

Spectral Irradiance Calibrations



NBS
Special
Publication
250-20



James H. Walker
Robert D. Saunders
John K. Jackson
Donald A. McSparron

U.S. Department of Commerce
National Bureau of Standards

Center for Radiation Research

The Center for Radiation Research is a major component of the National Measurement Laboratory in the National Bureau of Standards. The Center provides the Nation with standards and measurement services for ionizing radiation and for ultraviolet, visible, and infrared radiation; coordinates and furnishes essential support to the National Measurement Support System for ionizing radiation; conducts research in radiation related fields to develop improved radiation measurement methodology; and generates, compiles, and critically evaluates data to meet major national needs. The Center consists of five Divisions and one Group.

Atomic and Plasma Radiation Division

Carries out basic theoretical and experimental research into the spectroscopic and radiative properties of atoms and highly ionized species; develops well-defined atomic radiation sources as radiometric or wavelength standards; develops new measurement techniques and methods for spectral analysis and plasma properties; and collects, compiles, and critically evaluates spectroscopic data. The Division consists of the following Groups:

- Atomic Spectroscopy
- Atomic Radiation Data
- Plasma Radiation

Radiation Physics Division

Provides the central national basis for the measurement of far ultraviolet, soft x-ray, and electron radiation; develops and disseminates radiation standards, measurement services, and data for these radiations; conducts theoretical and experimental research with electron, laser, ultraviolet, and soft x-ray radiation for measurement applications; determines fundamental mechanisms of electron and photon interactions with matter; and develops advanced electron- and photon-based measurement techniques. The Division consists of the following Groups:

- Far UV Physics
- Electron Physics
- Photon Physics

Radiometric Physics Division

Provides national measurement standards and support services for ultraviolet, visible, and infrared radiation; provides standards dissemination and measurement quality assurance services; conducts research in optical radiation, pyrometry, photometry, and quantum radiometry; and develops spectroradiometric and spectrophotometric standards and calibration procedures. The Division consists of the following Groups:

- Spectral Radiometry
- Spectrophotometry
- Radiometric Measurement Services

Radiation Source and Instrumentation Division

Develops, operates, and improves major NBS radiation facilities including the electron Linac and race track microtron; develops, designs, and builds electronic and mechanical instrumentation for radiation programs and facilities; provides national leadership in the standardization of nuclear instrumentation; and develops new competence in radiation sources and instrumentation. The Division consists of the following Groups:

- Accelerator Research
- Linac Operations
- Electronic Instrumentation
- Mechanical Instrumentation

Ionizing Radiation Division

Provides primary national standards, measurement services, and basic data for applications of ionizing radiation; develops new methods of chemical and physical dosimetry; conducts theoretical and experimental research on the fundamental physical and chemical interactions of ionizing radiation with matter; provides essential standards and measurement support services to the National Measurement Support System for Ionizing Radiation; and develops and operates radiation sources needed to provide primary radiation standards, fields, and well-characterized beams of radiation for research on radiation interactions and for development of measurement methods. The Division consists of the following Office and Groups:

- Office of Radiation Measurement
- Radiation Theory
- Radiation Chemistry and Chemical Dosimetry
- Neutron Measurements and Research
- Neutron Dosimetry
- Radioactivity
- X-Ray Physics
- Dosimetry

Nuclear Physics Group

Engages in forefront research in nuclear and elementary particle physics; performs highly accurate measurements and theoretical analyses which probe the structure of nuclear matter; and improves the quantitative understanding of physical processes that underlie measurement science.

NBS MEASUREMENT SERVICES: SPECTRAL IRRADIANCE CALIBRATIONS

James H. Walker

Robert D. Saunders

John K. Jackson

Donald A. McSparron

Center for Radiation Research
National Measurement Laboratory
National Bureau of Standards
Gaithersburg, MD 20899



U.S. DEPARTMENT OF COMMERCE, Clarence J. Brown, Acting Secretary
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director
Issued September 1987

Library of Congress Catalog Card Number: 87-619862

National Bureau of Standards Special Publication 250-20
Natl. Bur. Stand. (U.S.), Spec. Publ. 250-20, 102 pages (Sept. 1987)
CODEN: XNBSAV

Commercial products—materials and instruments—are identified in this document for the sole purpose of adequately describing experimental or test procedures. In no event does such identification imply recommendation or endorsement by the National Bureau of Standards of a particular product; nor does it imply that a named material or instrument is necessarily the best available for the purpose it serves.

**U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1987**

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325

PREFACE

The calibration and related measurement services of the National Bureau of Standards are intended to assist the makers and users of precision measuring instruments in achieving the highest possible levels of accuracy, quality, and productivity. NBS offers over 300 different calibration, special test, and measurement assurance services. These services allow customers to directly link their measurement systems to measurement systems and standards maintained by NBS. These services are offered to the public and private organizations alike. They are described in NBS Special Publication (SP) 250, NBS Calibration Services Users Guide.

The Users Guide is being supplemented by a number of special publications (designated as the "SP 250 Series") that provide a detailed description of the important features of specific NBS calibration services. These documents provide a description of the: (1) specifications for the service; (2) design philosophy and theory; (3) NBS measurement system; (4) NBS operational procedures; (5) assessment of measurement uncertainty including random and systematic errors and an error budget; and (6) internal quality control procedures used by NBS. These documents will present more detail than can be given in an NBS calibration report, or than is generally allowed in articles in scientific journals. In the past NBS has published such information in a variety of ways. This series will help make this type of information more readily available to the user.

This document (SP 250-20), NBS Measurement Services: Spectral Irradiance Calibrations, by J. H. Walker, R. D. Saunders, J. K. Jackson, and D. A. McSparron, is the twentieth to be published in this new series of special publications. It describes the calibration of the spectral irradiance of tungsten quartz-halogen lamps over the wavelength region of 250 to 2400 nm, and of uv-emitting deuterium lamps over the range of 200 to 350 nm (see test numbers 39040C, 39050C, and 39070S in the SP 250 Users Guide). Inquiries concerning the technical content of this document or the specifications for these services should be directed to the authors or one of the technical contacts cited in SP 250.

The Center for Radiation Research (CRR) is in the process of publishing 21 documents in this SP 250 series, covering all of the calibration services offered by CRR. A complete listing of these documents can be found inside the back cover.

NBS would welcome suggestions on how publications such as these might be made more useful. Suggestions are also welcome concerning the need for new calibration services, special tests, and measurement assurance programs.

George A. Uriano
Director
Measurement Services

Chris E. Kuyatt
Director
Center for Radiation Research

ABSTRACT: This paper describes the measurement methods and the instrumentation used in the realization and transfer of the NBS scale of spectral irradiance. The basic measurement equation for the irradiance realization is derived. The spectral responsivity function, linearity of response, and "size of source" effect of the spectroradiometer are described. The analysis of sources of error and the estimates of uncertainty are described. The assigned uncertainties (3σ level) in spectral irradiance range from 2.2% at 250 nm to 1.0% at 654.6 nm to 6.5% at 2400 nm.

Key Words: blackbody; calibrations; radiometry; response linearity; slit-scattering function; spectral irradiance; standards.

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
II.	SCALE DERIVATION AND TRANSFER.....	2
III.	MEASUREMENT APPARATUS.....	8
A.	Variable Temperature Blackbody.....	9
B.	Lamp Sources.....	11
1.	Pyrometer Lamp.....	11
2.	Special Integrating Sphere Source.....	11
3.	Spectral Irradiance Working Standards.....	13
4.	Test Lamps.....	13
C.	Spectroradiometer.....	13
1.	Fore-optics.....	13
2.	Monochromator.....	16
3.	Detectors.....	16
D.	Control and Data Acquisition System.....	17
IV.	MEASUREMENT OF INSTRUMENT AND SOURCE PARAMETERS.....	18
A.	Spectral Responsivity Function.....	18
B.	Linearity of Response.....	19
C.	Size of Source.....	20
D.	Polarization.....	21
V.	PROCESS OF SPECTRAL IRRADIANCE REALIZATION.....	21
VI.	PROCESS OF SPECTRAL IRRADIANCE TRANSFER.....	23
VII.	SAFETY CONSIDERATIONS.....	23
VIII.	SCALE REALIZATION DATA ANALYSIS.....	24
IX.	UNCERTAINTY ESTIMATION.....	25
A.	Integrating Sphere Source Spectral Radiance Uncertainty.....	26
B.	Radiance to Irradiance Transfer Uncertainty.....	28
C.	Test Lamp Irradiance Transfer Uncertainty.....	28
D.	Overall Uncertainty of the Primary Working Standards.....	29
E.	Overall Uncertainty of a Group of Test Lamps.....	29
X.	REFERENCES.....	31

TABLE OF CONTENTS (continued)

APPENDIX A: Report of Calibration and Type FEL Lamp Standards
of Spectral Irradiance - 1986

APPENDIX B: FASCAL Description in Optical Radiation News

APPENDIX C: Detailed Procedures for
Routine Spectral Irradiance Calibrations

APPENDIX D: Data Reduction and Quality Control

APPENDIX E: Deuterium Lamp Standards of Spectral Irradiance - 1986

APPENDIX F: Spectral Irradiance Deuterium Lamp Report of Calibration

LIST OF FIGURES

FIGURE 1.	Spectral Radiance Measurement Setup.....	4
FIGURE 2.	Spectral Irradiance Measurement Setup.....	5
FIGURE 3.	Irradiance Calculation Geometry.....	6
FIGURE 4.	Variable Temperature Blackbody Schematic.....	10
FIGURE 5.	Central Section of Variable Temperature Blackbody....	12
FIGURE 6.	Mapping Profile of Integrating Sphere Aperture.....	14
FIGURE A-1.	Modified Type FEL.....	A-7
FIGURE C-1.	Modified Type FEL.....	C-16
FIGURE C-2.	FEL Modification.....	C-17
FIGURE C-3.	Kinematic Lamp Mount.....	C-18
FIGURE C-4.	Alignment Jig.....	C-19
FIGURE E-1.	Deuterium Lamp Standard.....	E-8
FIGURE E-2.	Electrical Circuit for Operating Deuterium Lamps..	E-9

LIST OF TABLES

TABLE I.	Integrating Sphere Spectral Radiance Uncertainty (3σ) in Percent.....	33
TABLE II.	Radiance to Irradiance Transfer Uncertainty (3σ) in Percent.....	34
TABLE III.	Test Lamp Irradiance Transfer Uncertainty (3σ) in Percent.....	35
TABLE IV.	1986 Spectral Irradiance Scale Uncertainty (3σ) in Percent.....	36
TABLE V.	1986 Spectral Irradiance Scale Transfer Uncertainty (3σ) in Percent.....	37
TABLE D-1.	Measurement Design for Type FEL Spectral Irradiance Standards.....	D-8
TABLE D-2A.	Standard Lamp Coefficients.....	D-9
TABLE D-2B.	Position Coefficients.....	D-9
TABLE D-3.	Standard Lamp Drift Rates.....	D-10
TABLE E-1.	Deuterium Lamp Uncertainty Estimates (3σ).....	E-7

I.

INTRODUCTION

Spectral irradiance, denoted E_λ , is defined as the radiant flux of wavelength λ incident on a surface per unit wavelength interval and per unit area on the surface. Mathematically

$$E_\lambda = d^2\phi/d\lambda \cdot dA \quad (1)$$

where $d^2\phi$ is the element of incident flux and $d\lambda$ and dA are the elements of wavelength and area respectively.

The National Bureau of Standards (NBS) presently issues two types of spectral irradiance standards. Type FEL (ANSI designation) lamps, modified to a medium bipost base, are calibrated as standards of spectral irradiance at 31 wavelengths over the spectral range 250 to 2400 nm. These lamp standards are designated in NBS Special Publication 250 [1] as item 39040C (former designation 7.5G) for 250 to 1600 nm. For 250 to 2400 nm the lamp standards are designated as item 39070S. Deuterium lamp standards of spectral irradiance are calibrated at 16 wavelengths over the spectral range 200 to 350 nm. These lamp standards are designated as item 39050C (former designation 7.5J).

In 1963, the National Bureau of Standards established a scale of spectral irradiance [2] using a group of 200 W, quartz-halogen, tungsten coiled-coil filament lamps. Although these lamps were compact and relatively easy to use, the spectral irradiance below 400 nm was insufficient for many applications. For this reason, the scale was transferred to a group of 1000 W, quartz-halogen lamps which increased the spectral irradiance by about a factor of five. The uncertainties (3σ level) assigned to this scale were about 3% in the visible-infrared spectral region and 8% in the ultraviolet spectral region.

A widespread need for higher accuracy led NBS, in the early 1970's, to initiate development of an improved scale of spectral irradiance. The new

scale, with estimated uncertainties about 1/3 those of the earlier scale, was first disseminated in 1973 [3]. The detailed techniques for realizing this scale have undergone several evolutionary changes in the past decade. This report is a description of the current process of realization of the NBS spectral irradiance scale and of the current procedures for the routine spectral irradiance calibrations.

The modified type FEL quartz halogen lamps are issued with uncertainties (stated in percent), estimated at the 3σ level, ranging from 2.2% at 250 nm to 1.0% at 654.6 nm to 6.5% at 2400 nm. The uncertainties estimated for the deuterium lamps are 7.5% at 200 and 210 nm and 5% for the spectral range 220 nm to 350 nm. The deuterium lamps are used mainly in the range 200 nm to 250 nm because of the increased flux available as compared to the modified type FEL lamps. The spectral irradiance values transferred to the deuterium lamps in the spectral range 200 to 250 nm are based on the hydrogen and blackbody line arcs developed primarily for use in the vacuum ultraviolet [4]. From 250 nm to 350 nm the reported spectral irradiance values are transferred from the modified type FEL lamps. The equipment used for the deuterium lamp calibrations is identical to that used for the modified type FEL lamp calibrations, and the measurement procedures are very similar. The body of this report will be limited to a description of the calibration of the modified type FEL lamps. Details of the calibration of the deuterium lamps are given in Appendix E. Appendix F is a sample report of calibration for the deuterium lamps.

II.

SCALE DERIVATION AND TRANSFER

The NBS scale of spectral irradiance is derived from the NBS scale of spectral radiance [5] which is based on a realization of the International Practical Temperature Scale (IPTS-68) starting with a gold point blackbody [6]. The average spectral radiance over the exit aperture of a special integrating sphere source is determined and then the flux from the sphere source which enters the receiving aperture of the spectroradiometer is calculated. This technique is used to determine the spectral irradiance at the detector receiving aperture and thus establishes a spectral irradiance

scale. As a matter of convenience the scale is transferred to a group of four, 1000 W, quartz-halogen lamp primary working standards using an averaging sphere-monochromator combination designed for spectral irradiance measurements. These lamps are used to maintain the NBS scale of spectral irradiance. The lamps are recalibrated every 50 to 100 burning hours.

Figure 1 shows the setup used to measure the spectral radiance of the special integrating sphere source. Figure 2 shows the setup used to transfer the spectral irradiance scale to a group of primary working standards.

