viewed from the sphere wall and from each other) are of the first order. If these conditions are fulfilled, then the sphere error $\delta k'$ in comparing the total luminous fluxes of lamps A and B is given to first order accuracy by the formula,

$$\begin{aligned}\delta k' \approx \Big[&(\text{Fractional Flux Absorbed by A}) \\ &-(\text{Fractional Flux Absorbed by B}) \\ &+(\text{Fractional Screened Flux of A Absorbed}) \\ &-(\text{Fractional Screened Flux of B Absorbed})\Big]. \qquad (9)\end{aligned}$$

Eq (9) is <u>not</u> valid, of course, if the illuminance distributions of lamps A and B differ widely.

In most practical cases, the sphere-wall absorptance is much larger than the lamp and the baffle absorptances; this means that

$$(1-r) \gg \left[r(2-r_S-r_N)\underline{a}'^2 4^{-1} + r\underline{\lambda b}'^2\right].$$

If this inequality holds, then $\delta k'$ becomes approximately,

$$\delta k' \approx \left[r(\underline{\lambda}_A \underline{b}_A'^2 - \underline{\lambda}_B \underline{b}_B'^2)(1-r)^{-1} + (1-r)\int_0^{2\delta} d\theta' \sin\theta' \cos\theta' (g_A(\theta') - g_B(\theta'))2^{-1}\right]. \quad (10)$$

Now define an average value of $(g_A(\theta)-g_B(\theta))$ over the <u>screened</u> region of the sphere wall by the formula,

$$\overline{(g_A(\theta)-g_B(\theta))}_{SC} = (2\sin^2\delta)^{-1}\int_0^{2\delta} d\theta' \sin\theta' \cos\theta' (g_A(\theta')-g_B(\theta')).$$

Then eq (10) for $\delta k'$ can be written,

$$\delta k' \approx \left[r(\underline{\lambda}_A \underline{b}_A'^2 - \underline{\lambda}_B \underline{b}_B'^2)(1-r)^{-1} + (1-r)\overline{(g_A(\theta)-g_B(\theta))}_{SC}\sin^2\delta\right];$$

this formula assumes that the magnitude and the sign of the average value of $(g_A(\theta)-g_B(\theta))$ over the screened region of the sphere wall are known; usually this information is not available, and it is reasonable to consider $\overline{(g_A(\theta)-g_B(\theta))}_{SC}$ as a random variable. In this case, the two components of $\delta k'$ should be added in quadrature, so that the formula for $\delta k'$ becomes,

$$\delta k' \approx \left[(r(\underline{\lambda}_A \underline{b}_A'^2 - \underline{\lambda}_B \underline{b}_B'^2)(1-r)^{-1})^2 + ((1-r)\overline{(g_A(\theta)-g_B(\theta))}_{SC}\sin^2\delta)^2\right]. \quad (11)$$

4.5. Optimum Baffle and Lamp Positions to Minimize the Error in Measuring Total Luminous Flux

Referring to figure 3 and eq (9), it is seen that the sphere error $\delta k'$ can be reduced by decreasing the magnitude of the fractional screened fluxes of lamps A and B. It is also clear from figure 3 that the fractional screened flux is a function of the positions of the baffle and the lamp within the sphere. Note particularly that in the general case, where a fraction of the lamp flux is directly incident upon the north surface of the baffle, the fractional screened flux <u>includes</u> that incident upon the baffle. If the lamp illuminance distribution is spherically uniform, then the fractional screened flux is equal to the <u>sum</u> of:

(1), the fractional solid angle (that is, the fraction of a complete sphere) subtended by the projection of the baffle from the sphere window onto the sphere wall, at the lamp center; plus (2), the fractional solid angle subtended by the baffle at the lamp center. (A more realistic situation is a spherically uniform lamp illuminance distribution up to a limiting colatitude angle which may - or may not - include part of the baffle.) Thus it is desired to find the baffle and lamp positions which will minimize the sum of (1) and (2) above; this is equivalent to minimizing the total screened solid angle, as viewed from the lamp center. It can be shown that this total screened solid angle is approximately equal to $\pi \underline{a}'^2[(\underline{h}'+\underline{l}')^{-2}+4(1-\underline{h}')^{-2}(1-\underline{l}')^{-2}]$, where $\underline{h}'=\underline{h}/R$ and $\underline{l}'=\underline{l}/R$.

The positions of the baffle and the lamp which minimize the preceding expression for the total screened solid angle, viewed from the lamp center, are found to be

$$\underline{h}' = \underline{l}' = 0.212.$$

Thus the optimum positions of the baffle and the lamp when the lamp illuminance distribution is spherically uniform, are: (1), the baffle placed 0.212 of the sphere radius from the center of the sphere, and 0.788 of the sphere radius from the sphere window; and (2), the lamp center placed 0.212 of the sphere radius from the center of the sphere, and 1.212 of the sphere radius from the sphere window; both the baffle and the lamp are assumed to be coaxial with the sphere axis which passes through the center of the sphere window.

If the lamp position is fixed, and only the baffle position is varied, then to every lamp position corresponds a baffle position which minimizes the total screened solid angle; for a spherically uniform lamp illuminance distribution, the optimum values of $\underline{h}'$ and $\underline{l}'$ are related by the equation,

$$\underline{h}' = [(1-\underline{l}')^{2/3}-4^{1/3}]/[(1-\underline{l}')^{2/3}+4^{1/3}].$$

If, for example, $\underline{l}'=0$ (the lamp at the center of the sphere), then the optimum value of $\underline{h}'$ is 0.386.

Now assume that the lamp has a spherically uniform illuminance distribution up to a limiting colatitude angle which <u>excludes</u> the baffle; in other words, <u>no</u> lamp flux strikes the baffle directly. Then it is found that the optimum baffle and lamp positions are

$$\underline{h}' = \underline{l}' = 0;$$

that is, the baffle and the lamp should both be located at the center of the sphere. (Note that the optimum values of $\underline{h}'$ and $\underline{l}'$ derived above for a coaxial baffle and lamp configuration, <u>also</u> hold for baffle and lamp positions along any chord of the sphere emanating from the sphere window, <u>except</u> that $\underline{h}'$ and $\underline{l}'$ must be replaced by $\underline{h}'\cos\Sigma$ and $\underline{l}'\cos\Sigma$, respectively, and these displacements along the chord are referenced to the chord center, which is a distance $R\cos\Sigma$ from the sphere window; here Σ is the angle between the chord and the sphere axis coaxial with the sphere window.)

4.6. Upper Bound on the Fractional Sphere Error

Eq (11) shows that: (1), if two lamps have the same fractional absorptance, the dominant term in the error in comparing their total luminous fluxes in an integrating sphere (if they have similar illuminance distributions) is the difference in their fractional screened fluxes; (2), if two lamps have the same fractional screened flux, the dominant term in the error in comparing their total luminous fluxes is the difference in their fractional absorptances.

It is useful to estimate an upper bound for the fractional sphere error in present NBS techniques for comparing the total luminous fluxes of 1000-watt incandescent lamps in a 2-meter integrating sphere [9]. The geometry employed is as follows: the baffle is placed 0.55 meter from the sphere window and is shaped roughly like a projection of the 1000-watt lamps; the baffle dimensions are 0.15 meter by 0.23 meter (the equivalent radius is 0.093 meter, to yield the same area); the lamps are separately placed at the center of the sphere for total flux measurement (that is, only one lamp is in the sphere at the time of measurement); the radius of the lamps is roughly 0.08 meter. The reflectance of the sphere wall and of the baffle surfaces is assumed to be 0.90 [7]. To proceed further, it is necessary to introduce the following reasonable assumptions: (1), the difference in the absorptance $\underline{\lambda}$ of the lamps is less than 0.05; (2), the magnitude of the quantity $\overline{(g_A(\theta)-g_B(\theta))}_{SC}$ is less than 0.5 (that is, the fractional screened fluxes of the lamps differ by less than half the fractional screened flux of a lamp of spherically uniform illuminance distribution).

With the preceding assumptions, eq (11) for the fractional sphere error $\delta k'$ yields 0.29% for the component of the sphere error due to the difference in fractional lamp absorptance, and 0.13% for the component of the sphere error due to the difference in fractional screened flux. Adding these two components in quadrature, as indicated in eq (11), yields an estimated upper bound of 0.32% for the fractional sphere error in present NBS techniques for comparing the total luminous fluxes of 1000-watt incandescent lamps in a 2-meter integrating sphere.

4.7. Factors Neglected

The preceding analysis has neglected several factors and their effects on the sphere error in comparing the total luminous fluxes of lamps in the integrating sphere. These factors are: (1), varying spectral reflectance of the sphere and the baffle coatings, (2), varying spectral absorptance of the lamp, (3), spatial variations in the sphere-wall reflectance, (4), specular component of the sphere-wall reflectance, (5), reflectance of the lamp, (6), deviations of the sphere-window transmittance from the cosine law, (7), detector signal-to-noise considerations, (8), deviations of the sphere wall from perfect sphericity.

Referring to eq (11), it is seen that the effect of <u>increasing</u> the spectral reflectance of the sphere wall is to <u>increase</u> the fractional fluxes absorbed by the lamps (whose total luminous fluxes are to be compared), and to <u>decrease</u> the absorption of the fractional screened fluxes of the lamps. It is also seen from eq (11) that the effect of <u>increasing</u> the spectral absorptances of the lamps is to <u>increase</u> the fractional fluxes absorbed by the lamps.

Theoretically, if the spectral distributions in the visible are given of, (1), the spectral reflectance $r(\lambda)$ of the sphere wall (λ is the wavelength), (2), the spectral absorptances $\underline{\lambda}_A(\lambda)$ and $\underline{\lambda}_B(\lambda)$ of the lamps A and B, (3), the spectral transmittance $t(\lambda)$ of the sphere window, and (4), the spectral luminous fluxes of the lamps, $J_A'(\lambda)$ and $J_B'(\lambda)$, normalized to unit luminous flux, then the average sphere error over the visible spectrum, $\overline{\delta k'}$, can be computed.

The approximate formula for $\overline{\delta k'}$ is (accurate to first order, and assuming that lamps A and B have similar spectral luminous flux distributions):

$$\begin{aligned}\overline{\delta k'} \approx \Big(&\Big[\int_{\lambda 1}^{\lambda 2} d\lambda'(r(\lambda')t(\lambda')(1-r(\lambda'))^{-1}(J_B'(\lambda')-J_A'(\lambda'))\Big]^2 \\ &+\Big[\int_{\lambda 1}^{\lambda 2} d\lambda' r^2(\lambda')t(\lambda')(1-r(\lambda'))^{-2}J_A'(\lambda')(\underline{\lambda}_A(\lambda')\underline{b}_A'^2-\underline{\lambda}_B(\lambda')\underline{b}_B'^2)\Big]^2 \\ &+\Big[\int_{\lambda 1}^{\lambda 2} d\lambda' r(\lambda')t(\lambda')J_A'(\lambda')\sin^2\delta\overline{(g_A(\theta)-g_B(\theta))}_{SC}\Big]^2\Big)^{0.5} \\ &X\Big(\int_{\lambda 1}^{\lambda 2} d\lambda' r(\lambda')t(\lambda')(1-r(\lambda'))^{-1}\Big)^{-1}. \qquad (12)\end{aligned}$$

Eq (12) is analogous to eq (11) for $\delta k'$ in that the error components are treated as random variables and hence are added in quadrature to obtain the total sphere error $\overline{\delta k'}$; λ_1 and λ_2 are the limits of the visible spectrum (approximately 0.38-0.78 micrometer [12]); $J_A'(\lambda)$ and $J_B'(\lambda)$ are normalized so that

$$\int_{\lambda 1}^{\lambda 2} d\lambda' J_A'(\lambda') = \int_{\lambda 1}^{\lambda 2} d\lambda' J_B'(\lambda') = 1.$$

Spatial variations in the reflectance of the sphere wall may be a significant source of error. Experimental work is needed to establish the magnitude of this effect.