The geometry used for the spectral irradiance determination is shown in Figure 3. The following method is used to determine the spectral irradiance at the receiving aperture of the spectroradiometer produced by the integrating sphere source. The spectral irradiance, E_λ , at the receiving aperture due to the spectral radiance, L_λ , at any point on the source aperture is

$$E_\lambda = \int_{\omega} L_\lambda \cdot d\omega \quad (2)$$

where ω is the solid angle defined by the receiving aperture and a point on the source aperture. To calculate the flux at the receiving aperture due to the entire source aperture, it is necessary to integrate over the entire projected area of the source aperture

$$\Phi_\lambda = \int_A \int_{\omega} L_\lambda \cdot d\omega \cdot dA \quad (3)$$

where $dA=dx \cdot dy \cdot \cos\theta$. L_λ is a function of θ , ϕ , x , and y so that

$$\Phi_\lambda = \int_A \int_{\omega} L_\lambda(\theta, \phi, x, y) \cdot \cos\theta \cdot d\omega \cdot dx \cdot dy \quad . \quad (4)$$

where:

θ is the angle between the normal to the surfaces of the apertures and a line connecting a single point on each aperture

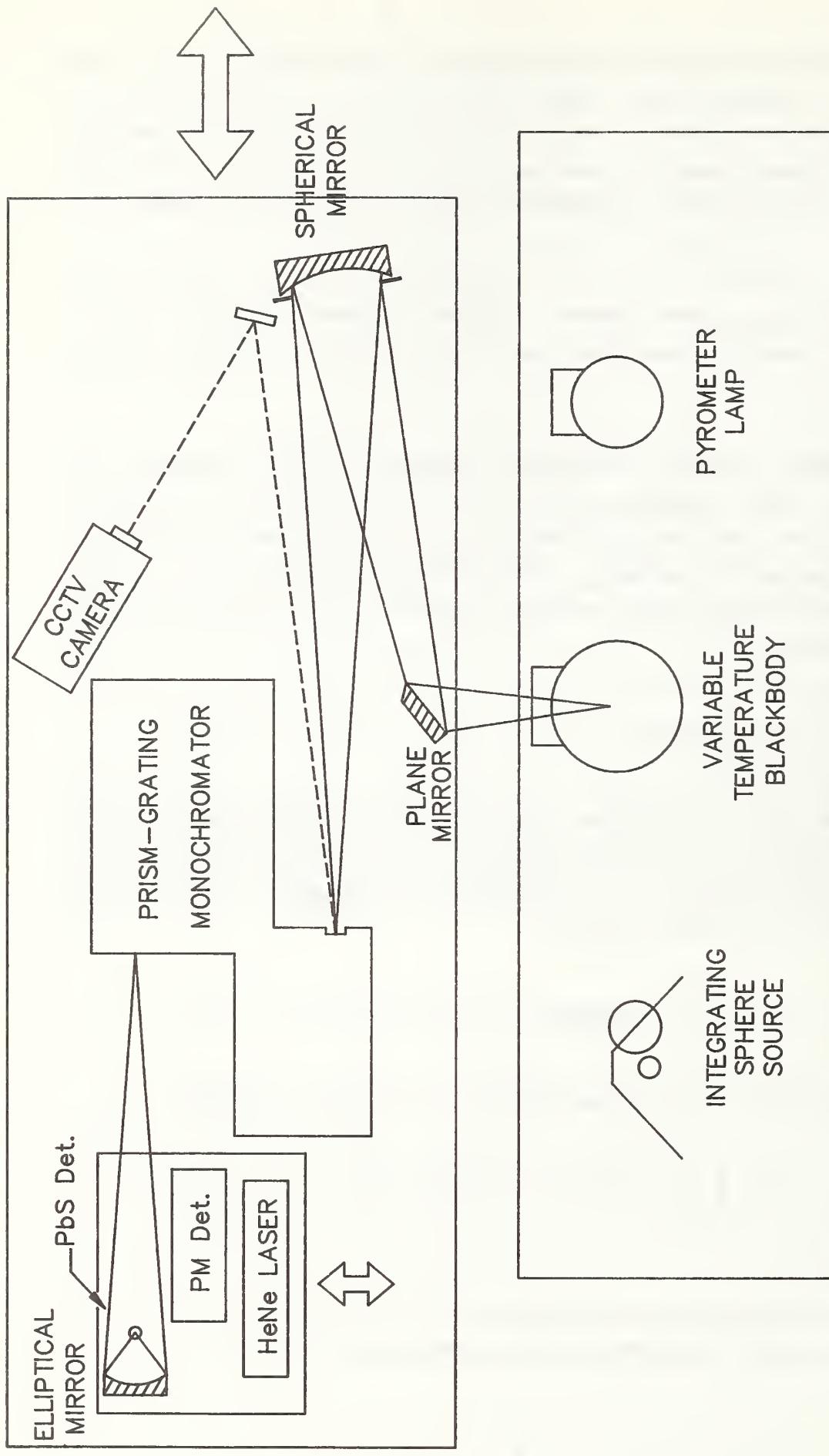


FIGURE 1. Spectral Radiance Measurement Setup

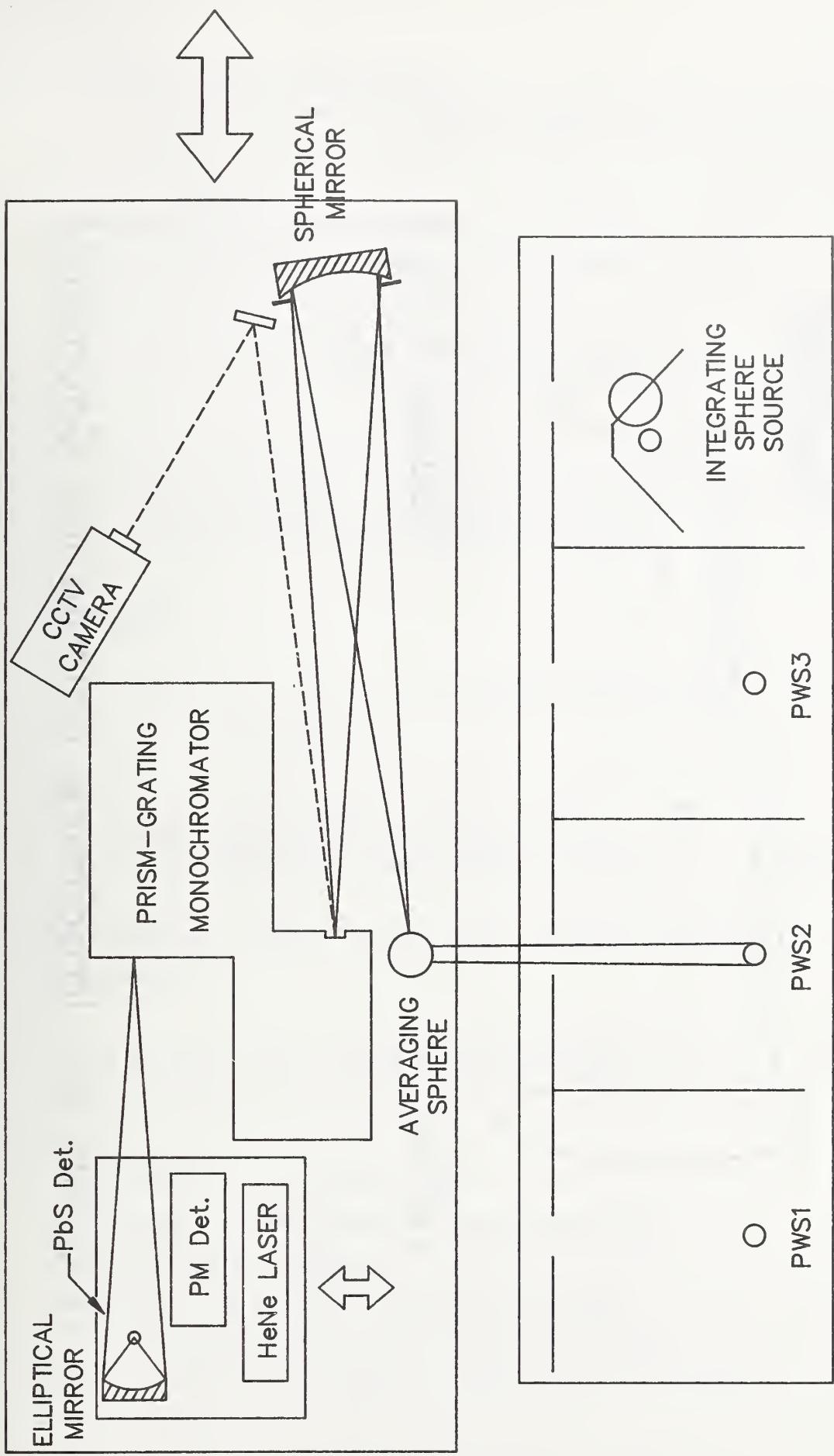


FIGURE 2. Spectral Irradiance Measurement Setup

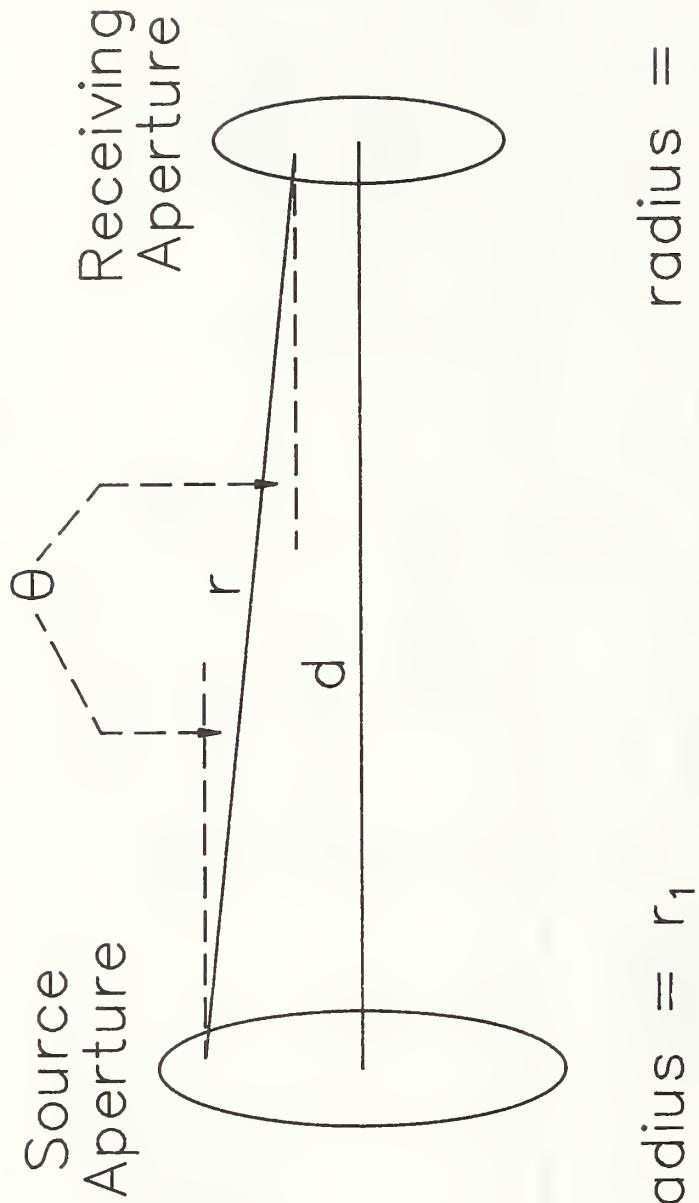


FIGURE 3. Irradiance Calculation Geometry

ϕ is the azimuthal angle

x is the horizontal location of a point on the source aperture

y is the vertical location of a point on the source aperture

Assuming that the source is Lambertian and nearly uniform, $L_\lambda(\theta, \phi, x, y)$ can be replaced by an average radiance \bar{L}_λ to give

$$\Phi_\lambda = \bar{L}_\lambda \cdot \int_A \int_\omega \cos\theta \cdot d\omega \cdot dx \cdot dy \quad (5)$$

where:

$$d\omega = \cos\theta / r^2 \cdot dx' \cdot dy'$$

x', y' is a point on the receiving aperture

r is the slant distance from x', y' to x, y

This gives

$$\Phi_\lambda = \bar{L}_\lambda \cdot \int_{A_{SA}} \int_{A_{RA}} \cos^2\theta / r^2 \cdot dx' \cdot dy' \cdot dx \cdot dy \quad (6)$$

where:

A_{SA} is the area of the source aperture

A_{RA} is the area of the receiving aperture

For circular, coaxial source and receiving apertures, this integral evaluates to

$$\Phi_\lambda = \bar{L}_\lambda \cdot \pi^2 / 2 \cdot \left[R^2 - (R^4 - 4 \cdot r_1^2 \cdot r_2^2)^{1/2} \right] \quad (7)$$

where:

$$R^2 = d^2 + r_1^2 + r_2^2$$

d is the normal distance between source and receiving apertures

r_1 is the radius of the source aperture

r_2 is the radius of the receiving aperture

A more convenient expression is

$$\Phi_\lambda = \bar{L}_\lambda \cdot (\pi \cdot r_1^2) \cdot (\pi \cdot r_2^2) / R^2 \cdot [1 + \delta + 2 \cdot \delta^2 + 5 \cdot \delta^3 + \dots] \quad (8)$$

where $\delta = (r_1^2 \cdot r_2^2) / R^4$. Finally,

$$E_\lambda = \Phi_\lambda / A_{RA} = \bar{L}_\lambda \cdot (\pi \cdot r_1^2) / R^2 \cdot [1 + \delta + \dots] \quad (8A)$$

The last step is to compare the spectroradiometer outputs produced by the integrating sphere source and each working standard.

Once the primary working standards have been calibrated, they are used to measure the spectral irradiance of test lamps. Modified type FEL test lamps are calibrated in groups of twelve and details of their calibration are covered in Appendix C.

III. MEASUREMENT APPARATUS

Spectral radiance and spectral irradiance calibrations are performed on the NBS Facility for Automated Spectroradiometric Calibrations (FASCAL). Appendix B is a concise description of this facility. Block diagrams of the measurement apparatus are shown in Figures 1 and 2. The principal components are:

- A. Variable Temperature Blackbody
- B. Sources
 - 1. Pyrometer Lamp
 - 2. Special Integrating Sphere Source
 - 3. Spectral Irradiance Primary Working Standards
 - 4. Test Lamps
- C. Spectroradiometer
 - 1. Fore-optics
 - a. Averaging Sphere
 - b. Mirrors and Entrance Slit Masks
 - 2. Monochromator
 - 3. Detectors
- D. Control and Data Acquisition System

A. Variable-Temperature Blackbody

The variable-temperature blackbody is used over a temperature range from about 800 °C to about 2400 °C.

A schematic cross-section of the variable-temperature blackbody is shown in Figure 4. The blackbody cavity is located in the central portion of a high density graphite tube, which is resistively heated in an argon atmosphere. Electric current is supplied to the graphite tube through water-cooled electrical connections at each end of the tube. The tube is surrounded by a double-walled graphite radiation shield, with carbon black fill between the walls. This assembly is surrounded by a water-cooled metal housing, with an observation port which can be sealed during evacuation of the atmosphere within the housing prior to flushing with argon. A window is provided at the top of the housing for visual pyrometer observation of the temperatures along the tube interior. A second window at the rear of the housing allows radiation from the rear wall of the graphite tube to fall on a silicon photodiode. The photodiode provides a signal for automatic control of the saturable-reactor power supply for the tube. A germanium photodiode, whose response extends further into the infrared region, replaces the silicon cell for operation at temperatures below 1000 °C. The blackbody mounting provides adjustment in two angular and three translational degrees of freedom, allowing for precise positioning and radiometric scanning over the target area and the beam solid angle.

The graphite tube is about 200 mm long, with an inner diameter of about 11 mm. The outer surface is tapered to improve temperature uniformity along its length. The wall is about 4 mm thick at mid-length where a 2 mm diameter hole in the wall allows for observation of the emitted flux. The tube is partitioned into small cylindrical sections by a series of thin graphite disks separated by thin graphite cylinders located at intervals along the bore. Holes in the graphite disks permit measurement of the temperatures in the middle and upper sections with a visual pyrometer. The holes vary in diameter from 6 mm for the uppermost disk to 0.75 mm for the disk below the central section. The central cylindrical section, which

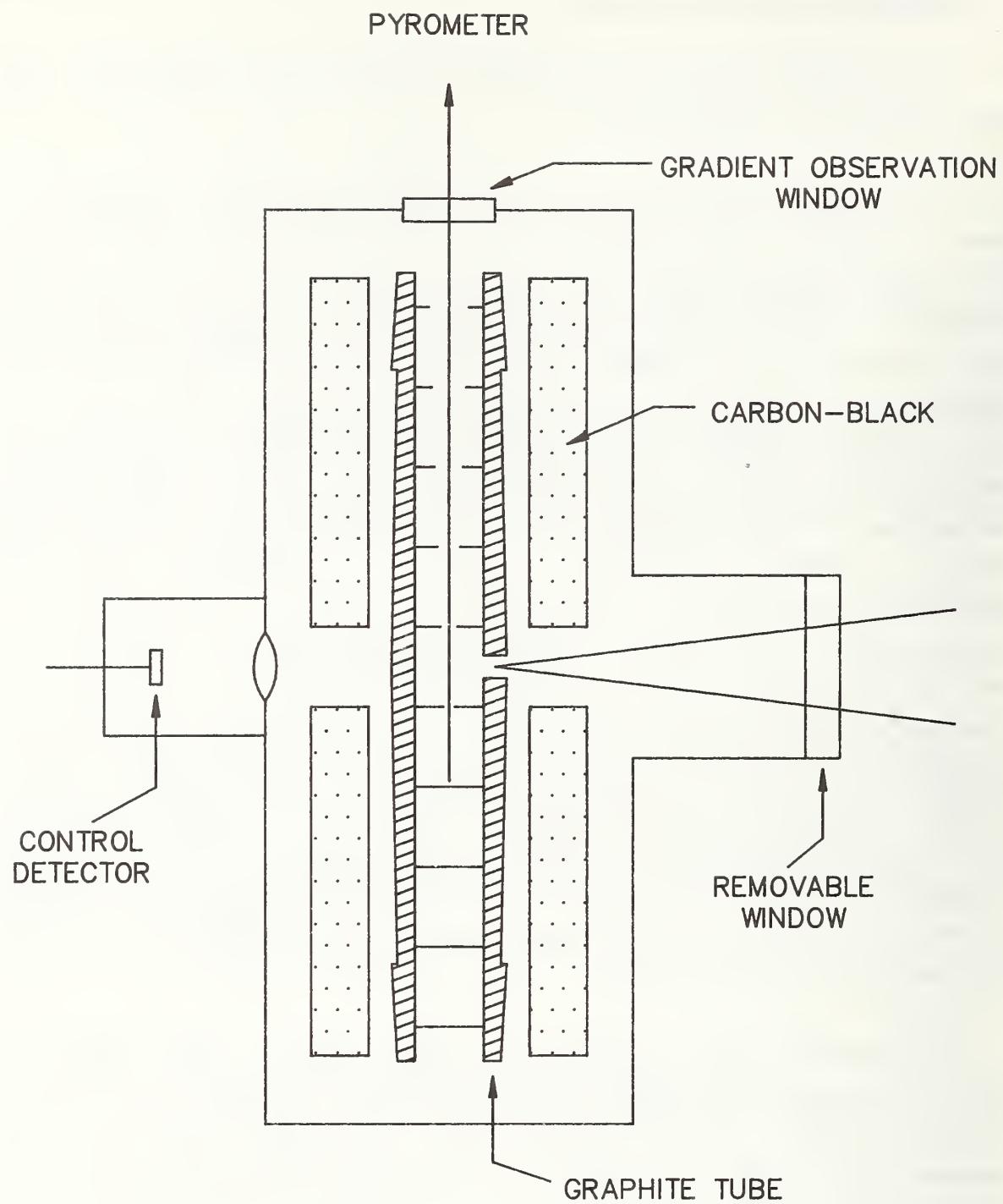


FIGURE 4. Variable Temperature Blackbody Schematic

provides the observed flux, is 9 mm high and 10 mm in diameter. The inside wall is threaded to reduce its partial reflectivity [7,8]. Figure 5 shows a cross-sectional view of the central section.

The blackbody emissivity has been assessed by measurements of the solid angle subtended by the cavity opening, the partial reflectivity of the graphite material [7], the temperature gradients, and the absorption by gases [8]. The solid angle subtended at the rear wall of the cavity by the inner edge of the observation hole is about 0.03 sr. The measured partial reflectivity of the graphite is 0.02 sr^{-1} . The measured temperature gradient over the length of the viewing cavity is less than 1 K. Experimental investigations of possible absorption of radiation by gases has disclosed only weak absorption lines at 589 and 589.6 nm (Na) and at 766.5 nm (K). The resulting estimate of emissivity is $0.9990 + 0.0005$.

B. Lamp Sources

1. Pyrometer Lamp. This lamp is used as a secondary standard for realizing the spectral radiance scale. It is a highly stable vacuum tungsten-strip lamp which is operated at a single current to produce a spectral radiance of about eight times that of a gold point blackbody at 654.6 nm (about 1530 K radiance temperature). The lamp drift rate is less than 0.02% per 100 hours when operated at a single current level.

2. Special Integrating Sphere Source. This source has been specially constructed to be unpolarized and to have high output in the IR part of its spectrum. It consists of a heat-sinked, water-cooled integrating sphere with a 1000 W quartz-halogen, modified type FEL lamp mounted next to the entrance port. The integrating sphere is 5.0 cm in diameter with a 23 mm diameter entrance port and a 20 mm diameter exit port located about 100° from the entrance port. The inside sphere wall is coated with pressed high purity polytetrafluoroethylene (PTFE) [16] to give high reflectivity in the IR. A modified type FEL lamp is mounted with its envelope about 3 mm from the entrance port of the sphere and located so that it does not directly irradiate the inside wall of the sphere opposite

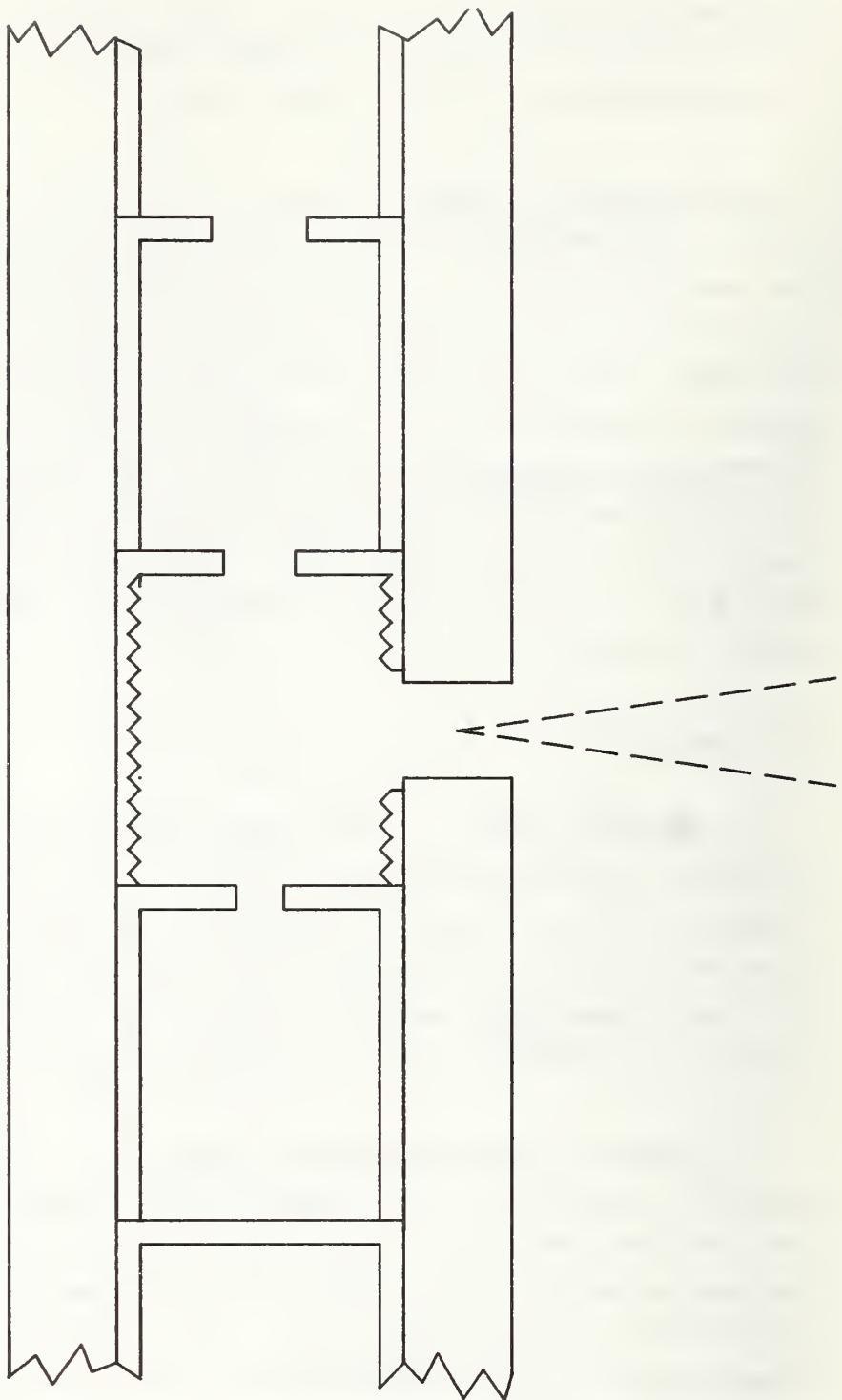


FIGURE 5. Central Section of Variable Temperature Blackbody

the exit port. The sphere itself is made of copper and is mounted in a heat-sinking copper plate. Copper tubing is soldered to the sphere and plate and the entire assembly is water-cooled to prevent the source from overheating. A precision circular aperture whose area has been accurately measured is attached at the exit port.

Because of the multiple reflections in the integrating sphere, entering radiation is randomized, producing a uniform, depolarized radiant flux at the exit port. The uniformity is verified when the exit port aperture is mapped during the irradiance realization procedure (Figure 6 shows a typical mapping profile). Depolarization was tested at 650 nm using an unpolarized source and a linear polarizer and found to be complete within the measurement precision of 0.1% (3σ level).

3. Spectral Irradiance Primary Working Standards. Four 1000 W quartz-halogen, modified type FEL lamps were selected as primary working standards. This type lamp has a clear bulb and a tungsten coiled-coil filament (CC-8) and has a rated life of 500 hours at 120 V. Before calibration, the lamp base is converted to a medium bipost base and the base structure is encapsulated in an epoxy-ceramic compound. The posts that form the bipost base are 6.35 mm (1/4 in) diameter cylindrical stainless steel rods that extend 20.64 mm (13/16 in) from the bottom of the epoxy-ceramic block. The posts are spaced 22.23 mm (7/8 in) between centers. A metal plate bearing the lamp identification number and indicating the electrical polarity is attached to the rear surface (side away from the spectroradiometer) of the epoxy-ceramic block.

4. Test Lamps. The test lamps are also modified type FEL lamps.

C. Spectroradiometer

1. Fore-optics

a. Averaging Sphere. The averaging sphere is 2.5 cm in diameter with a 1 cm² area precision circular entrance port and a 3 x 12 mm exit port located about 100° from the entrance port. The inside sphere wall is

			0.22	0.30	0.31								
			0.28	0.28	0.23	0.21	0.28	0.31	0.30	0.31	0.44		
			0.45	0.25	0.14	0.13	0.15	0.21	0.28	0.36	0.43	0.48	0.46
			0.42	0.21	0.08	0.03	0.06	0.09	0.15	0.20	0.31	0.42	0.48
-0.10			0.25	0.06	-0.04	-0.04	0.03	0.12	0.16	0.18	0.24	0.37	0.43
			0.32	0.11	-0.05	-0.11	-0.07	0.04	0.11	0.13	0.14	0.21	0.31
-0.44			0.21	0.00	-0.15	-0.18	-0.13	-0.02	0.05	0.10	0.11	0.15	0.22
			0.46	0.15	-0.07	-0.21	-0.22	-0.14	-0.05	-0.01	0.06	0.08	0.13
0.40			0.11	-0.12	-0.28	-0.26	-0.21	-0.14	-0.08	<u>0.00</u>	0.05	0.08	0.13
0.43			0.14	-0.11	-0.28	-0.29	-0.24	-0.18	-0.12	-0.05	0.00	0.06	0.14
-0.21			0.15	-0.10	-0.32	-0.34	-0.31	-0.25	-0.19	-0.14	-0.10	0.00	0.12
			0.12	-0.13	-0.36	-0.42	-0.41	-0.35	-0.30	-0.22	-0.16	-0.01	0.15
0.07			-0.14	-0.35	-0.45	-0.47	-0.42	-0.37	-0.30	-0.20	-0.03	0.16	0.36
			-0.29	-0.40	-0.44	-0.40	-0.34	-0.27	-0.16	0.00	0.17	0.35	0.50
			-0.41	-0.41	-0.38	-0.29	-0.21	-0.10	0.05	0.23	0.29		
												-0.27	-0.19
													-0.08

Values are % difference from central value

Wavelength = 654.6 nm

Target Area = 0.6 mm wide by 0.8 mm high

X Increment = 1.06 mm

Y Increment = 1.06 mm

Overall Mapping Correction = + 0.14%

FIGURE 6. Mapping Profile of Integrating Sphere Aperture

coated with pressed high purity PTFE. This material has been found to fluoresce at certain wavelengths under certain conditions [17], but when the sources being compared have approximately the same spectral distribution, fluorescence is not a problem. The radiation entering the sphere is randomized by multiple reflections in the sphere, thus producing uniform, depolarized radiant flux at the exit port. This uniformity was verified to within the measurement precision of 0.1% (3σ level) by radiometrically scanning the exit port of the sphere. Depolarization was tested at 500 nm and 650 nm using an unpolarized source and a linear polarizer and found to be complete within the measurement precision of 0.1% (3σ level).

The difference in the solid angle of irradiation for the irradiance lamp and the integrating sphere source is only a problem when the reflectance of the averaging sphere wall is not uniform. This high purity, 3 mm thick PTFE sphere coating provides this uniformity, and it was verified by determining the spectral irradiance of a lamp mirror-system [3] whose solid angle could be varied. Negligible difference (<0.1%) in the results was observed over the range of solid angles viewed (the conical full angle was varied from 1.85° to 10°).

b. Mirrors and Entrance Slit Masks. In the radiance measurement mode, the radiance source is imaged with unit magnification onto a polished stainless steel mask placed directly in front of the entrance slit of the monochromator. In the irradiance measurement mode, the exit port of the averaging sphere is imaged with unit magnification onto a different polished stainless steel mask. The mask determines the height of the system field stop (source target area) and the entrance slit determines the width. In the radiance mode the stop dimensions are 0.6 mm wide by 0.8 mm high. Also, in this mode the optic axis lies within 1.5° of the axis of the spherical mirror to minimize aberrations [9]. In the irradiance mode the stop dimensions are approximately 2 mm wide by 10 mm high. In this mode the off-axis angle is slightly larger, but in this case the image quality is less important because of the homogeneity of the flux exiting the averaging sphere.

2. Monochromator. A prism-grating double monochromator is employed to minimize spectral scattering and to avoid multiple orders. It is used over the wavelength range of 200 to 2400 nm. The dispersion varies with wavelength from about 1 to 4 nm/mm. The entrance aperture (solid angle) is rectangular in shape, with a vertical angle of 7° and a horizontal angle of 3.5°. The wavelength setting is calibrated against Hg and Th spectral line standards (discharge lamps). The lines used are:

Hg Lines	Th Lines
1529.58 nm	2400.80 nm
1013.97	2351.47
576.96	2063.44
546.06	1730.77
435.84	1351.81
404.66	1220.69
365.02	904.82
334.15	800.00
312.57	700.08
302.15	654.57
296.73	600.71
275.28	
253.65	

The wavelength calibration is repeatable to within 0.05 nm. The entrance, intermediate, and exit slits are adjustable together as a unit from 0.01 to 3.0 mm, resulting in a nearly triangular-shaped spectral bandpass.

3. Detectors. Two interchangeable detectors are used to cover the wavelength range of the spectroradiometer. For the 200 to 850 nm range, an end-on 11-stage photomultiplier with quartz window and S-20 spectral response is placed behind the exit slit. The detector is cooled to 258 K with a thermoelectric cooler. The anode current is amplified and converted to a 0 to 10 V signal by a programmable DC amplifier. To ensure linearity of response, the high voltage applied to the detector is normally selected to restrict the detector current to 500 nA or less.

A lead sulfide detector, cooled to 240 K by a thermoelectric cooler, is used for the 800 to 2400 nm range. The detector and the exit slit are placed at the foci of an ellipsoidal mirror, which images the exit slit upon the detector with a demagnification of about 7. The detector output is amplified and converted to a 0 to 1 V signal by a phase-

sensitive lock-in voltmeter, which is keyed to a 78 Hz sector disk placed just before the plane mirror in the radiance mode or just after the exit port of the averaging sphere in the irradiance mode.

The signal from either detector-amplifier combination is fed to a 5 1/2 digit voltmeter, capable of integration times ranging from one second to several minutes. To facilitate alignment of optics or sources, a HeNe laser is placed at the detector position, so that its beam passes through the monochromator and fore-optics in the reverse direction.

D. Control and Data Acquisition System

After initial alignment, the FASCAL system permits control of the entire measurement process from a remote operator console. Component positions, instrument settings, sequence of operations, and data collection are effected by either stored computer programs, operator commands, or a combination of the two.

The system is directed by a microcomputer equipped with a CRT terminal and keyboard and a high-speed disk system for program and data storage. A modular interface controller [10] provides the link between instruments and computer. All measurement signals are multiplexed into the digital voltmeter through the interface scanner, and the instruments are remotely programmed and controlled through interface modules. All instrument settings and signal outputs are printed and stored on disk for later analysis.