The specular component of the sphere-wall reflectance is estimated to produce a second order sphere error in comparing the total luminous fluxes of two lamps of similar illuminance distributions; hence this error can be neglected in a first order analysis. (To ensure the validity of this assumption, the baffle must be of adequate size to make the maximum angle of reflection, from the portions of the sphere wall directly illuminated by the source, to the sphere window, less than the critical angle at which specularity effects become important.)

The effect of luminous flux reflected from the lamp bulb is estimated to be negligible for extended sources.

The deviations of the sphere window from cosine-law transmittance (that is, from uniformly diffuse transmittance) are probably a significant source of error, except where the lamps compared have very similar illuminance distributions. Probably the best procedure (if the illuminance at the sphere window is high enough to provide an adequate signal-to-noise ratio at the detector) is to remove the window and replace it with a small auxiliary integrating sphere; the inner surface of this auxiliary sphere is then viewed by the detector.

Detector signal-to-noise considerations are important in limiting the maximum sphere diameter which can be used to compare lamps of a given flux output. At NBS, for example, the 2-meter diameter integrating sphere is not used to measure total luminous fluxes of less than 200 lumens [7]. Thus to optimize the accuracy of measurements of total luminous flux, the sphere diameter should be roughly that which equalizes the magnitudes of the computed sphere error $\overline{\delta k'}$, and the measurement error due to detector noise.

The effect of deviations of the sphere wall from perfect sphericity, on the sphere error in comparing two lamps of similar illuminance distributions, can be shown to be of second order (and hence negligible) for deviations which consist of flattened portions of first order area (that is, the area of each flattened portion is comparable with the baffle area).

5. Conclusions

The approximate mathematical theory of the photometric integrating sphere, developed in section 4, leads to the following conclusions:

For typical sphere parameters, the fractional sphere error in comparing the total luminous fluxes of two incandescent lamps is probably less than 0.2% _if_: (1), the viewfactor of the baffle from the sphere window is less than 0.025; (2), the lamp flux directly incident upon the baffle is negligible; (3), the lamps compared have similar illuminance distributions; (4), the lamp dimensions are similar; (5), the lamp absorptances differ by less than 0.02; (6), the total flux of each lamp is measured with _only_ that lamp in the sphere (the screening effect and the absorptance of the other lamp introduce errors if it is also present in the sphere).

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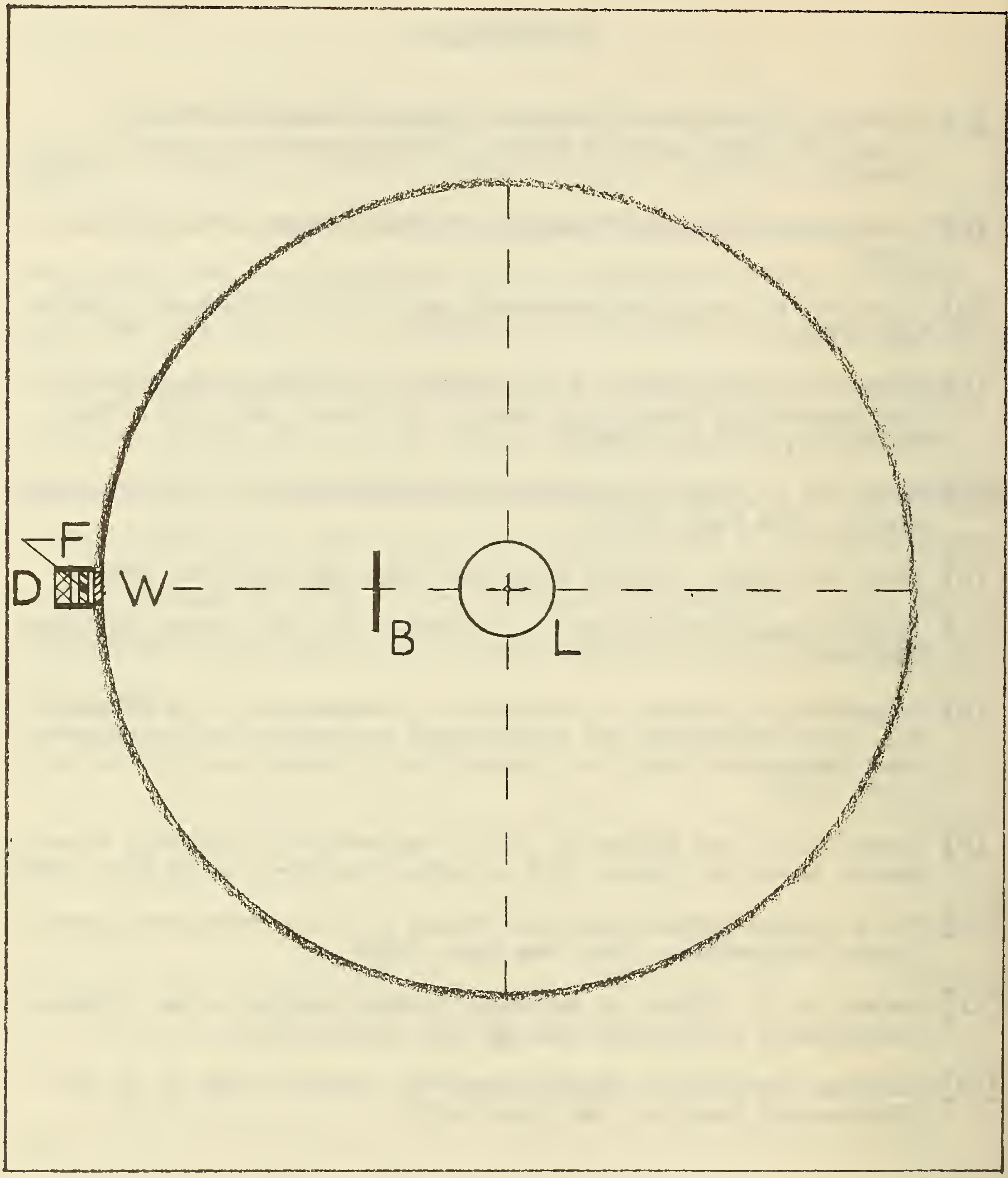

Figure 1. Cross section of typical integrating sphere:
B-baffle, D-detector, F-filter, L-lamp, W-window.

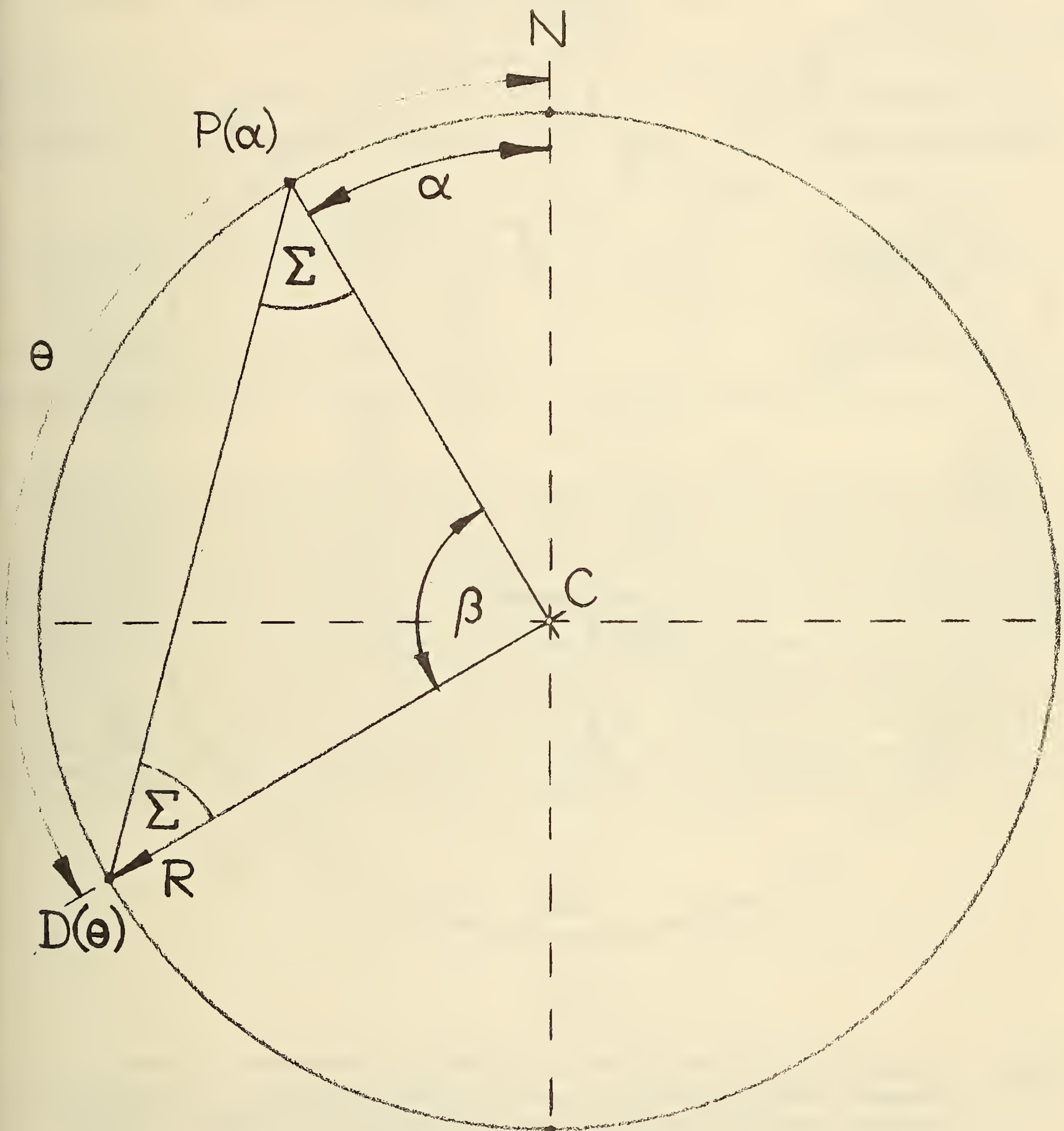

Figure 2. Cross section of empty sphere; viewfactor geometry.

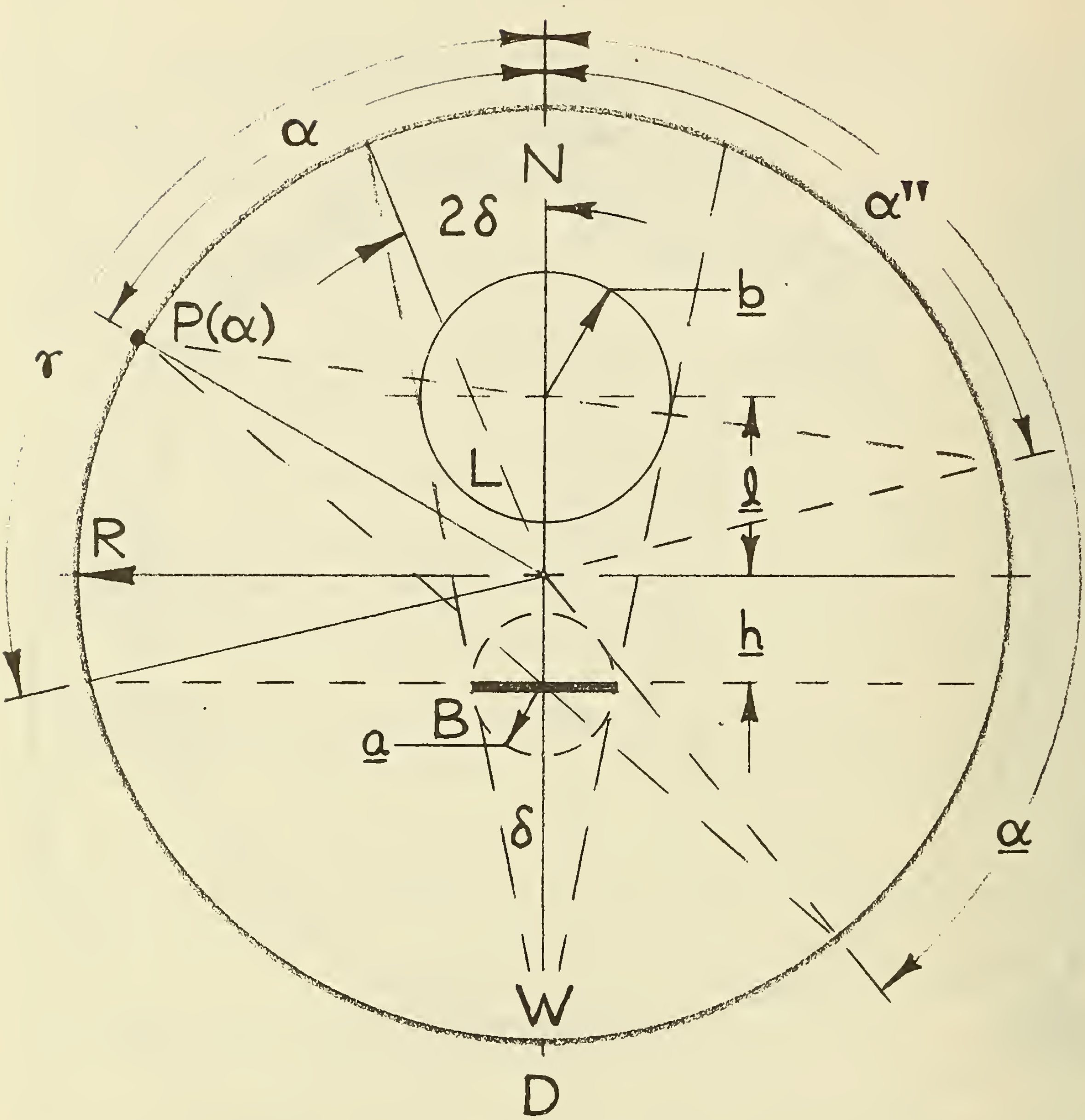

Figure 3. Integrating sphere geometry: B-baffle, D-detector, L-lamp, N-north pole, P(α)-source point, R-sphere radius, W-sphere window; a-baffle radius, b-lamp radius, h-displacement of baffle south of sphere equator, l-displacement of lamp north of sphere equator; α-colatitude angle of projection of baffle center from P(α) to opposite sphere wall, α"-colatitude angle of projection of lamp center from P(α) to opposite sphere wall, δ-half angle subtended by baffle at window, γ-colatitude angle of baffle plane intersection with sphere.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

An approximate mathematical theory of the photometric integrating sphere is developed. The analysis is accurate to the first order in the ratio of the baffle area to the sphere wall area. The sphere is assumed to be occupied by a circular baffle and a spherical lamp; the centers of the baffle and the lamp lie on a diameter of the sphere. The surfaces of the sphere and the baffle are assumed to reflect in a uniformly diffuse manner. The lamp is assumed to absorb a fraction of the radiation incident upon it, and to transmit (or specularly reflect) the remainder. The luminance distribution at the sphere window is derived for a general source input at any point of the sphere wall. A model lamp illuminance distribution is assumed, and a formula for the fractional error in comparing the total luminous fluxes of two lamps in the integrating sphere, is derived. The physical significance of the formula is described.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Optical Radiation Measurements:

Tables of Diffraction Losses

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Tables of Diffraction Losses

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Preface

This is the eighth issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series will consist primarily of reports of progress in, or details of, research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division.

The level of presentation in OPTICAL RADIATION MEASUREMENTS will be directed at a general technical audience. The equivalent of an undergraduate degree in engineering or physics, plus familiarity with the basic concepts of radiometry and photometry [e.g., G. Bauer, Measurement of Optical Radiations (Focal Press, London, New York, 1965)], should be sufficient for understanding the vast majority of material in this series. Occasionally a more specialized background will be required. Even in such instances, however, a careful reading of the assumptions, approximations, and final conclusions should permit the non-specialist to understand the gist of the argument if not the details.

At times, certain commercial materials and equipment will be identified in this series in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

Any suggestions readers may have to improve the utility of this series are welcome.

Henry J. Kostkowski, Chief
Optical Radiation Section
National Bureau of Standards

Contents

Figures

Tables of Diffraction Losses*

W. B. Fussell

Tables of diffraction losses are given for a range of typical experimental geometries for wavelengths from 0.2 to 100 micrometers. The scaling relationships for the diffraction losses for varying wavelengths and geometries are also given, and sample calculations are presented. General formulas are given for the diffraction losses; the formulas are derived from the Kirchhoff scalar paraxial diffraction theory. The accuracy of the tabulated values is estimated.

Key words: Diffraction; diffraction losses; Fresnel diffraction; Kirchhoff diffraction theory; photometry; radiometry; scalar diffraction theory.

1. Introduction

With the improved precision and accuracy of radiometric measurements, diffraction losses have become significant. It is useful, therefore, to compute and tabulate diffraction losses for a range of typical geometries and wavelengths. The Kirchhoff scalar paraxial diffraction theory is used to calculate these losses. This is an approximate model which evaluates the phase relationships over the diffracting aperture (see fig. 1) for each elemental source area, for a given detection point and wavelength; the resulting complex number is then integrated over the source area and the magnitude of the sum indicates the relative spectral irradiance at the given detection point, compared with other detection points on the detector area. The model assumes: a., all source points radiate independently (that is, incoherent radiation); b., there are no polarization effects (that is, no vector effects); c., off-axis angles are small, and hence obliquity effects can be neglected. (Section 6 outlines the derivation of the equations used to compute the tables.)

The mathematical formulas used to compute the diffraction losses are refinements of the basic Fraunhofer on-axis diffraction formula (see Blevin[1] [1]). The tabulated on-axis diffraction losses are estimated to be accurate to within 10% mathematically; the off-axis diffraction losses are estimated to be accurate to within 20%. (If the physical realities of an experiment differ from the assumptions of the Kirchhoff model, there will be additional errors besides those due to the mathematical approximations used to compute the tables; however, it is expected that

*Supported in part by the Calibration Coordination Group of the Department of Defense.

[1]Figures in brackets indicate the literature references at the end of this paper.

most situations in radiometry and photometry will be within the regime of the Kirchhoff model. Blevin [1], for example, finds excellent experimental agreement with the Kirchhoff model.) Thus, if it is desired to calculate the off-axis diffraction loss for a given experiment to within 0.1% of the spectral irradiance at the detector, then the geometry of the experiment should be such that the tabulated diffraction loss is less then 0.5% of the spectral irradiance at the detector, since an error of 20% of 0.5% is equal to 0.1%.

The geometries and wavelengths selected for the diffraction loss tables are:

a., wavelengths from 0.2 to 100 micrometers;

b., source (or detector) diameters from 0.5 to 5 cm;

c., source (or detector)-to-aperture distances from 5 to 20 cm;

d., aperture diameters from 0.005 to 0.5 cm.

The geometry and terminology used in the diffraction loss tables is shown in figure 1.

In general, if the circumference of the circle produced by projecting the aperture from every point on the detector (the geometry in this report is assumed to be circularly symmetric in all cases), onto the plane of the source, lies within the source, then the radiation incident on the detector is proportional to the <u>source radiance</u> (less diffraction losses). On the other hand, if the circumference of the circle produced by projecting the aperture from every point of the source, onto the plane of the detector, lies within the detector, then the radiation incident on the detector is the <u>total source radiation through the aperture</u> (less diffraction losses). (The diffraction losses for a given configuration are identical, whether the source is treated as a detector and the detector as a source, or vice versa; this is sometimes a conceptual advantage in that it transforms a source radiance measurement into a total aperture radiation measurement.) In this report, the source radiance geometry will always be meant unless it is explicitly stated that the total aperture radiation geometry is under consideration.

For a given geometry, the diffraction loss in the plane of the detector is least on the axis; the diffraction loss increases steadily as the distance from the axis increases (see sec. 6). Therefore, the diffraction loss realized with a circular detector increases steadily as the detector radius increases. The diffraction losses listed in the following tables are for the on-axis case (the "point" detector), and also for the case of a detector that sees 90% of the diameter of the source (the radius of such a detector is designated x_{max}). These diffraction losses, designated E'_{min} and $\bar{E}'_{max}$ respectively, bracket the loss for detector radii between zero and x_{max} to within roughly ±20% for geometries where the aperture diameter is much less than the source diameter, and more accurately for ratios of the aperture diameter to the source diameter larger than 0.1 (see the end of sec. 7).

2. Tables of Diffraction Losses as Functions of Wavelength and Geometry

Terminology:

λ is the wavelength in micrometers.

d is the source diameter in cm (or the detector diameter, for a total aperture radiation measurement; see sec. 1).

$\underline{b}$ is the source-aperture distance in cm.

D is the aperture diameter in cm.

v is the dimensionless quantity $\pi Dd(2\underline{b}\lambda)^{-1}$.

E'_{min} is the diffraction loss[1] for a point detector on-axis whose distance from the aperture is at least 10 times the source-aperture distance.

$\bar{E}'_{max}$ is the diffraction loss[1] averaged over the area of a circular detector of radius x_{max} (see sec. 1 and fig. 1); the radius x_{max} is defined to be that radius for which the field of view through the aperture covers the portion of the source disc whose diameter is 0.9 the source diameter; the distance of the detector from the aperture must be at least 10 times the source-aperture distance.

---

[1]The diffraction losses E'_{min} and $\bar{E}'_{max}$ are given as a percentage of the irradiance that would be present at the detector in the absence of diffraction. The mathematical formulas used to compute E'_{min} and $\bar{E}'_{max}$ are given in section 6. Upper bounds for the errors in E'_{min} and $\bar{E}'_{max}$ can be computed using the dimensionless quantity v, and formulas for such computations are given in section 7.

$\underline{\lambda} = \underline{0.2}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
5	v	39.3	78.5	157	393	785	1570	3930
	(%)E'_{min}	1.62	0.81	0.41	0.16	0.08	.05	-
	(%)$\bar{E}'_{max}$	2.59	1.27	0.62	0.24	0.12	.06	-
10	v	19.6	39.3	78.5	196	393	785	1960
	E'_{min}	3.24	1.62	0.81	0.33	0.17	0.10	-
	$\bar{E}'_{max}$	5.19	2.55	1.24	0.47	0.23	0.13	-
20	v	9.82	19.6	39.3	98.2	196	393	982
	E'_{min}	6.49	3.24	1.62	0.66	0.34	0.19	-
	$\bar{E}'_{max}$	<18*	5.09	2.48	0.95	0.47	0.25	-

$\underline{d} = \underline{1}$ (cm)

$\underline{b}$ (cm)								
5	v	78.5	157	314	785	1570	3140	7850
	(%)E'_{min}	0.81	0.41	0.20	0.08	0.04	0.02	0.01
	(%)$\bar{E}'_{max}$	1.31	0.65	0.32	0.12	0.06	0.03	0.01
10	v	39.3	78.5	157	393	785	1570	3930
	E'_{min}	1.62	0.81	0.41	0.16	0.08	0.04	0.02
	$\bar{E}'_{max}$	2.62	1.30	0.64	0.25	0.12	0.06	0.03
20	v	19.6	39.3	78.5	196	393	785	1960
	E'_{min}	3.24	1.62	0.81	0.33	0.16	0.08	0.04
	$\bar{E}'_{max}$	5.24	2.59	1.27	0.49	0.24	0.12	0.06

*(Note: These values are upper bounds.)