The spectroradiometer (fore-optics, monochromator, and detectors), a closed-circuit TV camera, and a photoelectric pyrometer are mounted on a carriage. The carriage can be moved by remote command along a linear track, to position the spectroradiometer in front of any of the sources mounted at fixed stations along the track. The average move time between stations is a few seconds, and positions are repeatable to about 0.1 mm. The TV camera presents a highly magnified image of the monochromator entrance slit mask to video displays at the spectroradiometer and at the operator console for initial source alignment and subsequent monitoring.

The pyrometer is used for the initial setting of the variable temperature blackbody to its approximate temperature.

IV. MEASUREMENT OF INSTRUMENT AND SOURCE PARAMETERS

A. Spectral Responsivity Function

The relative spectral responsivity function of the spectroradiometer is determined by an indirect method [11]. In this method, the relative responsivity function is treated as the product of two terms, the responsivity factor and the slit-scattering function, where the responsivity factor depends only upon the wavelength of the observed flux and the slit-scattering function depends only upon the difference between the wavelength setting of the monochromator and the wavelength of the flux. This factorization of the spectral responsivity function is valid if the instrument dispersion, aberrations, scattering, and diffraction are constant over the wavelength region of interest. This assumption is valid in the central portion of the relative responsivity function, but values for the distant wings are subject to error due primarily to changes in scattering and dispersion.

The responsivity factor is obtained by spectrally scanning a continuous source standard of spectral radiance using narrow (0.1 mm) slits. To determine the slit-scattering function, an integrating sphere irradiated by a high-powered laser is spectrally scanned by the spectroradiometer, with the slit widths set at the 0.6 mm width used in the scale realization and transfer. The plot of the output signal versus wavelength is the mirror image of the plot of the slit-scattering function versus wavelength. For a 647 nm Kr laser, the function is nearly triangular in shape with a width at half-height of 2.5 nm. Relative to the peak value, the measured values decrease to about 10^{-3} at 3 nm, 10^{-4} at 15 nm, and 10^{-7} at 70 nm from the central wavelength. At 150 nm from the central wavelength, the value decreases to 10^{-8} in the short-wavelength wing and to 10^{-9} in the long-wavelength wing. Scans with 488 nm (Ar), 514 nm (Ar), and 676 nm (Kr) yield similar results.

These values were confirmed over the central and near wing portions of the function by measurements with the direct method, using a dye laser tuned through a series of wavelengths with the spectroradiometer set at a fixed wavelength [12].

The measurement at 647 nm yielded the slit-scattering function used for 654.6 nm, where the spectral distribution mismatch of a variable temperature blackbody and a gold point blackbody requires an accurate determination of the relative responsivity function. However, the measurements in the visible cannot be applied with confidence to the short-wavelength region, since the dispersion varies by about a factor of 2.5. For this region, the central portion and near wings of the slit-scattering function are determined by scans of a spectral line discharge source, and values in the distant long-wavelength wing are deduced from a measurement of the integrated spectrally-scattered radiation. With the wavelength set at a selected value in the 200 to 250 nm region, the signal from a calibrated lamp (radiance temperature 2475 K at 654.6 nm) is recorded. A glass filter which blocks all radiation in the vicinity of the wavelength setting and passes about 90% of the radiation at longer wavelengths is inserted into the beam. The ratio of signals with and without filter is taken as the fractional contribution of spectrally scattered radiation to the signal. A second (identical) filter is added to insure that only scattered light is being observed in the filtered beam. Results with filters of different cutoff wavelengths (Corning filters CS 0-56 and CS 0-52) both indicate an integrated scattered light contribution of less than 0.2% at 225 nm. The slit scattering function calculated from this result and the known source distributions and responsivity factor are less than 10^{-9} at wavelengths greater than 200 nm from the central wavelength, in good agreement with the values measured in the visible.

B. Linearity of Response

The degree of linearity of the spectroradiometer response is determined with an automated beam conjoiner [13,14]. A beam from a constant source is split into two branches whose fluxes are independently attenuated or blocked before recombination and

further attenuation. The flux from both branches measured together should equal to the sum of the fluxes from each branch when measured separately (additivity). The device provides 96 levels of flux ranging over a factor of about 500. The levels are presented in random order to avoid systematic errors and are interspersed with 29 zero flux levels. A microcomputer controls the attenuating filters and records the filter positions and radiometer signals. The data is least-squares fitted to a polynomial response function to determine a correction factor by which the radiometer output signal must be multiplied to obtain a quantity proportional to radiant flux.

The response function of the spectroradiometer is dependent upon the detector-amplifier employed. With the photomultiplier tube in place (spectral range 200 to 850 nm), the instrument response at all wavelengths is linear to within 0.2% for a range of anode currents from 1 to 500 nA. Linearity measurements were performed at 900, 600, 300, and 250 nm. For currents much less than 1 nA, the signal is limited by noise. For currents greater than 1 mA the correction increases rapidly, rising to 3% at 7 mA. The anode current is restricted to less than 500 nA during measurements by selection of appropriate photomultiplier tube voltage. Correction factors for the amplifier ranges are determined from the measurement of a known electrical current and combined with the linearity correction factor.

Linearity tests of two PbS detectors resulted in a correction factor which is a linear function of the signal over the range 1 to 280 mV. The correction varies from 0.1% at 3 mV to about 9% at 300 mV. To avoid relying on large corrections, sources are typically operated at near equality in the PbS spectral region.

C. Size of Source

The "size of source" effect (signal contribution due to flux which originates outside the target area and is scattered into the measured beam by the fore-optics) is determined by observing the change in signal from a 0.6 by 0.8 mm area of a uniform diffuse source while placing

various size masks on the diffuse source. The masks expose source areas which closely approximate the radiant areas of the lamp, the blackbody and the integrating sphere source used in the scale realization. As a check, the effect is also evaluated by observing changes in the near-zero signal from a "black hole" (an absorbing cavity slightly larger than the 0.6 by 0.8 mm field stop) as the various surrounding area masks are positioned. The observed differences are used to apply a correction to the signals observed in source comparisons. The effect is measured at wavelengths of 654.6 and 350 nm, and values for other wavelengths are estimated from the assumption of an inverse wavelength dependence. The correction varies from 0.04% to 0.1% at 654.6 nm depending upon the elapsed time since the last mirror recoating.

D. Polarization

The polarization properties of the spectroradiometer and the sources do not play a significant role in the spectral irradiance realization and will not be discussed here. A discussion of polarization properties can be found in reference [5].

V. PROCESS OF SPECTRAL IRRADIANCE REALIZATION

The spectral radiance of the special integrating sphere source is determined so that it can be used as a transfer standard for determining spectral irradiance. The spectral radiance output from the center point of the integrating sphere aperture is compared to the spectral radiance output from a variable temperature blackbody. The temperature of the blackbody is determined by comparing it at 654.6 nm to a high stability vacuum pyrometer lamp calibrated for a single temperature (about 1530 K). The spectral radiance of the integrating sphere source is determined at 31 different wavelengths from 250 to 2400 nm. The aperture of the integrating sphere is mapped at 2000, 1050, 654.6 and 300 nm and its average spectral radiance is computed for each wavelength. Figure 6 shows a typical mapping profile of the integrating sphere aperture. The mapping correction varied less than 0.1% over the range of wavelengths measured.

The spectroradiometer is changed from the spectral radiance mode to the spectral irradiance mode (see Figures 1 and 2) and the spectral irradiances from the NBS primary working standards (PWS) are compared to the spectral irradiance from the integrating sphere source (ISS). Appropriate partitions and baffles are erected to reduce scattered light to less than 0.1%. The comparisons are done at the same 31 wavelengths at which the integrating sphere source was calibrated for spectral radiance. Two separate determinations are performed on each primary working standard. The spectral irradiance of a primary working standard is determined using the relationship

$$E_{\lambda}(\text{PWS}) = L_{\lambda} \cdot (\pi \cdot r_1^2) / R^2 \cdot S_{\text{PWS}} / S_{\text{ISS}} \quad (9)$$

where $S_{\text{PWS}} / S_{\text{ISS}}$ is the ratio of the irradiance signal from the primary working standard to the irradiance signal from the integrating sphere source. The first part of the expression comes from Equation (8A) where $\delta \approx 2 \cdot 10^{-16}$.

The absolute output from the integrating sphere source is monitored at six wavelengths (2000, 1600, 1050, 800, 600, and 400 nm) during the 30 to 40 operating hours necessary to calibrate the primary working standards. Finally, the blackbody is used again to perform an abbreviated spectral radiance calibration of the integrating sphere source. Spectral radiance drift corrections, linear with time, for the integrating sphere source can then be made if necessary.

The measurement of the spectral radiance or spectral irradiance at a single wavelength takes from about four to eight minutes, so it is only necessary for our detectors to have good short term stability.

VI.

PROCESS OF SPECTRAL IRRADIANCE TRANSFER

The four modified FEL primary working standards are used to perform spectral irradiance calibrations on test lamps. A lamp screening process is used to select test lamps suitable for calibration. Lamps are annealed and then are checked for stability, emission lines or absorption bands, and for variations in goniometric output. For a selected group of twelve test lamps, each lamp is measured four times, once in each of the four source positions and once against each of the four primary working standards. The screening of lamps can take several weeks and the calibration procedure for twelve test lamps takes from two to three weeks. Details of the routine spectral irradiance calibrations can be found in Appendix C.

VII.

SAFETY CONSIDERATIONS

The main hazards in the FASCAL laboratory are due to radiation from HeNe lasers, high intensity lamps, deuterium lamps, and mercury lamps. Laser signs are posted to alert personnel of possible hazards. Light baffles are in place when high intensity sources are operating and absorbing glasses are used when viewing sources directly. Warning signs are posted when deuterium lamps are operating and light baffles are in place. The mercury lamps are shielded to protect personnel from UV radiation. In addition, protective glasses are worn by personnel when in the vicinity of deuterium and mercury lamps.

There are also electrical hazards due to lamp and blackbody power supplies and to high voltage power supplies for detectors. Approved grounded cables are used on all electrical equipment.

VIII.

SCALE REALIZATION DATA ANALYSIS

The spectral irradiance scale is generally realized at the following 31 wavelengths:

250 nm	600 nm
260	654.6
270	700
280	800
290	900
300	1050
310	1150
320	1200
330	1300
340	1540
350	1600
400	1700
450	2000
500	2100
555	2300
	2400

Certain wavelength regions in the IR are skipped (around 1400 nm and 1800 to 1980 nm) in order to avoid atmospheric absorption bands.

Since the total operating time for each primary working standard during a complete scale realization is relatively short (8 to 12 hours), no effort is made to account for irradiance lamp drift. The final assignment of spectral irradiance is simply attributed to the lamp as of the midpoint of the burning time. Between scale realizations when the group of four primary working standards is being used as a basis for calibrating additional lamps, their drifts are taken into account. Various empirical drift models have been used [3]. The present drift equation is

$$E_{\lambda} = A + B \cdot t \quad (10)$$

where:

t is time in burning hours

A and B are constants determined by fitting

The fitting is performed independently at each wavelength.

Drift of the spectral radiance of the integrating sphere source is taken into account by simple linear interpolation in time between the initial and final spectral radiance values.

An interpolation equation was developed for calculating the spectral irradiance of tungsten halogen lamps at wavelengths between the 31 calibrated wavelengths. This equation is

$$E_\lambda = (A_0 + A_1 \cdot \lambda + \dots + A_n \cdot \lambda^n) \cdot \lambda^{-5} \cdot \exp(a + b/\lambda) . \quad (11)$$

Setting the polynomial equal to 1, multiplying both sides by λ^5 , and taking the log of both sides gives $\ln(E_\lambda \cdot \lambda^5) = a + b/\lambda$, in which it will be recognized that $\exp(a)$ is an effective gray-body emissivity and b is closely related to the reciprocal of the distribution temperature. A least squares fitting using a weighting of 1 is performed to determine a and b . With a and b thus fixed, Equation (11) is least squares fitted using a weighting of $1/E_\lambda^2$ (assuming constant percentage measurement error) to determine A_0 , A_1 , ... A_n . In practice it has been found that the final fit is considerably improved if the spectrum is broken into two spectral regions, 250 to 400 nm and 350 to 1600 nm, for separate fitting. See reference [3] for examples of fitting Equation (11) to lamp data. This method is only valid for the continuous spectrum and does not predict emission lines and absorption bands. Spectral irradiance values predicted using Equation (11) have an uncertainty of about 0.5%.

IX.

UNCERTAINTY ESTIMATION

The spectral irradiance scale uncertainty analysis is broken down into three parts. First, the uncertainty in the spectral radiance of the integrating sphere source is determined. Second, the uncertainty in the transfer to the spectral irradiance primary working standards is determined. Third, the uncertainty in the transfer from the primary

working standards to the irradiance test lamps is determined. The overall uncertainty in the primary working standards is determined by combining in quadrature the first and second parts. The overall uncertainty in a group of test lamps is determined by combining in quadrature all three parts. All uncertainties are estimated at the 3σ level.

A. Integrating Sphere Source Spectral Radiance Uncertainty

The uncertainties in the spectral radiance values assigned to the integrating sphere source are obtained from the observed precision of the measurements and the estimated systematic error in both the measured and the provided quantities (e.g., temperature of melting gold). Uncertainties obtained from the observed precision and from the published values of the physical constants are based upon three standard deviations. Uncertainties of systematic errors are estimated at the equivalent of three standard deviations.

In order to examine the contributions of the various errors to the uncertainty in the spectral radiance of the integrating sphere source, an approximate equation for the complete measurement process was derived by using the Wien approximation to the Planck relation. The details of the derivation are described in reference [5]. The resulting equation is

$$L_\lambda \approx \left[s_\lambda \cdot \epsilon_B \cdot d \cdot M_\lambda \right] \left[c_1 / [\pi \cdot \lambda^5 \cdot (e^{c_2 / \lambda \cdot T_{Au}})] \right] \left[s_r \cdot f_r \cdot M_r / \epsilon_B \right]^{\lambda_r / \lambda} \quad (12)$$

where, with VTBB denoting the variable temperature blackbody and GPBB denoting the gold point blackbody, the definitions of the quantities are:

M_λ , signal ratio of the VTBB-integrating sphere source comparison

M_r , signal ratio of the GPBB-VTBB comparison

s_λ , size-of-source correction for the VTBB-integrating sphere source comparison

ϵ_B , effective emissivity of the VTBB

d , correction for integrating sphere source drift during calibration

s_r , size-of-source correction for the GPBB-VTBB comparison

f_r , linearity-range factor correction

T_{Au} , IPTS-68 temperature of melting gold

c_1 , first radiation constant

c_2 , second radiation constant

λ , wavelength of the VTBB-integrating sphere source comparison

λ_r , wavelength of the GPBB-VTBB comparison, 654.6 nm

Spectral radiance uncertainties due to the factors of Equation (12) are obtained from the partial derivative with respect to those factors and the estimated uncertainty in the factor. Differences between errors calculated by Equation (12) and those calculated by the exact Planck relation are negligible. Note that for the wavelengths λ and λ_r this process yields the error due to inserting the wrong wavelength in the spectral radiance calculation, not the error due to an incorrect wavelength setting.

In addition to the factors which appear explicitly in Equation (12), uncertainties in the ratios M_λ and M_r arise from errors in the wavelength settings λ (0.1 nm) and λ_r (0.05 nm), in the current measurements of the vacuum pyrometer lamps (0.2 mA) and the integrating sphere source lamp (0.3 mA), and in the measured spectral responsivity function. The uncertainties in the ratios due to wavelength setting and electric current are assessed at a number of wavelengths by measurement of the change in signal ratio when varying these quantities. The technique for determining the effect upon the signal ratios due to the uncertainties in the measured spectral responsivity function is derived in reference [18]. The spectral radiance uncertainties due to these factors are then deduced from the ratio uncertainties as before. The signal ratio, lamp current and wavelength setting errors are considered random; the remaining errors are systematic.

Table I lists the uncertainties obtained by this process. The calculated uncertainties, in percent of spectral radiance, are tabulated for a number of wavelengths over the calibration range. The individual values are combined in quadrature to yield the combined uncertainty for

each wavelength. These uncertainties apply to the spectral radiances values of the integrating sphere source.