$\underline{\lambda} = \underline{0.2}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	157	314	628	1570	3140	6280	15700
5	(%)E'_{min}	0.41	0.20	0.10	0.04	0.02	0.01	0.00
	(%)$\overline{E}'_{max}$	0.66	0.33	0.16	0.06	0.03	0.01	0.01
	v	78.5	157	314	785	1570	3140	7850
10	E'_{min}	0.81	0.41	0.20	0.08	0.04	0.02	0.01
	$\overline{E}'_{max}$	1.32	0.66	0.32	0.13	0.06	0.03	0.01
	v	39.3	78.5	157	393	785	1570	3930
20	E'_{min}	1.62	0.81	0.41	0.16	0.08	0.04	0.02
	$\overline{E}'_{max}$	2.64	1.31	0.65	0.25	0.12	0.06	0.02

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)								
	v	393	785	1570	3930	7850	15700	39300
5	(%)E'_{min}	0.16	0.08	0.04	0.02	0.01	0.00	0.00
	(%)$\overline{E}'_{max}$	0.26	0.13	0.07	0.03	0.01	0.01	0.00
	v	196	393	785	1960	3930	7850	19600
10	E'_{min}	0.32	0.16	0.08	0.03	0.02	0.01	0.00
	$\overline{E}'_{max}$	0.53	0.26	0.13	0.05	0.03	0.01	0.00
	v	98.2	196	393	982	1960	3930	9820
20	E'_{min}	0.65	0.32	0.16	0.06	0.03	0.02	0.01
	$\overline{E}'_{max}$	1.06	0.53	0.26	0.10	0.05	0.02	0.01

$\underline{\lambda} = \underline{0.5}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	15.7	31.4	62.8	157	314	628	1570
5	(%)E'_{min}	4.05	2.03	1.01	0.41	0.21	0.12	-
	(%)E'_{max}	6.48	3.18	1.55	0.59	0.29	0.16	-
	v	7.85	15.7	31.4	78.5	157	314	785
10	E'_{min}	8.11	4.05	2.03	0.82	0.42	0.24	-
	E'_{max}	<20*	6.37	3.10	1.19	0.59	0.32	-
	v	3.93	7.85	15.7	39.3	78.5	157	393
20	E'_{min}	-	8.11	4.06	1.64	0.84	0.48	-
	E'_{max}	-	<20*	6.19	2.37	1.17	0.64	-

$\underline{d} = \underline{1}$ (cm)

b (cm)		.005	.01	.02	.05	.1	.2	.5
	v	31.4	62.8	126	314	628	1260	3140
5	(%)E'_{min}	2.03	1.01	0.51	0.20	0.10	0.05	0.03
	(%)E'_{max}	3.28	1.62	0.80	0.31	0.15	0.07	0.03
	v	15.7	31.4	62.8	157	314	628	1570
10	E'_{min}	4.05	2.03	1.01	0.41	0.20	0.11	0.05
	E'_{max}	6.55	3.24	1.59	0.61	0.30	0.15	0.07
	v	7.85	15.7	31.4	78.5	157	314	785
20	E'_{min}	8.11	4.05	2.03	0.81	0.41	0.21	0.11
	E'_{max}	<20*	6.48	3.18	1.23	0.59	0.29	0.14

*(Note: These values are upper bounds.)

$\underline{\lambda} = \underline{0.5}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	62.8	126	251	628	1260	2510	6280
5	(%)E'_{min}	1.01	0.51	0.25	0.10	0.05	0.03	0.01
	(%)$\bar{E}'_{max}$	1.65	0.82	0.41	0.16	0.08	0.04	0.01
	v	31.4	62.8	126	314	628	1260	3140
10	E'_{min}	2.03	1.01	0.51	0.20	0.10	0.05	0.02
	$\bar{E}'_{max}$	3.30	1.64	0.81	0.32	0.15	0.07	0.03
	v	15.7	31.4	62.8	157	314	628	1570
20	E'_{min}	4.05	2.03	1.01	0.41	0.20	0.10	0.04
	$\bar{E}'_{max}$	6.59	3.28	1.62	0.63	0.31	0.15	0.06

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)								
	v	157	314	628	1570	3140	6280	15700
5	(%)E'_{min}	0.41	0.20	0.10	0.04	0.02	0.01	0.00
	(%)$\bar{E}'_{max}$	0.66	0.33	0.16	0.06	0.03	0.02	0.01
	v	78.5	157	314	785	1570	3140	7850
10	E'_{min}	0.81	0.41	0.20	0.08	0.04	0.02	0.01
	$\bar{E}'_{max}$	1.32	0.66	0.33	0.13	0.06	0.03	0.01
	v	39.3	78.5	157	393	785	1570	3930
20	E'_{min}	1.62	0.81	0.41	0.16	0.08	0.04	0.02
	$\bar{E}'_{max}$	2.65	1.32	0.66	0.26	0.13	0.06	0.02

$\underline{\lambda} = \underline{1}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
5	v	7.85	15.7	31.4	78.5	157	314	785
	$(\%)E'_{min}$	8.11	4.05	2.03	0.82	0.42	0.24	-
	$(\%)\bar{E}'_{max}$	<20*	6.37	3.10	1.19	0.59	0.32	-
10	v	3.93	7.85	15.7	39.3	78.5	157	393
	E'_{min}	-	8.11	4.06	1.64	0.84	0.48	-
	$\bar{E}'_{max}$	-	<20*	6.19	2.37	1.17	0.64	-
20	v	1.96	3.93	7.85	19.6	39.3	78.5	196
	E'_{min}	-	-	8.12	3.28	1.69	0.96	-
	$\bar{E}'_{max}$	-	-	<20*	4.74	2.34	1.27	-

$\underline{d} = \underline{1}$ (cm)

$\underline{b}$ (cm)								
5	v	15.7	31.4	62.8	157	314	628	1570
	$(\%)E'_{min}$	4.05	2.03	1.01	0.41	0.20	0.11	0.05
	$(\%)\bar{E}'_{max}$	6.55	3.24	1.59	0.61	0.30	0.15	0.07
10	v	7.85	15.7	31.4	78.5	157	314	785
	E'_{min}	8.11	4.05	2.03	0.81	0.41	0.21	0.11
	$\bar{E}'_{max}$	<20*	6.48	3.18	1.23	0.59	0.29	0.14
20	v	3.93	7.85	15.7	39.3	78.5	157	393
	E'_{min}	-	8.11	4.05	1.63	0.82	0.42	0.22
	$\bar{E}'_{max}$	-	<20*	6.37	2.45	1.19	0.59	0.28

*(Note: These values are upper bounds.)

$\underline{\lambda} = \underline{1}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	31.4	62.8	126	314	628	1260	3140
5	(%)E'_{min}	2.03	1.01	0.51	0.20	0.10	0.05	0.02
	(%)$\bar{E}'_{max}$	3.30	1.64	0.81	0.32	0.15	0.07	0.03
	v	15.7	31.4	62.8	157	314	628	1570
10	E'_{min}	4.05	2.03	1.01	0.41	0.20	0.10	0.04
	$\bar{E}'_{max}$	6.59	3.28	1.62	0.63	0.31	0.15	0.06
	v	7.85	15.7	31.4	78.5	157	314	785
20	E'_{min}	8.11	4.05	2.03	0.81	0.41	0.20	0.09
	$\bar{E}'_{max}$	<20*	6.55	3.24	1.26	0.61	0.30	0.12

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)								
	v	78.5	157	314	785	1570	3140	7850
5	(%)E'_{min}	0.81	0.41	0.20	0.08	0.04	0.02	0.01
	(%)$\bar{E}'_{max}$	1.32	0.66	0.33	0.13	0.06	0.03	0.01
	v	39.3	78.5	157	393	785	1570	3930
10	E'_{min}	1.62	0.81	0.41	0.16	0.08	0.04	0.02
	$\bar{E}'_{max}$	2.65	1.32	0.66	0.26	0.13	0.06	0.02
	v	19.6	39.3	78.5	196	393	785	1960
20	E'_{min}	3.24	1.62	0.81	0.32	0.16	0.08	0.03
	$\bar{E}'_{max}$	5.29	2.64	1.31	0.52	0.25	0.12	0.05

*(Note: These values are upper bounds.)

$\underline{\lambda} = \underline{2}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
5	v	3.93	7.85	15.7	39.3	78.5	157	393
	(%) $\underline{E'}_{min}$	-	8.11	4.06	1.64	0.84	0.48	-
	(%) $\overline{E}'_{max}$	-	<20*	6.19	2.37	1.17	0.64	-
10	v	1.96	3.93	7.85	19.6	39.3	78.5	196
	$\underline{E'}_{min}$	-	-	8.12	3.28	1.69	0.96	-
	$\overline{E}'_{max}$	-	-	<20*	4.74	2.34	1.27	-
20	v	0.982	1.96	3.93	9.82	19.6	39.3	98.2
	$\underline{E'}_{min}$	-	-	-	6.55	3.38	1.93	-
	$\overline{E}'_{max}$	-	-	-	<18*	4.68	2.55	-

$\underline{d} = \underline{1}$ (cm)

b (cm)								
5	v	7.85	15.7	31.4	78.5	157	314	785
	(%) $\underline{E'}_{min}$	8.11	4.05	2.03	0.81	0.41	0.21	0.11
	(%) $\overline{E}'_{max}$	<20*	6.48	3.18	1.23	0.59	0.29	0.14
10	v	3.93	7.85	15.7	39.3	78.5	157	393
	$\underline{E'}_{min}$	-	8.11	4.05	1.63	0.82	0.42	0.22
	$\overline{E}'_{max}$	-	<20*	6.37	2.45	1.19	0.59	0.28
20	v	1.96	3.93	7.85	19.6	39.3	78.5	196
	$\underline{E'}_{min}$	-	-	8.11	3.25	1.64	0.84	0.43
	$\overline{E}'_{max}$	-	-	<20*	4.90	2.37	1.17	0.56

*(Note: These values are upper bounds.)

$\underline{\lambda} = \underline{2}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
5	v	15.7	31.4	62.8	157	314	628	1570
	(%)E'_{min}	4.05	2.03	1.01	0.41	0.20	0.10	0.04
	(%)$\bar{E}'_{max}$	6.59	3.28	1.62	0.63	0.31	0.15	0.06
10	v	7.85	15.7	31.4	78.5	157	314	785
	E'_{min}	8.11	4.05	2.03	0.81	0.41	0.20	0.09
	$\bar{E}'_{max}$	<20*	6.55	3.24	1.26	0.61	0.30	0.12
20	v	3.93	7.85	15.7	39.3	78.5	157	393
	E'_{min}	-	8.11	4.05	1.62	0.81	0.41	0.17
	$\bar{E}'_{max}$	-	<20*	6.48	2.53	1.23	0.59	0.24

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)								
5	v	39.3	78.5	157	393	785	1570	3930
	(%)E'_{min}	1.62	0.81	0.41	0.16	0.08	0.04	0.02
	(%)$\bar{E}'_{max}$	2.65	1.32	0.66	0.26	0.13	0.06	0.02
10	v	19.6	39.3	78.5	196	393	785	1960
	E'_{min}	3.24	1.62	0.81	0.32	0.16	0.08	0.03
	$\bar{E}'_{max}$	5.29	2.64	1.31	0.52	0.25	0.12	0.05
20	v	9.82	19.6	39.3	98.2	196	393	982
	E'_{min}	6.48	3.24	1.62	0.65	0.32	0.16	0.07
	$\bar{E}'_{max}$	<18*	5.28	2.63	1.04	0.51	0.25	0.09

*(Note: These values are upper bounds.)

$\underline{\lambda} = \underline{5}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	1.57	3.14	6.28	15.7	31.4	62.8	157
5	(%)E'_{min}	-	-	10.1	4.09	2.11	1.21	-
	(%)$\bar{E}'_{max}$	-	-	<23*	5.93	2.93	1.59	-
	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
10	E'_{min}	-	-	-	8.19	4.22	2.41	-
	$\bar{E}'_{max}$	-	-	-	<20*	5.85	3.19	-
	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
20	E'_{min}	-	-	-	-	8.44	4.82	-
	$\bar{E}'_{max}$	-	-	-	-	<20*	6.37	-

$\underline{d} = \underline{1}$ (cm)

b (cm)								
	v	3.14	6.28	12.6	31.4	62.8	126	314
5	(%)E'_{min}	-	10.1	5.07	2.03	1.02	0.53	0.27
	(%)$\bar{E}'_{max}$	-	<23*	7.96	3.06	1.48	0.73	0.35
	v	1.57	3.14	6.28	15.7	31.4	62.8	157
10	E'_{min}	-	-	10.1	4.06	2.05	1.06	0.54
	$\bar{E}'_{max}$	-	-	<23*	6.13	2.96	1.46	0.70
	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
20	E'_{min}	-	-	-	8.13	4.09	2.11	1.08
	$\bar{E}'_{max}$	-	-	-	<20*	5.93	2.93	1.39

*(Note: These values are upper bounds.)

$\underline{\lambda} = \underline{5}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	6.28	12.6	25.1	62.8	126	251	628
5	(%)E'_{min}	10.1	5.07	2.53	1.01	0.51	0.26	0.11
	(%)$\bar{E}'_{max}$	<23*	8.19	4.05	1.58	0.77	0.37	0.15
	v	3.14	6.28	12.6	31.4	62.8	126	314
10	E'_{min}	-	10.1	5.07	2.03	1.02	0.51	0.22
	$\bar{E}'_{max}$	-	<23*	8.11	3.16	1.53	0.74	0.30
	v	1.57	3.14	6.28	15.7	31.4	62.8	157
20	E'_{min}	-	-	10.1	4.06	2.03	1.02	0.43
	$\bar{E}'_{max}$	-	-	<23*	6.32	3.06	1.48	0.59

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)								
	v	15.7	31.4	62.8	157	314	628	1570
5	(%)E'_{min}	4.05	2.03	1.01	0.41	0.20	0.10	0.04
	(%)$\bar{E}'_{max}$	6.61	3.30	1.64	0.65	0.32	0.15	0.06
	v	7.85	15.7	31.4	78.5	157	314	785
10	E'_{min}	8.11	4.05	2.03	0.81	0.41	0.20	0.08
	$\bar{E}'_{max}$	<20*	6.60	3.28	1.30	0.64	0.31	0.12
	v	3.93	7.85	15.7	39.3	78.5	157	393
20	E'_{min}	-	8.11	4.05	1.62	0.81	0.41	0.16
	E'_{max}	-	<20*	6.57	2.59	1.27	0.62	0.24

*(Note : These values are upper bounds.)

$\underline{\lambda} = \underline{10}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
5	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
	(%)E'_{min}	-	-	-	8.19	4.22	2.41	-
	(%)$\bar{E}'_{max}$	-	-	-	<20*	5.85	3.19	-
10	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
	E'_{min}	-	-	-	-	8.44	4.82	-
	$\bar{E}'_{max}$	-	-	-	-	<20*	6.37	-
20	v	0.196	0.393	0.785	1.96	3.93	7.85	19.6
	E'_{min}	-	-	-	-	-	9.65	-
	$\bar{E}'_{max}$	-	-	-	-	-	<20*	-

$\underline{d} = \underline{1}$ (cm)

b (cm)								
5	v	1.57	3.14	6.28	15.7	31.4	62.8	157
	(%)E'_{min}	-	-	10.1	4.06	2.05	1.06	0.54
	(%)$\bar{E}'_{max}$	-	-	<23*	6.13	2.96	1.46	0.70
10	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
	E'_{min}	-	-	-	8.13	4.09	2.11	1.08
	$\bar{E}'_{max}$	-	-	-	<20*	5.93	2.93	1.39
20	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
	E'_{min}	-	-	-	-	8.19	4.22	2.16
	$\bar{E}'_{max}$	-	-	-	-	<20*	5.85	2.78

*(Note : These values are upper bounds.)

$\underline{\lambda} = \underline{10}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	3.14	6.28	12.6	31.4	62.8	126	314
5	(%)E'_{min}	-	10.1	5.07	2.03	1.02	0.51	0.22
	(%)$\bar{E}'_{max}$	-	<23*	8.11	3.16	1.53	0.74	0.30
	v	1.57	3.14	6.28	15.7	31.4	62.8	157
10	E'_{min}	-	-	10.1	4.06	2.03	1.02	0.43
	$\bar{E}'_{max}$	-	-	<23*	6.32	3.06	1.48	0.59
	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
20	E'_{min}	-	-	-	8.11	4.06	2.05	0.86
	$\bar{E}'_{max}$	-	-	-	<20*	6.13	2.96	1.18

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)								
	v	7.85	15.7	31.4	78.5	157	314	785
5	(%)E'_{min}	8.11	4.05	2.03	0.81	0.41	0.21	0.08
	(%)$\bar{E}'_{max}$	<20*	6.60	3.28	1.30	0.64	0.31	0.12
	v	3.93	7.85	15.7	39.3	78.5	157	393
10	E'_{min}	-	8.11	4.05	1.62	0.81	0.41	0.16
	$\bar{E}'_{max}$	-	<20*	6.57	2.59	1.27	0.62	0.24
	v	1.96	3.93	7.85	19.6	39.3	78.5	196
20	E'_{min}	-	-	8.11	3.24	1.62	0.81	0.33
	$\bar{E}'_{max}$	-	-	<20*	5.19	2.55	1.24	0.47

*(Note : These values are upper bounds.)

$\underline{\lambda} = \underline{20}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
5	(%)E'_{min}	-	-	-	-	8.44	4.82	-
	(%)$\overline{E}'_{max}$	-	-	-	-	<20*	6.37	-
	v	0.196	0.393	0.785	1.96	3.93	7.85	19.6
10	E'_{min}	-	-	-	-	-	9.65	-
	$\overline{E}'_{max}$	-	-	-	-	-	<20*	-
	v	0.098	0.196	0.393	0.982	1.96	3.93	9.82
20	E'_{min}	-	-	-	-	-	-	-
	$\overline{E}'_{max}$	-	-	-	-	-	-	-

$\underline{d} = \underline{1}$ (cm)

b (cm)								
	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
5	(%)E'_{min}	-	-	-	8.13	4.09	2.11	1.08
	(%)$\overline{E}'_{max}$	-	-	-	<20*	5.93	2.93	1.39
	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
10	E'_{min}	-	-	-	-	8.19	4.22	2.16
	$\overline{E}'_{max}$	-	-	-	-	<20*	5.85	2.78
	v	0.196	0.393	0.785	1.96	3.93	7.85	19.6
20	E'_{min}	-	-	-	-	-	8.44	4.32
	$\overline{E}'_{max}$	-	-	-	-	-	<20*	5.56

*(Note : These values are upper bounds.)

$\underline{\lambda} = \underline{20}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	1.57	3.14	6.28	15.7	31.4	62.8	157
5	(%)E'_{min}	-	-	10.1	4.06	2.03	1.02	0.43
	(%)$\bar{E}'_{max}$	-	-	<23*	6.32	3.06	1.48	0.59
	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
10	E'_{min}	-	-	-	8.11	4.06	2.05	0.86
	$\bar{E}'_{max}$	-	-	-	<20*	6.13	2.96	1.18
	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
20	E'_{min}	-	-	-	-	8.13	4.09	1.73
	$\bar{E}'_{max}$	-	-	-	-	<20*	5.93	2.36

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)								
	v	3.93	7.85	15.7	39.3	78.5	157	393
5	(%)E'_{min}	-	8.11	4.05	1.62	0.81	0.41	0.16
	(%)$\bar{E}'_{max}$	-	<20*	6.57	2.59	1.27	0.62	0.24
	v	1.96	3.93	7.85	19.6	39.3	78.5	196
10	E'_{min}	-	-	8.11	3.24	1.62	0.81	0.33
	$\bar{E}'_{max}$	-	-	<20*	5.19	2.55	1.24	0.47
	v	0.982	1.96	3.93	9.82	19.6	39.3	98.2
20	E'_{min}	-	-	-	6.49	3.24	1.62	0.66
	$\bar{E}'_{max}$	-	-	-	<18*	5.09	2.48	0.95

*(Note : These values are upper bounds.)

$\underline{\lambda} = \underline{50}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
5	v	0.157	0.314	0.628	1.57	3.14	6.28	15.7
	(%)E'_{min}	-	-	-	-	-	12.1	-
	(%)$\overline{E}'_{max}$	-	-	-	-	-	<23*	-
10	v	0.079	0.157	0.314	0.785	1.57	3.14	7.85
	E'_{min}	-	-	-	-	-	-	-
	$\overline{E}'_{max}$	-	-	-	-	-	-	-
20	v	0.039	0.079	0.157	0.393	0.785	1.57	3.93
	E'_{min}	-	-	-	-	-	-	-
	$\overline{E}'_{max}$	-	-	-	-	-	-	-

$\underline{d} = \underline{1}$ (cm)

b (cm)								
5	v	0.314	0.628	1.26	3.14	6.28	12.6	31.4
	(%)E'_{min}	-	-	-	-	10.2	5.28	2.70
	(%)$\overline{E}'_{max}$	-	-	-	-	<23*	7.32	3.48
10	v	0.157	0.314	0.628	1.57	3.14	6.28	15.7
	E'_{min}	-	-	-	-	-	10.6	5.40
	$\overline{E}'_{max}$	-	-	-	-	-	<23*	6.95
20	v	0.079	0.157	0.314	0.785	1.57	3.14	7.85
	E'_{min}	-	-	-	-	-	-	10.8
	$\overline{E}'_{max}$	-	-	-	-	-	-	<20*

*(Note : These values are upper bounds.)

$\underline{\lambda} = \underline{50}$ (μm)

$\underline{d} = \underline{2}$ (cm)

$\underline{b}$ (cm)	$\underline{D}$ = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	0.628	1.26	2.51	6.28	12.6	25.1	62.8
5	(%)$\underline{E}'_{min}$	-	-	-	10.1	5.08	2.56	1.08
	(%)$\overline{E}'_{max}$	-	-	-	<23*	7.66	3.70	1.48
	v	0.314	0.628	1.26	3.14	6.28	12.6	31.4
10	$\underline{E}'_{min}$	-	-	-	-	10.2	5.12	2.16
	$\overline{E}'_{max}$	-	-	-	-	<23*	7.41	2.96
	v	0.157	0.314	0.628	1.57	3.14	6.28	15.7
20	$\underline{E}'_{min}$	-	-	-	-	-	10.2	4.32
	$\overline{E}'_{max}$	-	-	-	-	-	<23*	5.91

$\underline{d} = \underline{5}$ (cm)

$\underline{b}$ (cm)		.005	.01	.02	.05	.1	.2	.5
	v	1.57	3.14	6.28	15.7	31.4	62.8	157
5	(%)$\underline{E}'_{min}$	-	-	10.1	4.05	2.03	1.01	0.41
	(%)$\overline{E}'_{max}$	-	-	<23*	6.48	3.18	1.55	0.59
	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
10	$\underline{E}'_{min}$	-	-	-	8.11	4.05	2.03	0.82
	$\overline{E}'_{max}$	-	-	-	<20*	6.37	3.10	1.19
	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
20	$\underline{E}'_{min}$	-	-	-	-	8.11	4.06	1.64
	$\overline{E}'_{max}$	-	-	-	-	<20*	6.19	2.37

*(Note : These values are upper bounds.)

$\underline{\lambda} = \underline{100}$ (μm)

$\underline{d} = \underline{0.5}$ (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
5	v	0.079	0.157	0.314	0.785	1.57	3.14	7.85
	(%)E'_{min}	-	-	-	-	-	-	-
	(%)$\bar{E}'_{max}$	-	-	-	-	-	-	-
10	v	0.039	0.079	0.157	0.393	0.785	1.57	3.93
	E'_{min}	-	-	-	-	-	-	-
	$\bar{E}'_{max}$	-	-	-	-	-	-	-
20	v	0.020	0.039	0.079	0.196	0.393	0.785	1.96
	E'_{min}	-	-	-	-	-	-	-
	$\bar{E}'_{max}$	-	-	-	-	-	-	-

$\underline{d} = \underline{1}$ (cm)

b (cm)								
5	v	0.157	0.314	0.628	1.57	3.14	6.28	15.7
	(%)E'_{min}	-	-	-	-	-	10.6	5.40
	(%)$\bar{E}'_{max}$	-	-	-	-	-	<23*	6.95
10	v	0.079	0.157	0.314	0.785	1.57	3.14	7.85
	E'_{min}	-	-	-	-	-	-	10.8
	$\bar{E}'_{max}$	-	-	-	-	-	-	<20*
20	v	0.039	0.079	0.157	0.393	0.785	1.57	3.93
	E'_{min}	-	-	-	-	-	-	-
	$\bar{E}'_{max}$	-	-	-	-	-	-	-

*(Note : These values are upper bounds.)