B. Radiance to Irradiance Transfer Uncertainty

The uncertainty in the transfer from the integrating sphere source to the spectral irradiance primary working standards is obtained from examining the contributions of the various errors in the following measurement equation,

$$E_{\lambda}(\text{PWS}) = m \cdot d_1 \cdot f \cdot (S_{\text{PWS}}/S_{\text{ISS}}) \cdot L_{\lambda}(\text{ISS}) \cdot \left[(\pi \cdot r_1^2)/R^2 \right] \quad (13)$$

where:

$E_{\lambda}(\text{PWS})$, spectral irradiance of a primary working standard

m , mapping correction for the average spectral radiance of the integrating sphere source

d_1 , integrating sphere source drift correction

f , linearity-range factor correction

$S_{\text{PWS}}/S_{\text{ISS}}$, signal ratio of the primary working standard-integrating sphere source comparison

$L_{\lambda}(\text{ISS})$, spectral radiance of the integrating sphere source

$(\pi \cdot r_1^2) \cdot (\pi \cdot r_2^2)/R^2$, geometric factor in the irradiance calculation (see Equations 7, 8, and 9)

In addition to the factors which appear explicitly in Equation (13), uncertainties in the ratio $S_{\text{PWS}}/S_{\text{ISS}}$ arise from errors in the wavelength settings and in the electrical current measurements of the sources. There are also uncertainties due to spectral scattering, stray light, and averaging sphere responsivity. All these uncertainties have been evaluated and are listed in Table II.

C. Test Lamp Irradiance Transfer Uncertainty

The uncertainty in the transfer from the spectral irradiance primary working standards to a group of irradiance test lamps is obtained from

examining the contributions of the various errors in the following measurement equation,

$$E_{\lambda}(\text{TL}) = f \cdot (S_{\text{TL}}/S_{\text{PWS}}) \cdot E_{\lambda}(\text{PWS}) \quad (14)$$

where:

$E_{\lambda}(\text{TL})$, spectral irradiance of a test lamp

f , linearity-range factor correction

$S_{\text{TL}}/S_{\text{PWS}}$, signal ratio of the test lamp-primary working standard comparison

$E_{\lambda}(\text{PWS})$, spectral irradiance of a primary working standard

In addition to the factors which appear explicitly in Equation (14), uncertainties in the ratio $S_{\text{TL}}/S_{\text{PWS}}$ arise from errors in the wavelength settings and in the electrical current measurements of the sources. All these uncertainties have been evaluated and are listed in Table III.

D. Overall Uncertainty of the Primary Working Standards

Table IV lists the overall uncertainties of the primary working standards. It is made up by combining the results of Tables I and II. The differences between lines Ia and Ib (and between IIIa and IIIb) are caused by the systematic uncertainty introduced by an assumed uncertainty of 0.4 K in the gold point temperature.

E. Overall Uncertainty of a Group of Test Lamps

Table V lists the overall uncertainties of a group of test lamps. It is made up by combining the results of Tables I, II, and III and adding a model error. The model error is necessary because the primary working standards drift with time. A time drift model is applied for each of the primary working standards [see Equation (10)] but the possibility that this drift may be wrong introduces an additional uncertainty in Table V, but not included in Table II or Table IV. This uncertainty was obtained by comparing the calculated extrapolated spectral irradiance with further scale realizations. When the primary working standards are used between

scale realizations, this additional uncertainty must be combined in quadrature with the other uncertainties.

The differences between lines Ia and Ib (and between IVa and IVb) are again caused by the systematic uncertainty introduced by an assumed uncertainty of 0.4 K in the gold point temperature.

- [1] Uriano, G.A., Garner, E.L., Kirby, R.K. and Reed, W.P., eds., NBS Calibration Services Users Guide 1986-88. Nat. Bur. Stand. (U.S.), Special Publication 250, (July, 1986).
- [2] Stair, R., Schneider, W.E., and Jackson, J.K., A New Standard of Spectral Irradiance, Appl. Opt. 2, 1151-1154 (1963).
- [3] Saunders, R.D. and Shumaker, J.B., The 1973 NBS Scale of Spectral Irradiance, Nat. Bur. Stand. (U.S.) Tech Note 594-13 (Apr. 1977).
- [4] Klose, J.Z. and Bridges, J.M., NBS Measurement Services: Radiometric Standards in the Vacuum Ultraviolet, NBS Special Publication 250-3.
- [5] Walker, J.H., Saunders, R.D. and Hattenburg, A.T., NBS Measurement Services: Spectral Radiance Calibrations, NBS Special Publication 250-1.
- [6] Waters, W.R., Walker, J.H., and Hattenburg, A.T., NBS Measurement Services: Radiance Temperature Calibrations, NBS Special Publication 250-7.
- [7] De Vos, J.C., Evaluation of the Quality of a Blackbody, Physica 20: 669-689 (1954).
- [8] Kostkowski, H.J., Erminy, D.E., and Hattenburg, A.T., High Accuracy Spectral Radiance Calibration of Tungsten-Strip Lamps, Advances in Geophysics, Vol. 14. New York, NY, Academic Press Inc., 111-127 (1970).
- [9] Wilkinson, F.J., Astigmatism Errors in Radiance Measurements, Metrologia 20, 11-18 (1984).

- [10] Popenoe, C.H. and Campbell, M.S., MIDAS Modular Interactive Data Acquisition System - Description and Specification, Nat. Bur. Stand. (U.S.) Tech. Note 790, (August, 1973).
- [11] Kostkowski, H.J., The Relative Spectral Responsivity and Slit-Scattering Function of a Spectroradiometer, Chapter 7 of Self-Study Manual on Optical Radiation Measurements: Part I -- Concepts, Natl. Bur. Stand. Tech. Note 910-4, 2-34, (June, 1979).
- [12] Saunders, R.D. and Shumaker, J.B., Apparatus Function of a Prism-Grating Double Monochromator. (submitted to Applied Optics).
- [13] Saunders, R.D. and Shumaker, J.B., Automated Radiometric Linearity Tester, Appl. Opt. 23, 3504-3506 (1984).
- [14] Coslovi, L. and Righini, F., Fast Determination of the Nonlinearity of Photodetectors, Appl. Opt. 19, 3200-3203 (1980).
- [15] The International Practical Temperature Scale of 1968, Metrologia 5(2), 35-44 (April, 1969).
- [16] Weidner, V.R. and Hsia, J.J., Reflection Properties of Pressed Polytetrafluoroethylene Powder, J. Opt. Soc. Am., 71 (July, 1981).
- [17] Saunders, R.D. and Ott, W.R., Spectral Irradiance Measurements: Effect of UV Produced Fluorescence in Integrating Spheres, Appl. Opt. 15, 827 (April, 1976).
- [18] Kostkowski, H.J. and Nicodemus, F.E., An Introduction to the Measurement Equation, Chapter 5 of Self-Study Manual on Optical Radiation Measurements: Part I -- Concepts, Nat. Bur. Stand. (U.S.) Tech. Note 910-2, 58-92 (February, 1978).

TABLE I
INTEGRATING SPHERE SOURCE SPECTRAL RADIANCE UNCERTAINTY (3σ)
IN PERCENT

Source of Error	Wavelength (nm)							
	250	350	654.6	900	1300	1600	2000	2400
T_{Au} (s)	1.29	0.92	0.49	0.36	0.25	0.20	0.16	0.13
M_r (r)	0.16	0.11	0.08	0.20	0.17	0.12	0.09	0.36
M_λ (r)	0.25	0.18	0.08	0.20	0.22	0.33	0.66	1.08
s_r (s)	0.26	0.19	0.10	0.07	0.05	0.04	0.03	0.03
s_λ (s)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
f_r (s)	0.26	0.19	0.10	0.07	0.05	0.04	0.03	0.03
d (s)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
ϵ_B (s)	0.16	0.09	0.00	0.03	0.05	0.06	0.07	0.07
λ_r setting (r)	0.15	0.08	0.04	0.02	0.01	0.00	0.01	0.01
λ setting (r)	0.03	0.04	0.03	0.01	0.02	0.01	0.01	0.01
c_1 (s)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
c_2 (s)	0.13	0.10	0.05	0.04	0.03	0.02	0.02	0.01
Lamp currents:								
Quinn-Lee (r)	0.11	0.08	0.04	0.03	0.02	0.02	0.01	0.01
1530 K (r)	0.05	0.04	0.02	0.02	0.01	0.01	0.01	0.01
ISS (r)	0.08	0.06	0.03	0.02	0.02	0.01	0.01	0.01
Spect Resp (s)	0.08	0.06	0.03	0.02	0.02	0.02	0.01	0.01
QUADRATURE SUM	1.41	1.01	0.55	0.49	0.41	0.44	0.70	1.16
QUADRATURE SUM WITHOUT T_{Au}	0.58	0.42	0.25	0.34	0.33	0.39	0.69	1.15

Notes: Random errors denoted by (r), systematic errors by (s)

Sources of error described on page 26

TABLE II

 RADIANCE TO IRRADIANCE TRANSFER UNCERTAINTY (3σ)
 IN PERCENT

Source of Error	Wavelength (nm)							
	250	350	654.6	900	1300	1600	2000	2400
S_{PWS}/S_{ISS} (r)	0.42	0.08	0.06	0.84	0.86	1.46	2.60	5.73
f (s)	0.26	0.19	0.10	0.07	0.05	0.04	0.03	0.03
m (s)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
d_1 (s)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
λ (r)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Lamp currents:								
ISS (r)	0.08	0.06	0.03	0.02	0.02	0.01	0.01	0.01
PWS (r)	0.08	0.06	0.03	0.02	0.02	0.01	0.01	0.01
Geom Factor (s)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Spec Scat (s)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Stray Light (s)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Av Sph Resp (s)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
SYSTEMATIC ERR.	0.36	0.31	0.27	0.26	0.26	0.25	0.25	0.25
RANDOM ERR.	0.43	0.11	0.08	0.84	0.86	1.46	2.60	5.73
QUADRATURE SUM	0.57	0.33	0.28	0.88	0.90	1.48	2.61	5.74

Notes: Random errors denoted by (r), systematic errors by (s)

Sources of error described on page 28

TABLE III

 TEST LAMP IRRADIANCE TRANSFER UNCERTAINTY (3σ)
 IN PERCENT

Source of Error	Wavelength (nm)							
	250	350	654.6	900	1300	1600	2000	2400
S_{TL}/S_{PWS} (r)	0.87	0.21	0.15	0.42	0.68	0.72	1.59	2.60
f (s)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Lamp Currents:								
PWS (r)	0.08	0.06	0.03	0.02	0.02	0.01	0.01	0.01
TL (r)	0.08	0.06	0.03	0.02	0.02	0.01	0.01	0.01
SYSTEMATIC ERR.	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
RANDOM ERR.	0.88	0.22	0.16	0.42	0.68	0.72	1.59	2.60
QUADRATURE SUM	0.88	0.22	0.16	0.42	0.68	0.72	1.59	2.60

Notes: Random errors denoted by (r), systematic errors by (s)

Sources of error described on page 29

TABLE IV

1986 SPECTRAL IRRADIANCE SCALE UNCERTAINTY (3σ)
IN PERCENT

(derived from Tables I and II)

	250 nm	350 nm	654.6 nm	900 nm	1300 nm	1600 nm	2000 nm	2400 nm
I. NBS SPECTRAL RADIANCE SCALE								
a. Absolute error (with respect to SI units)	1.41	1.01	0.55	0.49	0.41	0.44	0.70	1.16
b. NBS long term reproducibility (without T_{Au} , see Table I)	0.58	0.42	0.25	0.34	0.33	0.39	0.69	1.15
II. RADIANCE TO IRRADIANCE TRANSFER								
a. Systematic errors	0.36	0.31	0.27	0.26	0.26	0.25	0.25	0.25
b. Random errors (3σ precision)	0.43	0.11	0.08	0.84	0.86	1.46	2.60	5.73
III. SPECTRAL IRRADIANCE SCALE UNCERTAINTY (Quadrature Sum)								
a. With respect to SI units	1.52	1.06	0.62	1.01	0.99	1.55	2.71	5.85
b. NBS long term reproducibility	0.81	0.53	0.38	0.94	0.96	1.53	2.70	5.85

TABLE V

1986 SPECTRAL IRRADIANCE SCALE TRANSFER UNCERTAINTY (3σ)
IN PERCENT

(derived from Tables I, II and III)

	250 nm	350 nm	654.6 nm	900 nm	1300 nm	1600 nm	2000 nm	2400 nm
I. NBS SPECTRAL RADIANCE SCALE								
a. Absolute error (with respect to SI units)	1.41	1.01	0.55	0.49	0.41	0.44	0.70	1.16
b. NBS long term reproducibility	0.58	0.42	0.25	0.34	0.33	0.39	0.69	1.15
II. RADIANCE TO IRRADIANCE TRANSFER								
a. Systematic errors	0.36	0.31	0.27	0.26	0.26	0.25	0.25	0.25
b. Random errors (3σ precision)	0.43	0.11	0.08	0.84	0.86	1.46	2.60	5.73
c. Model error	1.38	0.80	0.78	0.77	0.77	0.82	1.00	1.20
III. TEST LAMP IRRADIANCE TRANSFER								
a. Systematic errors	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
b. Random errors (3σ precision)	0.88	0.22	0.16	0.42	0.68	0.72	1.59	2.60
IV. UNCERTAINTY OF REPORTED VALUES (Quadrature Sum)								
a. With respect to SI units	2.23	1.35	1.01	1.34	1.42	1.89	3.29	6.51
b. NBS long term reproducibility	1.83	0.99	0.88	1.29	1.40	1.88	3.29	6.51

APPENDIX A

REPORT OF CALIBRATION AND
TYPE FEL LAMP STANDARDS OF
SPECTRAL IRRADIANCE - 1986

TABLE OF CONTENTS - APPENDIX A

1. Report of Calibration.....	A-1
2. Type FEL Lamp Standards of Spectral Irradiance - 1986.....	A-4

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

Gaithersburg, MD 20899

REPORT OF CALIBRATION

of
One Standard of Spectral Irradiance
(250 nm to 1600 nm)
Supplied to:

(See your Purchase Order No.

dated .)

1. Material

One 1000-watt, quartz-halogen, modified type FEL, tungsten coiled-coil filament lamp has been supplied by the National Bureau of Standards as a standard of spectral irradiance and bears the designation F-000.

2. Calibration

The lamp was calibrated using the equipment and procedures described in NBS Special Publication 250-20, "Spectral Irradiance Calibrations at NBS", Walker, J.H., Saunders, R.D., Jackson, J.K., and McSparron, D.A., (1987), a copy of which is enclosed. The preparation and operation of the modified type FEL lamp supplied for this calibration are described in the enclosure, "Type FEL Lamp Standards of Spectral Irradiance - 1986". Note particularly paragraph IV of this enclosure which describes the orientation of the test lamp.

3. Results

The results of this test are given in the attached Table 1. The uncertainties of the reported values at the 3σ level are summarized in Table 2. Details on the estimation of these uncertainties are given in SP 250-20.

Prepared by:

Approved by:

John K. Jackson
Radiometric Physics Division
Center for Radiation Research

Donald A. McSparron
Radiometric Physics Division
Center for Radiation Research

NBS Test No.: 534/
Date:

Page 1 of 3

REPORT OF CALIBRATION

TABLE 1

Spectral irradiance (W/cm^3) at 50.0 cm from Lamp F-000 when operated on dc with the polarity as indicated on the identification plate attached to the lamp base.