λ = 100 (μm)

d = 2 (cm)

b (cm)	D = (cm)	.005	.01	.02	.05	.1	.2	.5
	v	0.314	0.628	1.26	3.14	6.28	12.6	31.4
5	(%)E'_{min}	-	-	-	-	10.2	5.12	2.16
	(%)E'_{max}	-	-	-	-	<23*	<16*	2.96
	v	0.157	0.314	0.628	1.57	3.14	6.28	15.7
10	E'_{min}	-	-	-	-	-	10.2	4.32
	E'_{max}	-	-	-	-	-	<23*	5.91
	v	0.079	0.157	0.314	0.785	1.57	3.14	7.85
20	E'_{min}	-	-	-	-	-	-	8.65
	E'_{max}	-	-	-	-	-	-	<20*

d = 5 (cm)

b (cm)								
	v	0.785	1.57	3.14	7.85	15.7	31.4	78.5
5	(%)E'_{min}	-	-	-	8.11	4.05	2.03	0.82
	(%)E'_{max}	-	-	-	<20*	6.37	3.10	1.19
	v	0.393	0.785	1.57	3.93	7.85	15.7	39.3
10	E'_{min}	-	-	-	-	8.11	4.06	1.64
	E'_{max}	-	-	-	-	<20*	6.19	2.37
	v	0.196	0.393	0.785	1.96	3.93	7.85	19.6
20	E'_{min}	-	-	-	-	-	8.12	3.28
	E'_{max}	-	-	-	-	-	<20*	4.74

*(Note: These values are upper bounds.)

3. Scaling the Diffraction Loss Tables

The range of the diffraction loss tables can be extended by using scaling relationships (provided that the errors in the formulas used to compute the diffraction losses do not become excessive in the extended range). It is clear from the formulas in section 6 for the quantities E'_{min} and $\bar{E}'_{max}$ given in the tables, that the scaling relationships are simple only if the ratio of the aperture diameter to the source diameter, Dd^{-1}, is constant. Subject to this condition, the scaling relationships are as follows:

Quantity	Scales as (constant Dd^{-1})
E'_{min}, $\bar{E}'_{max}$	λ, $\underline{b}$, D^{-2} (or d^{-2}) ;
Upper Bounds	$\lambda^{0.5}$, $\underline{b}^{0.5}$, D^{-1} (or d^{-1}).

(The upper bounds are the quantity denoted E(v,v,0) in sec. 6.)

4. Effective Wavelengths to Use in the Diffraction Loss Tables

The effective wavelength, λ^{-}, for computing the diffraction loss for a given experimental geometry with a source of spectral radiance distribution $S_\lambda(\lambda)$, is defined to be that wavelength which yields the average spectral diffraction loss when substituted into the approximate Kirchhoff scalar paraxial model (see sec. 1). Furthermore, if the approximate formula for the effective diffraction loss for a circular detector, eq (12) of section 6, is valid (see sec. 7 for a discussion of the mathematical errors in the formulas used in this report), then the diffraction loss scales proportionally to the wavelength, and an explicit equation for λ^{-} can be derived in the form,

$$\lambda^{-} = \frac{\int_{\lambda 1}^{\lambda 2} \lambda d\lambda S_\lambda(\lambda)}{\int_{\lambda 1}^{\lambda 2} d\lambda S_\lambda(\lambda)} ,$$

where $\lambda 1$ and $\lambda 2$ are the short- and longwavelength limits to $S_\lambda(\lambda)$.

If $S_\lambda(\lambda)$ is the Planck blackbody spectral radiance function [2], denoted $L_\lambda(\lambda,T)$ at temperature T, then λ^{-} can be related to the temperature by approximate equation (derived by Blevin[1]),

$$\lambda^{-} = 5324/T \text{ (micrometers)}, \tag{1}$$

if T is in degrees Kelvin. Thus λ^{-} is about $1.84\lambda_{max}$, the wavelength of maximum spectral radiance for a blackbody at temperature T.

The effective wavelength, $\lambda^{=}$, for computing the luminous diffraction loss for a source of spectral radiance distribution $S_\lambda(\lambda)$, is given by the equation,

$$\bar{\bar{\lambda}} = \frac{\int_{\lambda 1}^{\lambda 2} \lambda d\lambda V(\lambda) S_\lambda(\lambda)}{\int_{\lambda 1}^{\lambda 2} d\lambda V(\lambda) S_\lambda(\lambda)},$$

where $V(\lambda)$ is the spectral luminous efficiency function for photopic vision and $\lambda 1$ and $\lambda 2$ are the limits of the visible spectrum [3]. If $S_\lambda(\lambda)$ is the Planck blackbody spectral radiance function, then Blevin [1] has shown that $\bar{\bar{\lambda}}$ is 0.572 micrometers for a blackbody temperature of 2856 K (CIE Illuminant A).

5. Sample Diffraction Loss Calculations

5.1. Sample Diffraction Loss Calculations for a Simple Case

A simple example is the following: Compute the average diffraction loss over the face of a circular detector which views a 500 K blackbody through a small aperture. The geometry is that of a source radiance measurement (see fig. 1). The diameter of the blackbody aperture (d) is 1 cm; the distance from the blackbody aperture to the diffracting aperture ($\underline{b}$) is 5 cm; the diameter of the diffracting aperture (D) is 0.1 cm; the distance from the diffracting aperture to the detector ($\underline{a}$) is 60 cm; the detector diameter ($2x_o$) is 5 cm. Since the blackbody temperature is 500 K, eq (1) shows that the effective diffraction wavelength $\bar{\lambda}$ is 10.6 micrometers. Referring to the diffraction loss tables (sec. 2), it is seen that the tabulated wavelength closest to 10.6 micrometers is 10; at this wavelength, and at d = 1 cm, $\underline{b}$ = 5 cm, D = 0.1 cm, the on-axis diffraction loss E'_{min} (for $\underline{a}$ at least $10\underline{b}$, a condition which is met by this example) is found to be 2.05%; the corresponding area-average diffraction loss over the face of a detector of radius x_{max}, $\bar{E}'_{max}$, is found to be 2.96%. From the formula for X_{max},

$$x_{max} = 0.5[(0.9d-D)\underline{ab}^{-1} - D], \tag{2}$$

it is found that x_{max} is 4.8 cm; the detector radius is given above as 2.5 cm. Denoting the desired average diffraction loss over the face of the detector by the symbol $\bar{E}'$, it is reasonable to interpolate between E'_{min} and $\bar{E}'_{max}$ by the following area-weighting formula:

$$\bar{E}' = E'_{min} + [\bar{E}'_{max} - E'_{min}](x_o/x_{max})^2. \tag{3}$$

Thus $\bar{E}'$ is found to be 2.30% at the wavelength of 10 micrometers; the scaling table in section 3 shows that both E'_{min} and $\bar{E}'_{max}$ scale proportionally to the wavelength, so the desired value of $\bar{E}'$ at a wavelength of 10.6 micrometers is therefore obtained by multiplying 2.30% by the ratio 10.6/10 = 1.06 to get <u>2.44%</u>.

5.2. Sample Diffraction Loss Calculations for a Complex Case

Figure 2 shows the essential geometry of a circularly symmetric source-radiometer system currently in use at NBS. The source S is a blackbody whose temperature is roughly 300 K; the source aperture SA limits the radiating area; the radiometer aperture RA defines the solid angle in which radiation is received from SA; the radiometer cavity RC collects the radiation transmitted through RA. It is desired to calculate the diffraction loss for radiation from S transmitted through SA and RA to RC.

This is really a 2-step diffraction problem; the total diffraction loss DL is obtained from both:

a., the diffraction loss for radiation from S transmitted through SA to RA, denoted DL_a, and;

b., the diffraction loss for radiation from SA transmitted through RA to RC, denoted DL_b.

Thus the total diffraction loss, denoted DL, is

$$DL = DL_a + DL_b - DL_a DL_b,$$

since the diffraction loss at the detector is given as a percentage of the irradiance that would be present in the absence of diffraction.

The effective diffraction wavelength $\bar{\lambda}$ for this problem is found from the given temperature of 300 K and eq (1) of section 4 to be 17.7 micrometers. It is clear that the quantity of interest in computing DL_a is the effective radiance of SA, compared with the radiance of S. On the other hand, the quantity of interest in computing DL_b is the fraction of the total radiation from SA, transmitted through RA, which is collected by RC. Therefore, in computing DL_b it is necessary to treat RC as the source and SA as the detector, since (as explained in sec. 1) the diffraction loss formulas and the tables in this report all refer to the source radiance measurement geometry, and not to the total aperture radiation measurement geometry.

Referring to figure 2, and using the terminology of the tables, it is seen that the essential parameters for computing DL_a and DL_b are:

DL_a: $\bar{\lambda}$ = 17.7 micrometers, d = 0.2 cm, $\underline{b}$ = 0.35 cm, D = 0.05 cm,

$\underline{a}$ = 17.1 cm, x_o = 0.575 (source radiance measurement, see fig. 3);

DL_b: $\bar{\lambda}$ = 17.7 micrometers, d = 2.0 cm, $\underline{b}$ = 8.0 cm, D = 1.15 cm,

$\underline{a}$ = 17.1 cm, x_o = 0.025 cm (total aperture radiation measurement, see fig. 3).

To compute DL_a, note that d = 0.2 cm is smaller than 0.5 cm, the smallest tabulated value for d; therefore it is necessary to multiply d and D (to keep the ratio Dd^{-1} constant) by a scaling factor β to use the tables. Let $d' = \beta d$ be the scaled d and $D' = \beta D$ be the scaled D; if

β = 10, then d' = 2.0 cm and D' = 0.5 cm, which are tabulated values.

Furthermore, $\underline{b}$ = 0.35 cm is much smaller than 5.0 cm, the smallest tabulated value for $\underline{b}$; therefore it is necessary to multiply $\underline{b}$ by a scaling factor α to use the tables. Let $\underline{b}' = \alpha\underline{b}$ be the scaled $\underline{b}$; if α = 14.3, then $\underline{b}'$ = 5.0 cm, a tabulated value.

In addition, the effective wavelength $\bar{\lambda}$ = 17.7 micrometers is not a tabulated wavelength. Therefore $\bar{\lambda}$ is multiplied by a scaling factor θ to use the tables. Let $\bar{\lambda}' = \theta\bar{\lambda}$ be the scaled $\bar{\lambda}$; if θ = 1.13, then $\bar{\lambda}'$ = 20 micrometers, a tabulated value.

Next compute x_{max} from eq (2) of section 5.1 to get x_{max} = 3.15 cm, so that x_o/x_{max} = 0.18.

Referring to the diffraction loss tables for the values of $\bar{E}'_{min}$ and $\bar{E}'_{max}$ for the scaled parameters, $\bar{\lambda}'$ = 20 micrometers, d' = 2.0 cm, D' = 0.5 cm, $\underline{b}'$ = 5.0 cm (note that the condition that $\underline{a}$ be at least 10$\underline{b}$ is met for the geometry of DL_a), it is found that $\bar{E}'_{min}$ = 0.43% and $\bar{E}'_{max}$ = 0.59% for the scaled parameters. To interpolate between $\bar{E}'_{min}$ and $\bar{E}'_{max}$ to obtain the desired average diffraction loss $\bar{E}'$ over the radiometer aperture RA, for the scaled parameters, refer to eq (3) of section 5.1 and substitute the preceding values of $\bar{E}'_{min}$, $\bar{E}'_{max}$, and x_o/x_{max} into eq (3). The resulting value of $\bar{E}'$ = 0.435% for the scaled parameters is essentially equal to $\bar{E}'_{min}$.