<u>Wavelength (nm)</u>	Lamp No. F-000 <u>7.900 A</u>
250	0.160
260	0.280
270	0.480
280	0.770
290	1.160
300	1.690
310	2.380
320	3.280
330	4.410
340	5.770
350	7.400
400	20.20
450	41.00
500	68.20
555	107.0
600	129.0
654.6	158.0
700	179.0
800	208.0
900	217.0
1050	208.0
1150	192.0
1200	183.0
1300	164.0
1540	122.0
1600	114.0

NBS Test No.: 534/

Date:

Page 2 of 3

TABLE 2
1986 SPECTRAL IRRADIANCE SCALE TRANSFER UNCERTAINTY (3σ)
IN PERCENT

	250 nm	350 nm	654.6 nm	900 nm	1300 nm	1600 nm	2000 nm	2400 nm
--	-----------	-----------	-------------	-----------	------------	------------	------------	------------

I.	NBS SPECTRAL RADIANCE SCALE							
a.	Absolute error (with respect to SI units)	1.41	1.01	0.55	0.49	0.41	0.44	0.70
b.	NBS long term reproducibility	0.58	0.42	0.25	0.34	0.33	0.39	0.69
II.	RADIANCE TO IRRADIANCE TRANSFER							
a.	Systematic errors	0.36	0.31	0.27	0.26	0.26	0.25	0.25
b.	Random errors (3σ precision)	0.43	0.11	0.08	0.84	0.86	1.46	2.60
c.	Model error	1.38	0.80	0.78	0.77	0.77	0.82	1.00
III.	TEST LAMP IRRADIANCE TRANSFER							
a.	Systematic errors	0.01	0.01	0.01	0.01	0.01	0.01	0.01
b.	Random errors (3σ precision)	0.88	0.22	0.16	0.42	0.68	0.72	1.59
IV.	UNCERTAINTY OF REPORTED VALUES (Quadrature Sum)							
a.	With respect to SI units	2.23	1.35	1.01	1.34	1.42	1.89	3.29
b.	NBS long term reproducibility	1.83	0.99	0.88	1.29	1.40	1.88	3.29

I. Introduction

NBS supplies 1000-watt, quartz-halogen, modified type FEL lamps calibrated for spectral irradiance. These lamps are calibrated with procedures and equipment described in NBS Special Publication SP 250-20, "Spectral Irradiance Calibrations at NBS", Walker, J. H., Saunders, R. D., Jackson, J. K., and McSparron, D. A., 1987.

II. Lamp Description

Type FEL lamps are 1000-watt, clear bulb, quartz-halogen, tungsten coiled-coil filament (CC-8) lamps. They have a rated life of 500 hours at 120 volts. The lamps are manufactured with a two pin base. Before calibration, the lamp base is converted to a medium bipost base and the base structure is encapsulated in an epoxy-ceramic compound (see Figure 1). The posts that form the medium bipost base are 6.35 mm (1/4 in) diameter cylindrical stainless steel rods that extend 20.64 mm (13/16 in) from the bottom of the molded base. The posts are spaced 22.23 mm (7/8 in) between centers. A metal plate bearing the lamp identification number and indicating the electrical polarity is attached to the rear surface (the side facing away from the radiometer) of the molded lamp base.

III. Preparation and Screening

Before calibration all modified type FEL lamps are seasoned on direct current for 40 hours at 120 volts dc. The lamp output is then monitored at 654.6 nm for a 24 hour period to determine

the lamp's drift rate. Only lamps exhibiting a drift rate of less than 0.5% for this period are selected for calibration (about 10% of the last 200 lamps have failed this test).

Because previously issued type DXW lamps were found to occasionally have emission lines and absorption bands, all modified type FEL lamps are spectrally scanned from 250 to 800 nm (0.04 - 0.08 nm bandpass). None of the approximately 400 type FEL lamps checked to date has exhibited either emission lines or absorption bands.

At the working distance of 50.0 cm, the irradiance field from type FEL lamps has been observed to be non-uniform to a small extent. The amount of non-uniformity varies from lamp to lamp. At 800 nm, lamps are rotated in pitch and yaw from their aligned position. For rotations of $\pm 1^\circ$, lamps which show a departure of more than 1% from the irradiance at the aligned position are rejected for calibration (about 20% of the last 200 lamps tested have failed this test).

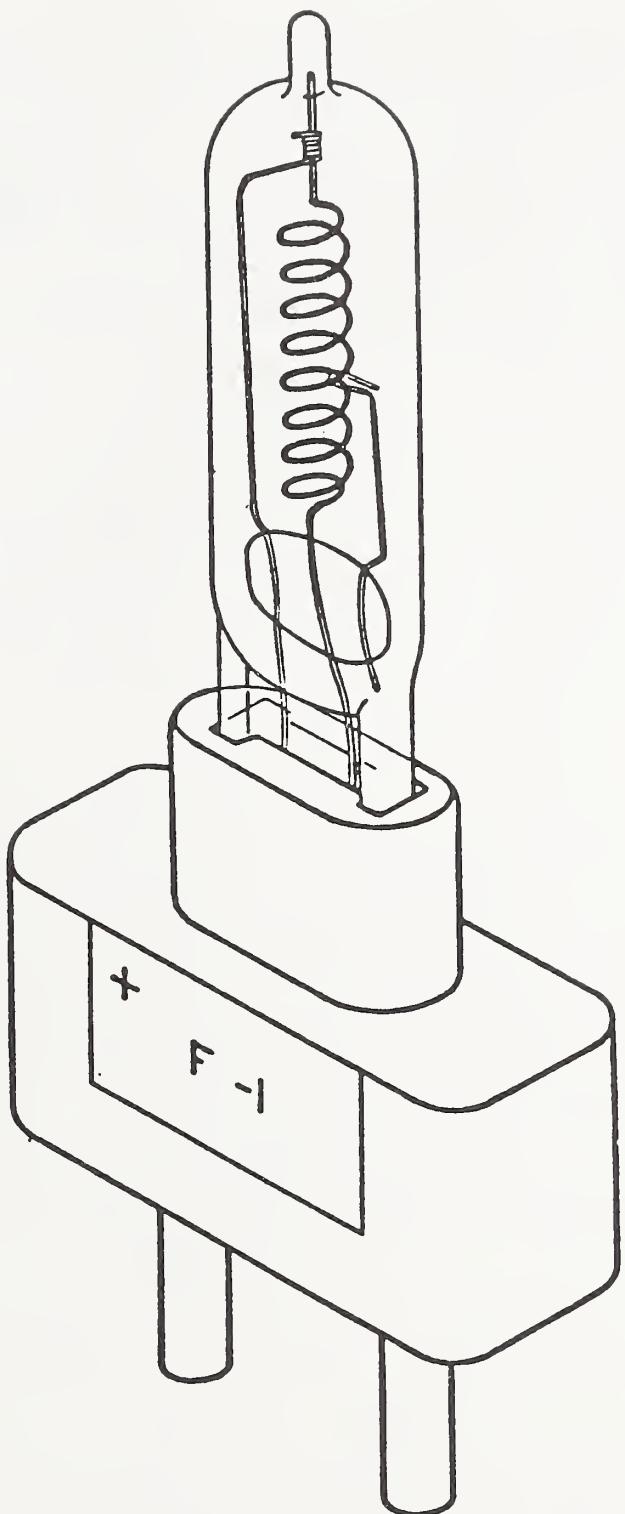
IV. Orientation

Prior to calibration, modified type FEL lamps are oriented as follows: the lamp is positioned base down with its identification plate facing away from the measuring instrument and with its base posts vertical. These posts are made perpendicular to and equidistant from the optical axis of the measuring instrument. The lower end of the base's positive post is set 9.53 cm (approximately 3.75 in) below the horizontal plane containing the optical axis. The plane tangent to both posts, on the side of the posts nearest the measuring instrument, is set perpendicular to the optical axis and to a distance of 50.0 cm

from the limiting aperture of the measuring instrument. Note that this alignment fixes the lamp base posts, not the filament, relative to the optical axis of the measuring instrument. It is possible for the center of the lamp filament to be several mm off the optical axis with the lamp correctly aligned.

V. Operation

Modified type FEL lamps are calibrated while operating on direct current with the designated contact at positive potential. The exact operating current (set to the nearest 0.1 ampere) is determined for each test lamp by matching its radiant output to the working standard lamps at 654.6 nm. Typically currents in the range of 7.8 - 8.0 amperes are used. Electrical measurements of lamp operating current are made potentiometrically to an accuracy of 0.01%. After positioning and alignment, the lamps are slowly (30 seconds) brought up to their designated electrical operating points and allowed to stabilize for at least ten minutes before irradiance measurements are made.



Modified Type FEL

FIGURE A-1

APPENDIX B

**FASCAL DESCRIPTION IN
OPTICAL RADIATION NEWS**

Optical Radiation News



Prepared by the staffs of the Optical Radiation and the Radiometric Physics Sections of NBS to report on items of interest in optical radiation measurements. Inquiries may be directed to Robert L. Booker, B308 Metrology Bldg., NBS, Washington, D.C. 20234 (301) 921-3864.

U.S. DEPARTMENT OF COMMERCE National Bureau of Standards

NO. 18

November 1976

FASCAL

The Facility for Automated Spectroradiometric Calibrations (FASCAL), the most recent and ambitious product of the Optical Radiation Section's automation efforts, has reached a stage of development whereby routine spectral irradiance calibrations have been automatically performed on this equipment since June.

Since there have been no previously published descriptions of this facility, its main technical features will be described here in some detail along with a description of current usage.

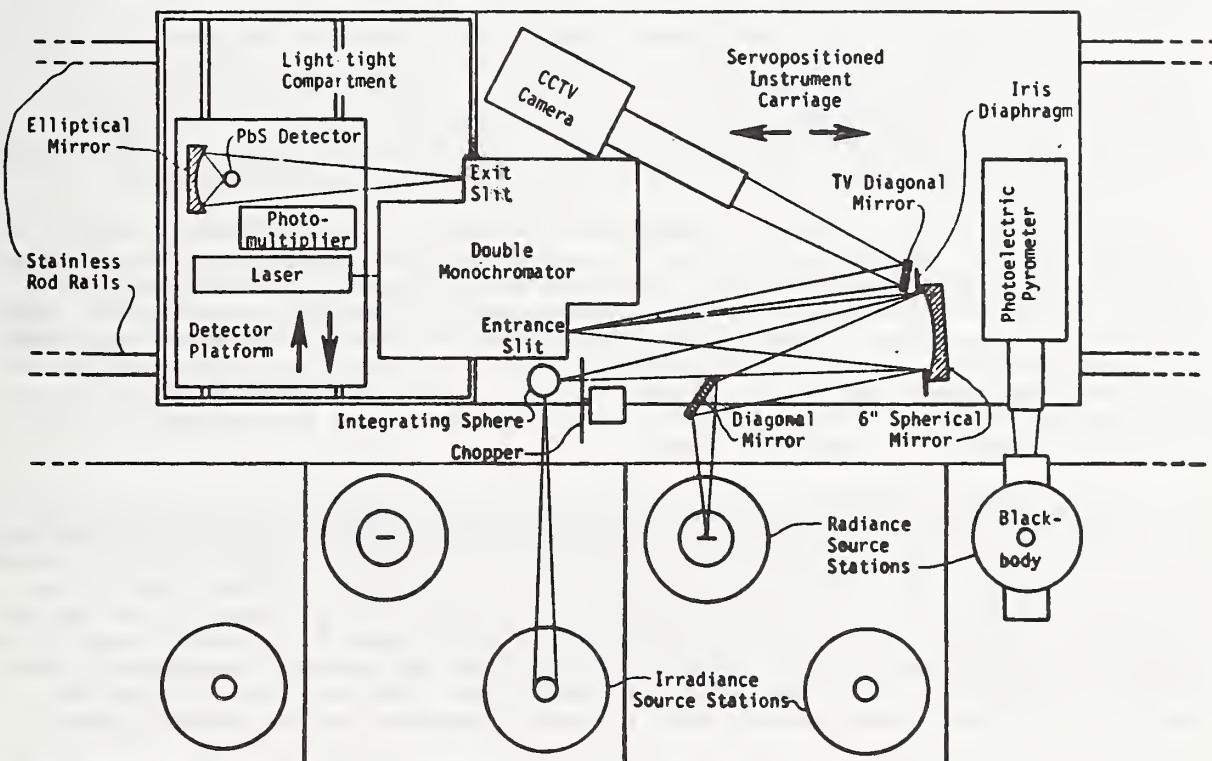


Figure 1.
OPTICAL ARRANGEMENT OF FASCAL SYSTEM
Top View

The FASCAL facility incorporates all of the usual elements required for precision temperature-based radiometry. They are configured in a linear arrangement, dominated by a heavy truss bridge structure 7.3 m long supporting a pair of ground 1½-inch diameter stainless steel rails. These rails were carefully aligned by a laser beam to within ± 0.03 mm tolerance in straightness and parallelism. Riding the rails on linear ball bushings is an instrument carriage in the form of a rectangular box 240 cm long, 68 cm wide and 50 cm in height. All optical elements, dispersers and detectors are mounted within the carriage and can be positioned along the track to intercept the radiation from various radiation sources placed at stationary points alongside the rail structure. There are twenty-five available source mounting stations spaced along the length of the structure.

The instrument carriage is driven through roller chains by a digital servo-positioning system and may be automatically positioned with a resolution of 0.1 mm and a repeatability of 0.01 mm. Positioning speed is sufficiently rapid that an average move between two stations takes only about two seconds. The actual carriage position is tracked by an incremental rotary encoder which has a digital visual display. The digital position information is also entered into a minicomputer. There is a unique central position, designated the "home" position, to which the carriage may be driven at any desired time to verify the functioning of the incremental encoder and to reference it to an absolute scale.

The instrument carriage is divided into two compartments. One is light-tight and houses detectors, and the other contains optics and associated electronics. The latter compartment is almost entirely enclosed to minimize dust collection and scattered light. The optical arrangement of the instrument carriage is shown schematically in Figure 1. The dispersing element is a prism-grating double monochromator, mounted so that the exit slit is within the light-tight detector compartment. Monochromatic radiation from the exit slit can be directed to either of two detectors on a detector platform that can be positioned remotely. Radiation in the visible and ultraviolet is detected by a thermoelectrically cooled photomultiplier having an extended S-20 response, while infrared radiation is detected by a thermoelectrically cooled PbS detector placed at the focus of an elliptical mirror. The wavelength of the monochromator may be remotely set by a high-speed stepping motor with a resolution of .025 nm through a range of 200 nm to 2500 nm. An absolute encoder having .025 nm resolution permits the actual wavelength setting to be visually displayed and entered into the computer. A He-Ne laser, also mounted on the detector platform, can be automatically positioned so that its beam passes through the monochromator and optics in the reverse direction to facilitate alignment of optics and sources.

The fore-optics are arranged to enable measurements to be made on either radiance or irradiance sources. Radiance sources are focused on the entrance slit by a 6-inch diameter spherical mirror with the optical path being turned approximately 90° by a flat diagonal mirror. The spherical mirror is rotated a few degrees for irradiance measurements. This allows the exit aperture of a small integrating sphere to be imaged on the entrance slit of the monochromator. Irradiance sources are placed 50 cm from the entrance aperture of the integrating sphere, and extensive light baffling of the irradiance sources and sphere minimizes the effects of scattered light. A motor-driven chopper is positioned in the optical path when the PbS detector is used.

The monochromator entrance slit is almost completely inaccessible to direct viewing due to the enclosures, baffling and closely packed optical elements and associated equipment. To provide a view of this slit, a closed-circuit television (CCTV) camera is mounted within the carriage and focused on the monochromator entrance slit through a small flat mirror mounted near the 6-inch spherical mirror. This has been invaluable in the initial alignment of radiance sources and in monitoring the positioning of the source image on the slit (or slit mask used to limit the slit height) during the course of experiments. The image of the entrance slit is magnified some twenty-five times such that the notch on tungsten strip lamps imaged onto the slit is readily observable on the monitor screens.

The instrument carriage also houses ancillary equipment such as power supplies for the thermoelectric coolers, a remotely programmable high-voltage power supply for the photomultiplier, and an automatic photoelectric pyrometer. The latter is focused on the radiance sources, including a variable-temperature, graphite-tube blackbody source that occupies the "home" position.

Cables from all equipment housed in the instrument carriage are bundled and passed through the bottom of the carriage, where they ride in a smooth trough between the rails as the carriage passes back and forth. All control and measurement cables from the carriage and source supplies lead to the operator's console.

Measuring instruments and equipment to communicate with the operator and the computer are housed in the console. The operator interface consists of analog and digital displays, a CCTV monitor displaying the monochromator entrance slit and a CRT terminal and keyboard. Instrumentation includes a 5½ digit DVM, a lock-in amplifier, a picoammeter, and remote controls for eight source power supplies. A MIDAS system^{1,2} provides the interface between instruments and computer. All measurement signals are multiplexed into the DVM through the MIDAS scanner, and all instruments may be remotely programmed and controlled through MIDAS modules. In addition, the current supplied to the lamp sources can be automatically monitored and controlled.

The MIDAS controller communicates serially at a rate of 1200 baud with a minicomputer having 32 K of core memory. The computer is equipped with a high-speed disk system for program and data file storage. It is operated in a time-shared mode so that it can service other experiments, in addition to FASCAL, simultaneously. Programming is done exclusively in BASIC interactive language.