The scaling process must now be reversed to obtain DL_a, the diffraction loss for the original unscaled parameters. Referring to the scaling table in section 3, it is seen that

$$DL_a = \bar{E}'(\text{scaled})\beta^2\alpha^{-1}\theta^{-1},$$

or DL_a = 6.19$\bar{E}'$(scaled) = 2.69%. This value is very close to that calculated for DL_a from the more accurate formula, eq (12) of section 6, 2.70%.

Unfortunately DL_b cannot be obtained from the tables in their present form. The values of $\bar{E}'_{min}$ and $\bar{E}'_{max}$ in the tables are computed by assuming that the detector-aperture distance $\underline{a}$ is much greater than the source-aperture distance $\underline{b}$. This clearly does not hold for the geometry of DL_b (see fig. 2), since $\underline{a}$ = 17.1 cm (as explained above, since this is a total aperture radiation measurement, the source is treated as the detector and vice versa) and $\underline{b}$ = 8.0 cm, and therefore $\underline{a}$ = 2.14$\underline{b}$ and the condition for the validity of the tables that $\underline{a}$ be at least 10$\underline{b}$ is not met.

In addition, since Dd^{-1} = 0.575 for the geometry of DL_b, the values of d and D cannot be scaled to fit the tables because Dd^{-1} = 0.5 is the largest value tabulated, and Dd^{-1} must be held constant in scaling.

In a situation of this kind, it is necessary to return to the general formula given in section 6, eq (12), for the average diffraction loss over the detector disc. This formula is not subject to the restriction of the tables, that the aperture-detector distance $\underline{a}$ be at least 10 times the source-aperture distance $\underline{b}$. In eq (12) the average diffraction loss over the detector disc is denoted $\bar{E}(u,v,w_o)$, where u, v, and w_o are dimensionless functions of the geometry and wavelength given by eqs (5), (6), and (8), respectively. Substituting the values given above for DL_b into eqs (5), (6), and (8), u, v, and w_o are computed and then substituted into eq (12) for $\bar{E}(u,v,w_o)$ to get $DL_b = 0.87\%$.

Finally, therefore, the total diffraction loss, DL, from the source S to the radiometer cavity RC, is found to be DL = 3.55%.

6. Formulas Used for Computing the Diffraction Loss Tables

The formulas used in computing the diffraction loss tables are derived from the basic Fresnel-Kirchhoff diffraction formula as given, for example, in Born and Wolf[4].

For a source radiance measurement (as shown in fig. 3), the diffraction losses increase with increasing detector radius x_o. It is felt that a reasonable upper bound for the detector radius, for a source radiance measurement, is defined by the condition that the detector field of view not extend beyond the inner portion of the source disc whose radius is 0.9 of the source radius. If this upper bound is denoted x_{max}, it is seen from figure 3 that x_{max} is given by eq (2) of section 5.1. The minimum source diameter, for a source radiance measurement, is that which makes $x_{max} = 0$; thus the minimum source diameter is $[D(1 + \underline{ba}^{-1})/0.9]$.

For a total aperture radiation measurement, the diffraction losses decrease with increasing detector radius. It is felt that a reasonable lower bound for the detector radius, for a total aperture radiation measurement, is defined by the condition that all the source radiation which passes through the aperture - except for diffraction losses - be incident upon that portion of the detector disc whose radius is 0.9 of the detector radius. If this lower bound is denoted x_{min}, it is seen from figure 3 that

$$x_{min} = 0.5[(d+D)(0.9)^{-1}\underline{ab}^{-1} + D].$$

Following the analysis of Blevin[1], it is found that the on-axis diffraction loss at the center of the detector, denoted E(u,v,0), for the source radiance geometry, is approximately

$$E(u,v,0) = \pi^{-1}[(v-u)^{-1} + (v+u)^{-1}], \tag{4}$$

where u and v are the dimensionless quantities,

$$u = \pi D^2(\underline{a}^{-1} + \underline{b}^{-1})(2\lambda)^{-1}, \tag{5}$$

$$v = \pi Dd(2\underline{b}\lambda)^{-1}. \tag{6}$$

If the aperture-detector distance $\underline{a}$ is much greater than the source-aperture distance $\underline{b}$, then u is approximately

$$u_{min} = \pi D^2(2\underline{b}\lambda)^{-1} = vDd^{-1}; \tag{7}$$

note that u_{min} is independent of $\underline{a}$.

Now let $E(u,v,w_o)$ denote the diffraction loss at the off-axis point in the detector plane whose radius is x_o (see fig. 3), and define a third dimensionless quantity,

$$w_o = \pi D x_o(\underline{a}\lambda)^{-1}. \tag{8}$$

Blevin [1] has shown that $E(u,v,w_o)$ is approximately

$$E(u,v,w_o) = \pi^{-2}\int_0^{\pi} d\theta[(-u + w_o\cos\theta + (v^2-w_o^2\sin^2\theta)^{0.5})^{-1} + (u + w_o\cos\theta + (v^2-w_o^2\sin^2\theta)^{0.5})^{-1}], \tag{9}$$

and that $E(u,v,w_o)$ increases steadily from the minimum value $E(u,v,0)$ as the radius of the off-axis detection point increases from $x = 0$ (on axis) out to the radius of the rim of the detector (which is also labeled x_o in fig. 3).

Referring to eq (4) for $E(u,v,0)$, it is seen that if the aperture-detector distance $\underline{a}$ is much greater than the source-aperture distance $\underline{b}$, then $E(u,v,0)$ is approximately $E(u_{min},v,0)$, denoted E'_{min}, and

$$E'_{min} = 2(\pi v)^{-1}(1 - D^2d^{-2})^{-1}. \tag{10}$$

Note that E'_{min} is independent of $\underline{a}$ and that it is the minimum value of $E(u,v,0)$, considered as a function of $\underline{a}$, since $E(u,v,0)$ decreases steadily to E'_{min} as $\underline{a}$ increases (assuming the other parameters are held constant).

Referring to eq (9) for $E(u,v,w_o)$, it is seen that the average diffraction loss over the surface of a detector of radius x_o, denoted $\bar{E}(u,v,w_o)$, is given by the formula,

$$\bar{E}(u,v,w_o) = w_o^{-2}\int_0^{w_o} 2w\,dw\,E(u,v,w). \tag{11}$$

Since the off-axis diffraction loss $E(u,v,w_o)$ increases steadily as the detection point moves away from the axis, it is clear that the average diffraction loss over the disc of radius x_o also increases steadily as x_o increases. Thus $\bar{E}(u,v,w_o)$ attains its maximum value, considered as a function of x_o, for a detector radius of x_{max}.

If the detector plane is now moved towards the aperture, holding the source diameter d, the source-aperture distance $\underline{b}$, and the aperture diameter D constant, then a point will be reached for which $x_{max} = 0$. The value of $\underline{a}$ at this point is denoted $\underline{a}_{min}$ (see fig. 3), and it is seen that

$$\underline{a}_{min} = \underline{b}D(0.9d - D)^{-1}.$$

It can be shown that the maximum value of $\bar{E}(u,v,w_{max})$, the average diffraction loss over the detector disc of radius x_{max}, considered as a function of the aperture-detector distance $\underline{a}$, occurs at $\underline{a}_{min}$; it can also be shown that

$$w_{max} + u = 0.9v,$$

where w_{max} is defined as

$$w_{max} = \pi D x_{max}(\underline{a}\lambda)^{-1}.$$

Note that the preceding analysis assumes that the detector radius is x_{max}, and that the radius varies with x_{max} as the detector is moved towards the aperture.

Now consider the behavior of the average diffraction loss over the disc of radius x_{max} as the detector plane is moved away from the aperture. It is clear that u will approach its minimum value u_{min} asymptotically in this case, and that consequently w_{max} will correspondingly approach its maximum value, considered as a function of $\underline{a}$, which is $v(0.9 - Dd^{-1})$. It can be shown that the average diffraction loss over the disc of radius x_{max}, $\bar{E}(u,v,w_{max})$, attains its minimum value, considered as a function of $\underline{a}$, when $\underline{a}$ is much larger than $\underline{b}$ (and hence u is approximately equal to u_{min} and w_{max} is approximately equal to $v(0.9 - Dd^{-1})$). This minimum value of $\bar{E}(u,v,w_{max})$ is denoted $\bar{E}'_{max}$ and is independent of $\underline{a}$.

Steel, De, and Bell [5] have derived a very useful and compact approximate formula for $\bar{E}(u,v,w_o)$,

$$\bar{E}(u,v,w_o) = (2\pi w_o)^{-1}\ln \frac{[(v+w_o)^2 - u^2]}{[(v-w_o)^2 - u^2]}. \tag{12}$$

Thus $\bar{E}'_{max}$ can be expressed approximately by the formula,

$$\bar{E}'_{max} = [2\pi v(0.9-Dd^{-1})]^{-1}\ln \left[19 \frac{(1.9-2Dd^{-1})}{(0.1+2Dd^{-1})}\right]. \tag{13}$$

7. Estimated Accuracy of the Diffraction Loss Tables

Steel, De, and Bell [5] show that an upper bound for the fractional error in E'_{min}, as computed from eq (10) of section 6, is $(2v)^{-1}$; thus E'_{min} is not given in the tables for values of v less than 5, in order to limit the estimated error in the tabulated values to less than 10% (of the value).

Similarly, Steel, De, and Bell [5] show that an upper bound for the fractional error in $\bar{E}'_{max}$, as computed from eq (13) of section 6, is $0.06 + 1.6v^{-1}$; thus $\bar{E}'_{max}$ is not given in the tables for values of v less than 12, in order to limit the estimated error in the tabulated values to less than 20% (of the value). However, an upper bound for $\bar{E}'_{max}$ is given for values of v between 6 and 12; this upper bound is the diffraction loss for the point on the axis at which the rim of the aperture appears to coincide with the rim of the source; in other words, the field of view through the aperture from this point coincides with the source disc (in fig. 3, this point is the distance $\underline{a}_o$ from the aperture). Blevin [1] shows that the diffraction loss for this point, denoted E(v,v,0), is given by the approximate formula,

$$E(v,v,0) = (\pi v)^{-0.5}.$$

Note that the ratio $[\bar{E}'_{max}/E'_{min}]$ depends on Dd^{-1} only, and varies approximately as follows:

Dd^{-1}	$\bar{E}'_{max}/E'_{min}$
0.0	1.64
0.1	1.45
0.2	1.39
0.3	1.35
0.4	1.32
0.5	1.29.

Thus $\bar{E}'_{max}$ and E'_{min} bracket the diffraction loss, for detector radii between zero and x_{max}, to within ±20% roughly for the worst case, $Dd^{-1} = 0$, and more accurately for larger values of Dd^{-1}.

Furthermore, if the Kirchhoff scalar paraxial model does not accurately represent the physical behavior of the experimental situation, then the diffraction loss values in the tables will contain an additional error besides those due to the mathematical approximations used to compute the tables.

A good criterion for the validity of the Kirchhoff model, as Stratton [6] points out, is that the diameter of the diffracting aperture must be much larger than the wavelength. In the terminology of figure 3, if

$$D/\lambda > 10,$$

then the Kirchhoff model is held to be valid; if this condition does not hold, then the exact vector model may be required.

8. References

[1] Blevin, W. R., *Diffraction Losses in Radiometry and Photometry,* Metrologia 6, 39 (April 1970).

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[3] *The photopic spectral luminous efficiency function, V(λ),* is given in: American Institute of Physics Handbook, 3rd ed., chap. 6, p. 184 (McGraw-Hill Book Co., New York, 1972).

[4] Born, M., and Wolf, E., *Principles of Optics,* 2nd ed., chap. 8, p. 382 (The MacMillan Co., New York, 1964).

[5] Steel, W. H., De, M., and Bell, J. A., *Diffraction Corrections in Radiometry,* J. Opt. Soc. Am. 62, 1099 (Sept. 1972).

[6] Stratton, J. A., *Electromagnetic Theory,* p. 463 (McGraw-Hill Book Co., New York, 1941).

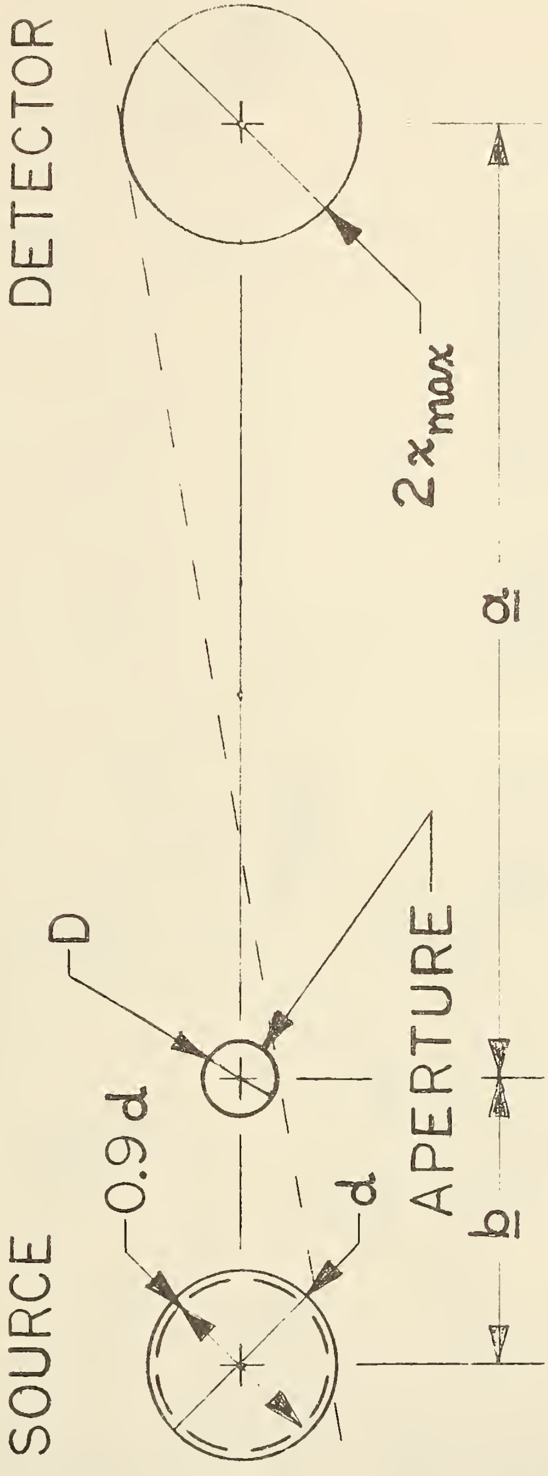

Figure 1. Diffraction geometry used in the diffraction loss tables.

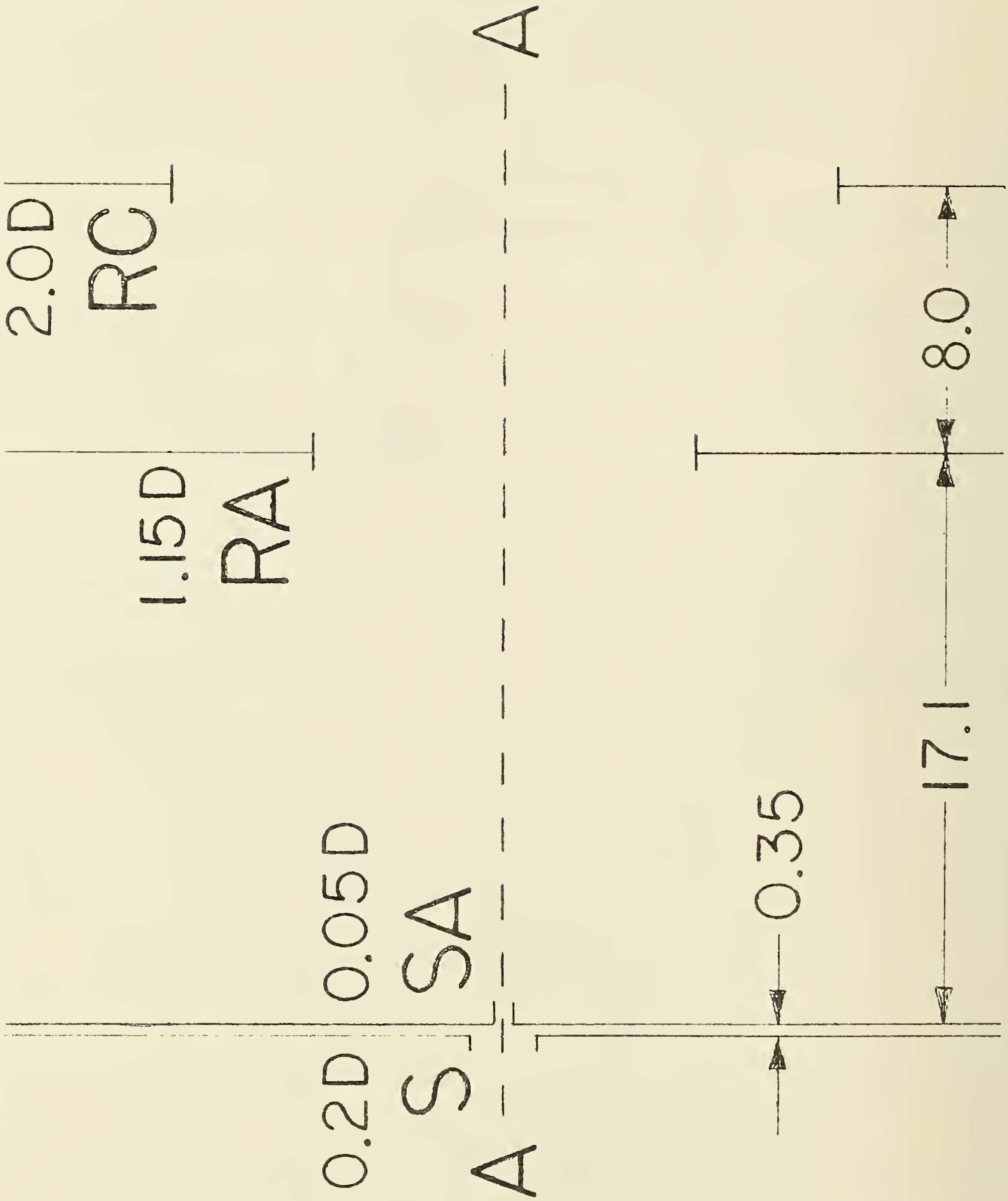

Figure 2. Diffraction geometry for the sample diffraction loss calculations; complex case: A-A, optical axis; RA, radiometer aperture; RC, radiometer cavity; S, 300 K blackbody source; SA, defining aperture for S (distances in cms; aperture diameters magnified 10 times with respect to distances along the axis).

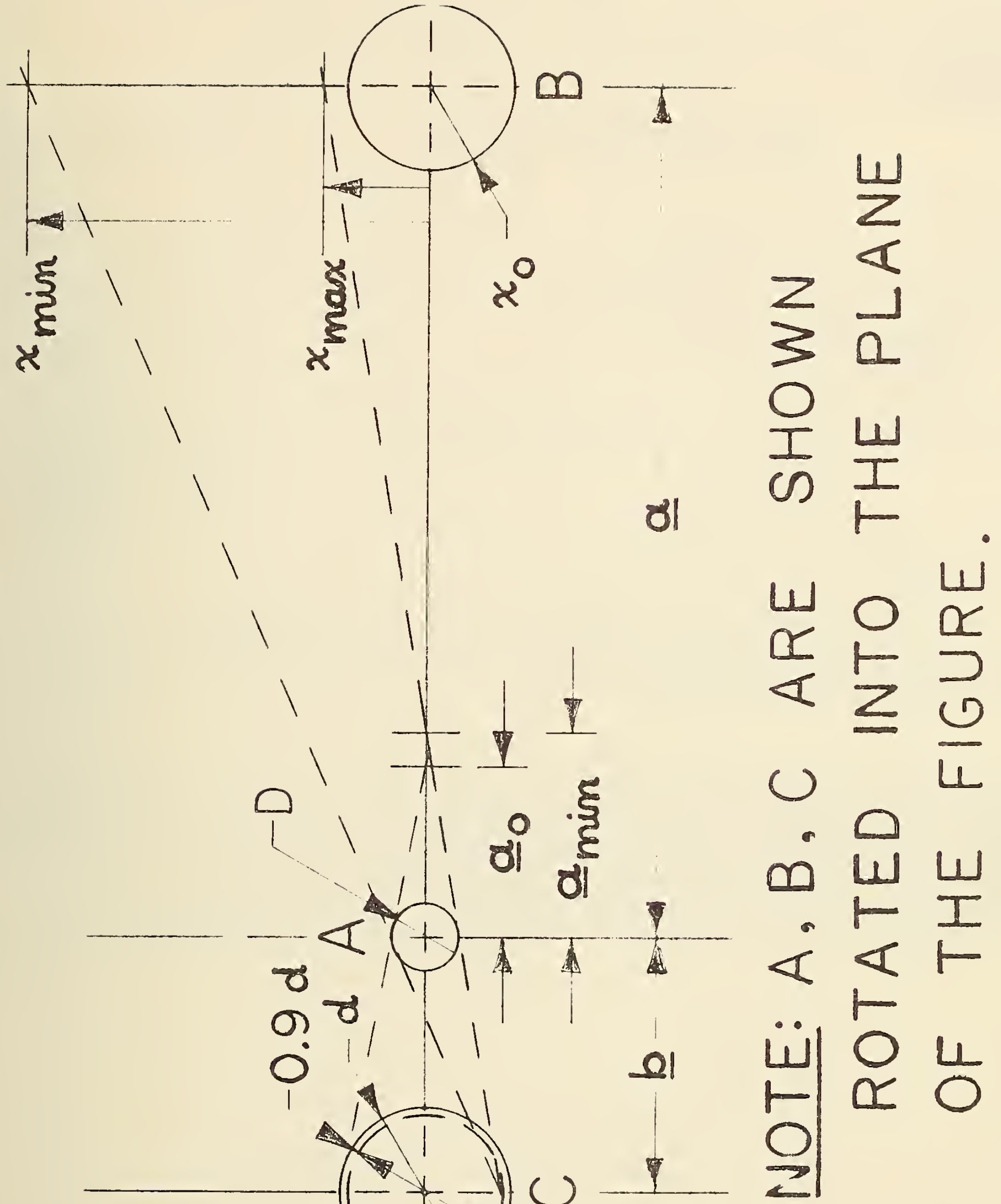

Figure 3. Diffraction geometry used in the general diffraction loss formulas: A, aperture; B, detector; C, source; d, source diameter; D, aperture diameter; x_o, detector radius; x_{max}, maximum detector radius for a source radiance measurement; x_{min}, minimum detector radius for a total aperture radiation measurement; $\underline{a}$, aperture-detector distance; $\underline{a}_{min}$, minimum aperture-detector distance; $\underline{a}_o$, aperture-detector distance for computing an upper bound for the diffraction loss; $\underline{b}$, source-aperture distance.

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Tables of diffraction losses are given for a range of typical experimental geometries for wavelengths from 0.2 to 100 micrometers. The scaling relationships for the diffraction losses for varying wavelengths and geometries are also given, and sample calculations are presented. General formulas are given for the diffraction losses; the formulas are derived from the Kirchhoff scalar paraxial diffraction theory. The accuracy of the tabulated values is estimated.

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