FASCAL is currently being used for routine spectral irradiance calibrations. These calibrations are carried out on groups of twelve 1000 W tungsten-halogen lamps preselected for stability, spectral composition, and directional uniformity. Three lamps from the group and one of our in-house standards (calibrated as described in the soon-to-be-published NBS Tech Note 594-13) are mounted in four of the outer row of lamp stations shown in Figure 1. Lamp alignment is accomplished with "reverse optics" using the laser in the detector compartment and a special alignment jig that is interchangeable with the integrating sphere. This jig includes a diagonal mirror that directs the laser beam to the lamp station for positioning the lamp in the plane perpendicular to the optical axis, and a 50 cm arm terminating in a dial gauge for setting the lamp-to-detector distance. Using the integrating sphere input to the monochromator, these four lamps are then intercompared automatically by FASCAL at our twenty-six customary wavelengths. Then another three lamps and a different in-house standard are measured in the same way. This process is performed sixteen times, with permutations of lamps and stations, until each of the twelve lamps has been compared against each in-house standard and each of the sixteen lamps has been measured in each of the four lamp stations. The redundancy of these measurements permits us to sense any systematic errors. For example, any dependence upon lamp station, or discrepancy among our four in-house standards would be thoroughly investigated.

We are now in the process of adding routine spectral radiance calibrations to FASCAL's repertoire. This is a more complicated problem requiring the rest of the features of FASCAL and we hope to report on these calibrations in the near future.

¹Optical Radiation News, No. 8 (March 1975).

²C. H. Popenoe and M. S. Campbell, MIDAS, Modular Interactive Data Acquisition System -- Description and Specification, NBS Tech Note 790 (August 1973).

APPENDIX C

DETAILED PROCEDURES FOR ROUTINE SPECTRAL IRRADIANCE CALIBRATIONS

TABLE OF CONTENTS - APPENDIX C

A.	LAMP PREPARATION.....	C-1
B.	ALIGNMENT INSTRUMENTATION.....	C-2
1.	HeNe Laser.....	C-2
2.	Averaging Sphere.....	C-2
3.	Plane Mirror Mount.....	C-2
4.	Lamp Socket.....	C-2
5.	Alignment Jig.....	C-3
C.	ALIGNMENT.....	C-3
1.	Generalized Alignment Description.....	C-3
2.	Detailed Alignment.....	C-3
D.	LAMP OPERATION.....	C-5
E.	LAMP SCREENING.....	C-5
1.	Goniometric Scans.....	C-5
2.	Lamp Stability.....	C-6
3.	Spectral Scans.....	C-7
F.	CALIBRATION PROCEDURES.....	C-8
1.	Turn On Procedure.....	C-8
2.	Start Up Procedure.....	C-8
3.	Data Taking Procedure.....	C-10
4.	Data Reduction.....	C-13

DETAILED PROCEDURES FOR ROUTINE SPECTRAL IRRADIANCE CALIBRATIONS

A. LAMP PREPARATION

The lamps issued by the N.B.S. as standards of spectral irradiance are commercially available 1000 W, clear quartz envelope, tungsten-halogen, coiled-coil filament lamps (ANSI designation FEL) modified to a medium bipost base (Figure C-1).

Unmodified lamps as received from the manufacturer are inspected for clarity of envelope, for symmetry of filament, and for electrical continuity. The lamps are annealed (run at 120 V dc - with the long filament support at positive potential) for 40 hr (8 % of their rated life). The lamps are then potted to a medium bipost base. Figure C-2 shows the exploded view of the mechanical modifications.

After potting, the lamps are again visually inspected and electrically checked. The lamps are cleaned with ethyl alcohol and a lint free cloth. They are then burned for 10-15 hr at 100 V dc to cure the potting materials. The lamps are again cleaned with ethyl alcohol to remove any deposits from the outgassing of the potting materials.

***** CAUTION *****

At no time should one's fingers come in contact with the lamp envelope. The contamination of the lamp envelope by any substance can cause permanent etching of that surface at the high temperatures at which these lamps operate. Care should also be taken not to look directly at these lamps because of possible eye damage due to the ultraviolet transmission of the quartz envelope.

B. ALIGNMENT INSTRUMENTATION

1. A HeNe laser, mounted in the detector compartment, is turned on, allowed to stabilize for 20 min, and positioned at the exit slit of the spectroradiometer. With the wavelength set at 632.8 nm and a 0.8 by 0.8 mm mask centered in the entrance slit, the laser is adjusted at the exit slit until its beam exits centered in the 0.8 by 0.8 mm mask. This beam defines the optical axis of the spectroradiometer for alignment purposes.

***** CAUTION *****
Care should be taken to avoid any direct eye contact with the laser beam.

2. A 3.8 mm diameter averaging sphere, with a 1 cm^2 circular entrance aperture and (at approximately 100°) a 3 by 12 mm exit port, is used to collect the flux from the spectral irradiance sources.

3. A plane mirror mount, which has a kinematically designed ball and slot base which is interchangeable with the base of the averaging sphere, has a plane mirror mounted so that the laser beam reflected from it traces a line that would be perpendicular to and centered on the averaging sphere entrance aperture.

4. A lamp socket (see Figure C-3) was especially designed for these lamps. It is kinematic in design, fixing the positive lamp post in a 90° 'V' notch with a stop plate at the bottom to fix the lamp height, and a horizontal wedge on the negative post permitting only lateral movement of that post. Each post is held in position with spring-loaded plungers.

5. An alignment jig (see Figure C-4) is described in Section C.2.

C. ALIGNMENT

1. Generalized Alignment Description

The lamps are mounted vertically, base down and with the brass identification plate facing away from the measuring instrument. For alignment purposes, the alignment center of the lamp is taken to be a point in a plane that is tangent to the lamp base posts on the side of the lamp nearest the measuring instrument. This point is equidistant from the two posts and at a distance of 95 mm (3.75 in) from the base of the positive (+) post. With the optical axis intersecting the plane at the point, the plane is set perpendicular to the optical axis and to a distance of 50.0 cm from the entrance aperture of the measuring instrument.

2. Detailed Alignment

To aid in alignment, an alignment jig is used. The jig contains a glass plate mounted so that one surface of the plate falls in the plane tangent to the surfaces of the base posts on the side of the posts nearest the measuring instrument. A crosshair has been marked on the plate 9.5 cm above the positive post and equidistant between the posts (at the height of the point).

With the mirror mount in place of the averaging sphere:

(a) The alignment jig is mounted vertically and then adjusted in height and in lateral translation until the optical axis (defined by the laser beam) is centered on the crosshair.

(b) The alignment jig is then adjusted in pitch and yaw until the laser beam is reflected back on to itself. This retroreflection is best determined as far back along the optical axis as is possible, about 50 cm on FASCAL.

(c) The plane mirror mount is replaced with the averaging sphere mount and the 50.0 cm calibration distance is measured from the averaging sphere entrance aperture to the plane tangent to the near surface of the alignment jig's posts.

Note that this alignment fixes the lamp base's posts (and the lamp socket in which they are mounted) relative to the optical axis of the measuring system. This permits the interchange of these lamps without the necessity of realignment. It should also be noted that the center of the lamp filament may be several millimeters off the optical axis when the lamp is properly aligned.

(d) Iris diaphram baffles are placed between the lamp and the mirror mount and centered on the laser beam. This limits the sphere's field of view to just the lamp and the adjacent area.

(e) The spectroradiometer is moved to the next lamp position and the procedures are repeated. When all four lamp positions are aligned, partitions are placed between the lamp mounts to eliminate lamp interreflections. At a distance of 3 to 4 M behind the lamps, black velveteen cloth is draped on stanchions to minimize any back scattering.

D. LAMP OPERATION

These lamps are calibrated while operating on direct current with the designated contact, as marked on its brass identification plate, at positive potential. The exact operating current is determined for each test lamp by matching its radiant output to the average output of the working standards at 654.6 nm and then adjusting it to the nearest 0.1 A towards a match at 300 nm. Typically currents in the range of 7.8 to 8.0 A are used. Electrical measurements of a lamp's operating current are made potentiometrically to an accuracy of 0.01 %. After positioning and alignment, the lamps are slowly (30 sec) brought up to their designated electrical operating point and allowed to stabilize for at least 10 min before irradiance measurements are made.

E. LAMP SCREENING

1. Goniometric Scans

Small angular changes ($\pm 1^\circ$) in the aligned positions of these lamps can cause significant changes (greater than 1%) in their viewed output. These changes can be caused by the shadowing of one coil by another and by the non-uniformity in the lamp envelope's transmission. To check for these variations, the lamp is mounted in a cradle so that its center (a point located half the diameter of the lamp base posts towards the center of the lamp from the lamp's aligned position) is at the center of rotation of the cradle's two angular rotations: about the horizontal axis which is perpendicular to the optical axis (pitch), and about the vertical axis which is perpendicular to

the optical axis (yaw). Goniometric scans are made at 800 nm and at a distance of 50.0 cm from a 1 cm² circular entrance aperture.

The computer program used for these measurements is "JKJMAP". This program monitors the lamp's current while measurements of the lamp's output are made at 0.5° increments over ± 1.5° by ± 1.5° rotations in pitch and yaw. Measurements begin at the (0°,0°) position - the aligned position, traverse out to (+1.5°,+1.5°), measure and step in 0.5° increments over the mapping area passing through (0°,0°) and returning to (0°,0°) after the (-1.5°,-1.5°) measurement. The signals at each measured position are then normalized to the average of the three (0°,0°) measurements. The matrix representation of this data is output to a printer. Lamps exhibiting changes of more than 1% over ± 1° changes in pitch and yaw are rejected for calibration.

2. Lamp Stability

Stability measurements are made in order to determine the approximate drift rates of each lamp. The measurements are made at 654.6 and 300 nm. The computer program used to perform these measurements is "RADCAL". The program sets lamp currents, sets wavelength, positions the spectroradiometer in front of each of the sources, takes the detector readings for the lamps and a shutter position, and performs the calculations to determine the ratios of the test lamps to a stable reference lamp.

The test lamps are aligned and are allowed to operate for about one hour at an operating current of approximately 7.9 A. The reference lamp is then turned on and allowed to stabilize for 20 min. The radiometric outputs of the test lamps are then

measured at 654.6 and 300 nm relative to the output of the reference lamp. The reference lamp is then turned off and the test lamps are left on overnight. The next day the reference lamp is turned back on and the radiometric outputs of the test lamps and the reference lamp are again compared. Lamps that exhibit changes of greater than 0.5 % in output over a 24 hr period at 654.6 nm are either retested for stability or rejected for calibration.

3. Spectral Scans

Measurements are made by taking a continuous analog scan of the lamp output with 0.02 mm slit widths (0.04 to 0.08 nm bandpasses) from 250 to 800 nm at a scanning rate of 20 nm per min.

Spectral scans of early lamps of this type (quartz-halogen type DXW) revealed the frequent presence of several emission lines and an irregular shaped absorption band centered near 279 nm. The most frequently observed emission lines were attributed to the presence of the neutral atoms of sodium and aluminium, impurities apparently introduced during the manufacturing process. The emission lines appeared as doublets at 308.2 and 309.3 nm (Al) , 394.4 and 396.2 nm (Al) and 589.0 and 589.6 nm (Na). All of the emission lines were small (less than 20% above the continuum with a 0.05 nm bandpass). Occasionally other smaller emission lines (less than 5% above the continuum) were observed, but were not attributed to any specific impurity. The absorption band at 279 nm was approximately 4 nm wide and in some lamps, the peak absorption was observed to be as large as 60% of the interpolated continuum output of the lamp. This absorption

band was observed to vary with burning time. Of the approximately 400 type FEL lamps scanned to date, no absorption bands or emission lines have been detected.

F. CALIBRATION PROCEDURES

The calibration is performed on the Facility for Automatic Spectroradiometric Calibrations (FASCAL).

1. Turn On Procedure

- a. Turn on HeNe alignment laser - needs 20 min to stabilize.
- b. Turn on wavelength drive.
- c. Turn on monochromator positioning motor and set to reference.
- d. Turn on potentiometer null detector.
- e. Turn on CRT for manual interaction with MIDAS.
- f. Turn on computer CRT and printer.

2. Start Up Procedure

- a. Move sector disk out of the optical path and lock it in place.
- b. Replace the 2 mm wide slit mask with the 0.8 by 0.8 mm mask.
- c. Remove the scattered light baffles and partitions.
- d. Replace the averaging sphere mount with the mirror mount.

-- After the laser has been on for at least 20 min --

- e. Set the wavelength to 632.8 nm and position the HeNe laser at the exit slit so that it exits the monochromater centered in the 0.8 by 0.8 mm entrance slit mask.
- f. Position the spectroradiometer in front of position # 4 and install the alignment jig (see Section C - Alignment).
- g. Align position # 4 and install the iris diaphram centered on the laser defined optical axis - move to position #3.
- h. Align position # 3 ,# 2, and # 1 in turn, centering the iris baffles on the optical axis before moving to the next position.
- i. Install partitions between the lamps to eliminate lamp interreflections and position background stanchions to minimize back scattering.
- j. Turn off the laser, position the photomultiplier (PM) tube at the monochromater exit slit, and open the PM shutter.
- k. Move the specrtoradiometer to a position beyond the lamp positions where one has easy access to the fore-optics.
- l. Replace the alignment mirror mount with the averaging sphere mount and place the cowl with the 55 mm wide by 36 mm high slot over the averaging

sphere housing to minimize the scattered light entering the sphere's entrance aperture.

- m. Replace the 0.8 by 0.8 mm mask with the 2.0 mm wide mask.
- n. Insert the lamps to be calibrated into their appropriate positions.
- o. Insert the program disk into the disk drive, bring up the computer system, and load the program "IRRCAL". This program reads lamp currents, sets wavelengths, sets PM tube voltages or PbS amplifier ranges, moves the spectroradiometer and reads the system voltage outputs for each of the four lamps, and stores - wavelength, cumulative burning hours on the standard lamp, and the system voltage outputs (average full scale minus average shutter) for each of the four lamps (three tests and one standard).

3. Data Taking Procedure

- a. Turn on the lamp power supplies and slowly bring the lamps up to their operating currents by turning them all to 3 A, then 5 A, then 6.5 A, and finally to their operating currents. Record and store the computer clock 'ON TIME'. Open the standard lamp's time file and read and record the total burning hours to date for this standard.
- b. While the lamps are stabilizing (20 min), document in the data book pertinent information such as run

identification number (Block # - see Appendix D),
the lamps being run, the positions in which the
lamps are mounted, and the lamp operating currents.

- c. Check to see if the 'system shutter' agrees with
the 'true shutter' (footnote 1). This is done
biweekly and at ultraviolet (250 nm), visible
(654.6 nm), and infrared (1300 nm) wavelengths.
- d. Calibrate the DVM versus the potentiometer to
insure accurate lamp current readings.
- e. Measurement Sequence

Move to position # 4
*

Set lamp currents - Read lamp voltages

I

Read data file

- wavelength
- PM tube voltage or PbS amplifier range
- # samples per match
- # matches
- acceptable precision (3σ precisions ranging

from 0.4 % at 250 nm to 0.1 % at 654.6 nm to 0.3 % at 1700 nm to
1.0 % at 2400 nm)

II

Set wavelength

Set PM tube voltage or PbS amplifier range/phase
amplifier

Read/set lamp currents

Wait - 3 sec, 10 sec if the PM tube voltage is changed
more than 50 V.

III

Read/set lamp currents

Move/read

- shutter
- position # 4 \
- position # 3 \ repeat (# matches
- position # 2 / times)
- position # 1 /
- shutter

Move to position # 4

Read/record computer clock time

Print results

- wavelength
- position # 1 through # 4
 - average full scale reading minus average shutter
 - standard deviation of the full scale matches

IV

Option - If any standard deviation of the full scale matches is greater than the 'acceptable precision' then you can repeat Part III or you can continue to Part V.

V

Store data

- wavelength
- cumulative burning hours on the standard lamp

- position # 1 through # 4
 - average full scale readings minus average shutter

VI

Go to Part I unless

- last PM data point
 - set lamp currents / read lamp voltages
 - shutter PM tube
 - position PbS cell at spectroradiometer exit slit
 - position and activate sector disk
 - go to Part I
- last PbS data point
 - set lamp currents / read lamp voltages
 - turn down lamps slowly (set 6.5, 5.0, 3.0, 0.0 A)
 - turn off lamps. Run time added to standard lamp time file.
 - if it is the end of the day then turn off equipment (See - Turn on Procedures - Section F.1.), otherwise turn on the laser, wait 20 min, remove lamps, and go to Section F.2.a.

4. Data Reduction

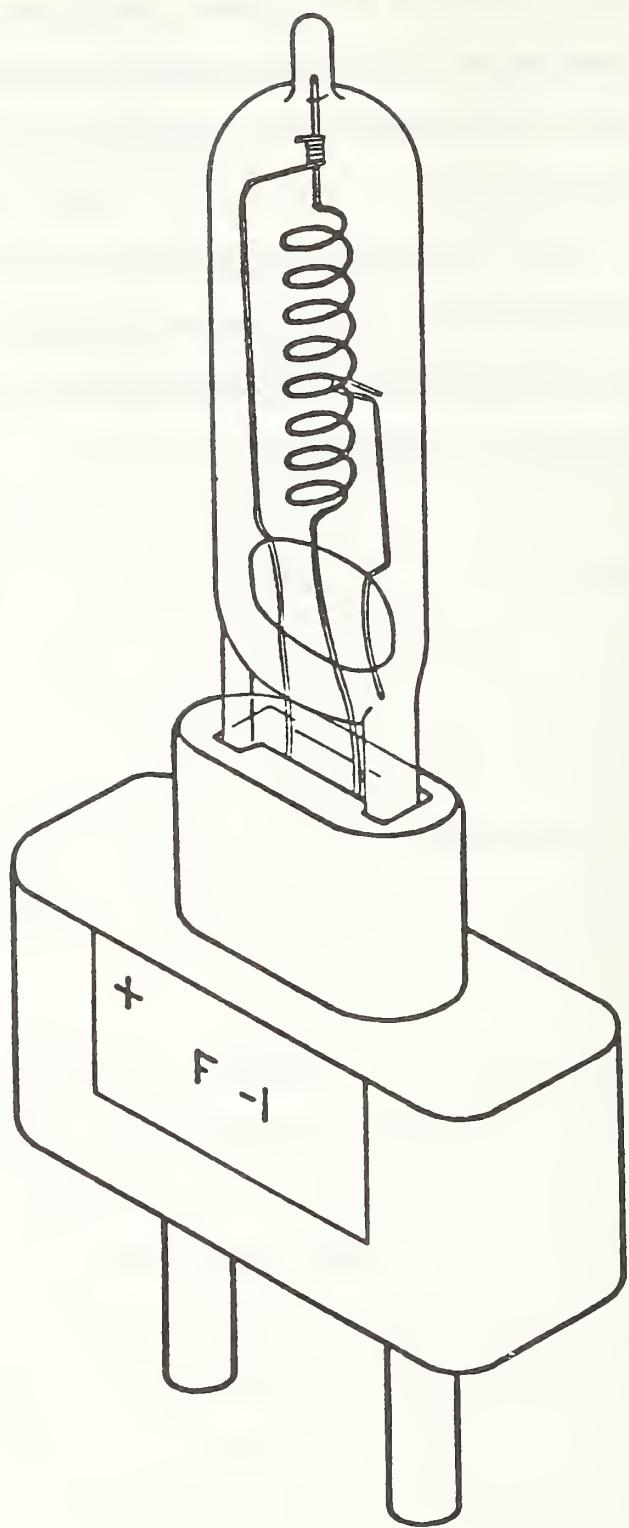
The initial data reduction program used is "IRREDR". This program first calculates the standard lamp's spectral irradiance by applying a time-dependent drift equation (determined from the

time drift history of the standard lamp - see Main Text section VIII). Then the spectral irradiance of the test lamps is determined by applying Equation (14) from section IX.C of the Main Text.

Since the output from the averaging sphere is homogeneous and nonpolarized, each lamp is viewed by the system as virtually identical. Because of this, the measurement is a 'null comparison' and the systematic corrections tend to cancel out. One variation to take into account is the lamp position. The background, the area viewed by the sphere in addition to the lamp, is different in each of the lamp positions. The difference in the assignments to each test lamp in each position is under statistical control. To date, these errors have been small relative to the transfer precisions and corrections have not been necessary. See Appendix D (Data Reduction and Quality Control).

Footnote 1. - The 'system shutter' is taken after a 12 cm translational movement of the spectroradiometer is made from the aligned position in position # 4. This results in the averaging sphere viewing the blackened back side of the position # 4 iris diaphragm baffle. The signal taken in this position, relative to the full scale reading, is compared to the signals obtained when the spectroradiometer is aligned in each of the four lamp positions and (i) that position's iris diaphragm is blocked - eliminating all direct radiation from reaching the averaging sphere entrance aperture and (ii) a 'stray light' measurement where a black rod (the same diameter as the lamp) is placed half

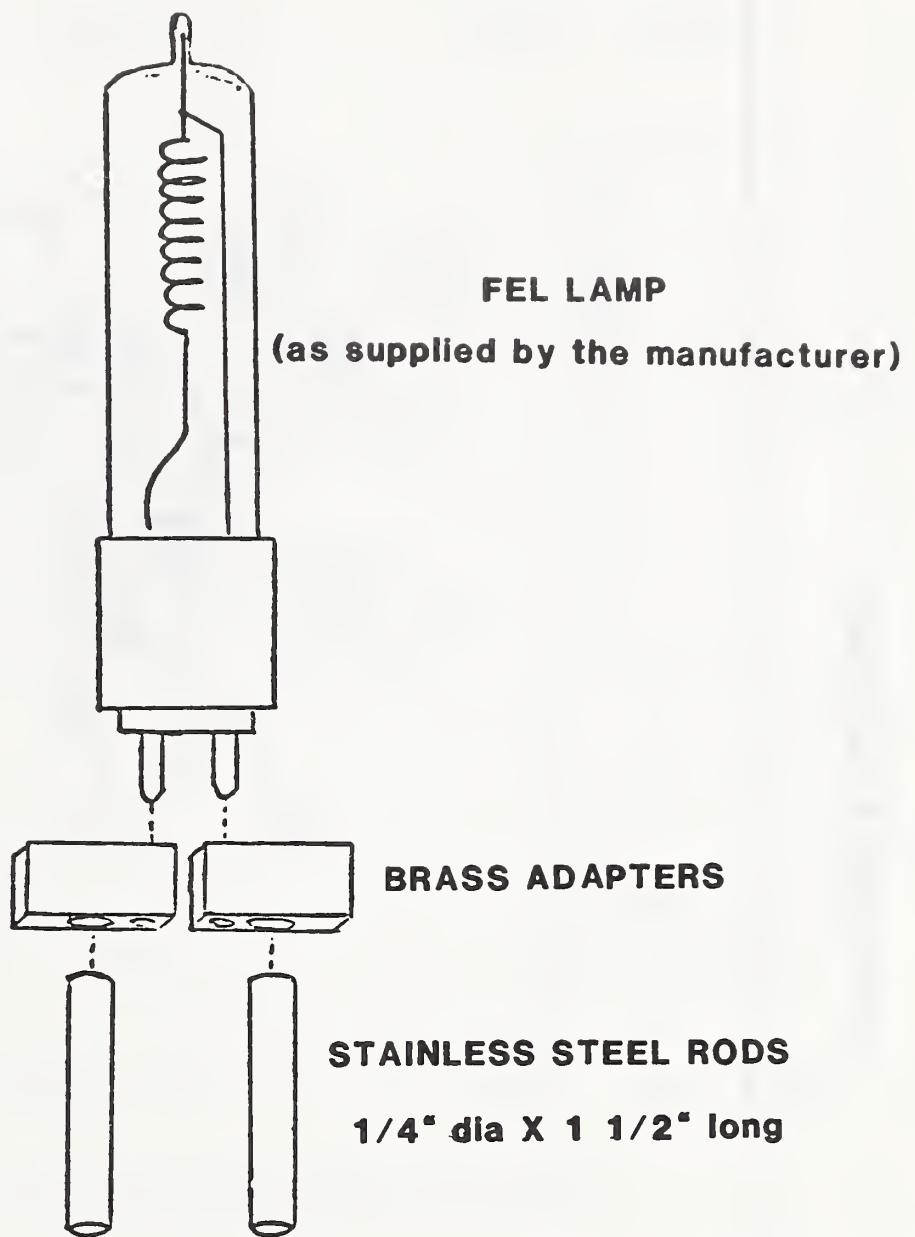
way between the lamp and the sphere entrance aperture - blocking all direct radiation from the lamp from reaching the averaging sphere aperture. The difference between the 'system shutter' and the 'blocking shutter' is negligible (well within our ability to measure at these levels), however, if the 'stray light' measurement differs from the 'system shutter', the source of the stray light is located and the appropriate shielding/baffling is added to minimize this effect.



MODIFIED TYPE FEL

FIGURE C-1

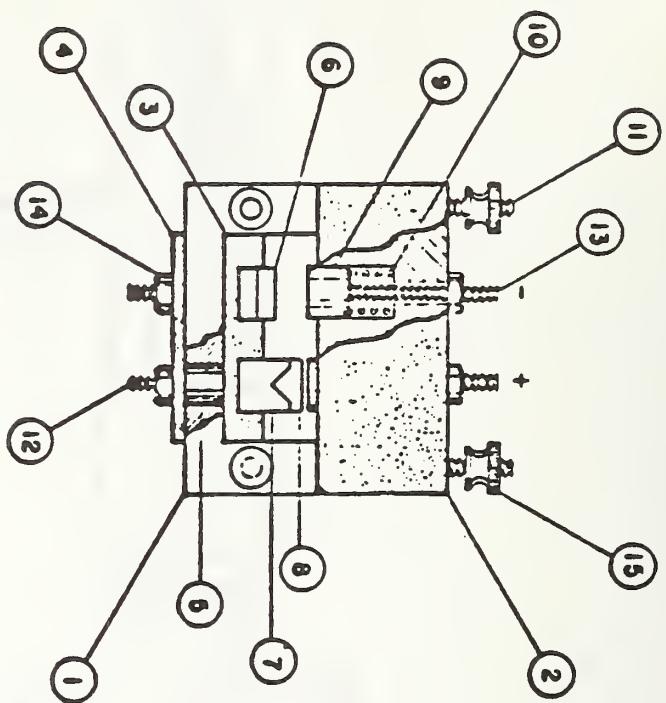
C-16



FEL MODIFICATION

FIGURE C-2

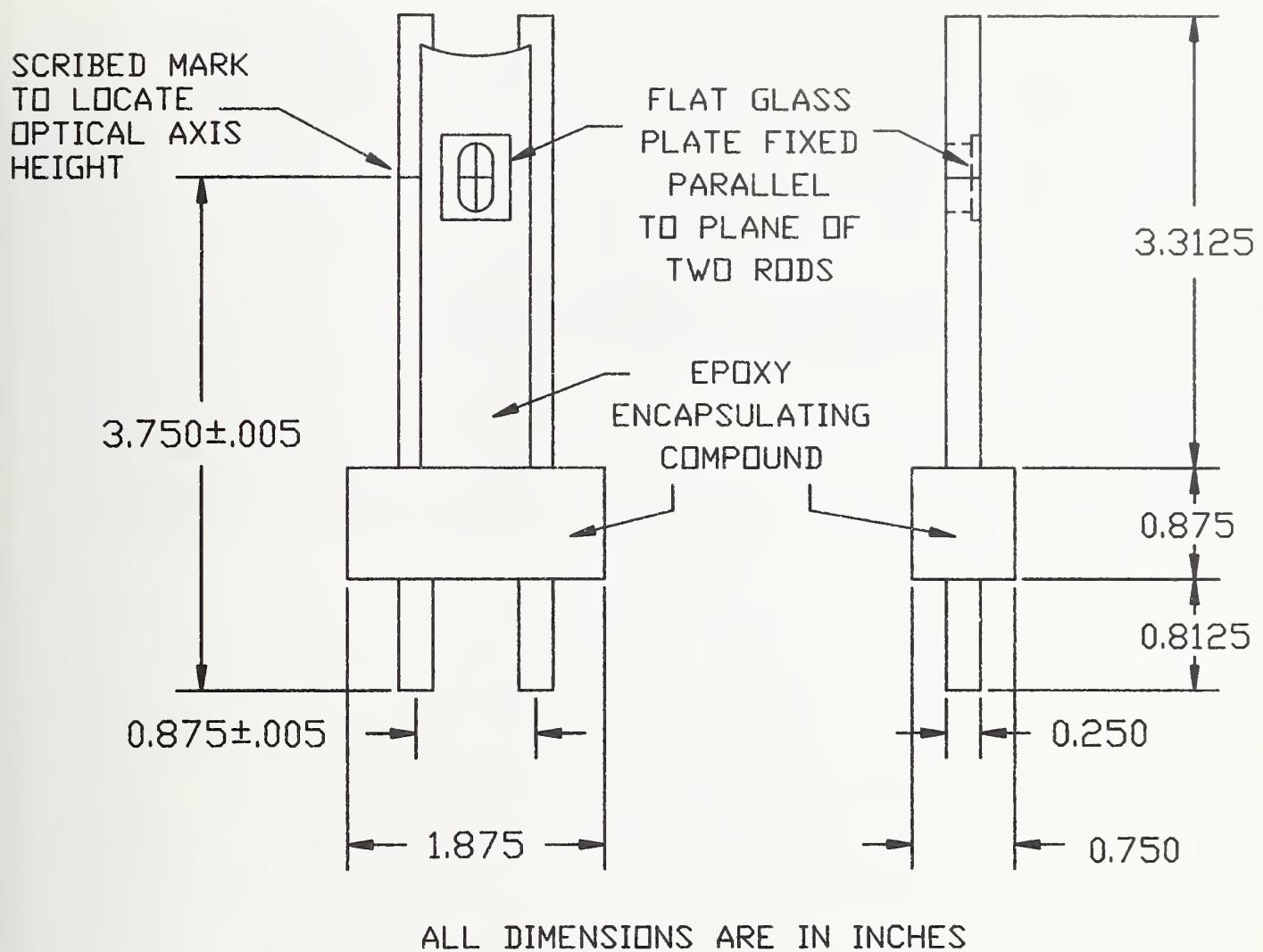
KINEMATIC LAMP MOUNT



NATIONAL BUREAU OF STANDARDS WASHINGTON, D. C. 20234	
ITEM	DESCRIPTION
MODEL	TYPE SCALE
Dimensions in inches	described
1. Dimensions	described
2. Materials	described
3. Surface treatment	described
4. Mounting dimensions	described
5. Weight	described
6. Dimensions	described
7. Weight	described
8. Dimensions	described
9. Weight	described
10. Dimensions	described
11. Weight	described
12. Dimensions	described
13. Weight	described
14. Dimensions	described
15. Weight	described
16. Dimensions	described
17. Weight	described
18. Dimensions	described
19. Weight	described
20. Dimensions	described
21. Weight	described
22. Dimensions	described
23. Weight	described
24. Dimensions	described
25. Weight	described
26. Dimensions	described
27. Weight	described
28. Dimensions	described
29. Weight	described
30. Dimensions	described
31. Weight	described
32. Dimensions	described
33. Weight	described
34. Dimensions	described
35. Weight	described
36. Dimensions	described
37. Weight	described
38. Dimensions	described
39. Weight	described
40. Dimensions	described
41. Weight	described
42. Dimensions	described
43. Weight	described
44. Dimensions	described
45. Weight	described
46. Dimensions	described
47. Weight	described
48. Dimensions	described
49. Weight	described
50. Dimensions	described
51. Weight	described
52. Dimensions	described
53. Weight	described
54. Dimensions	described
55. Weight	described
56. Dimensions	described
57. Weight	described
58. Dimensions	described
59. Weight	described
60. Dimensions	described
61. Weight	described
62. Dimensions	described
63. Weight	described
64. Dimensions	described
65. Weight	described
66. Dimensions	described
67. Weight	described
68. Dimensions	described
69. Weight	described
70. Dimensions	described
71. Weight	described
72. Dimensions	described
73. Weight	described
74. Dimensions	described
75. Weight	described
76. Dimensions	described
77. Weight	described
78. Dimensions	described
79. Weight	described
80. Dimensions	described
81. Weight	described
82. Dimensions	described
83. Weight	described
84. Dimensions	described
85. Weight	described
86. Dimensions	described
87. Weight	described
88. Dimensions	described
89. Weight	described
90. Dimensions	described
91. Weight	described
92. Dimensions	described
93. Weight	described
94. Dimensions	described
95. Weight	described
96. Dimensions	described
97. Weight	described
98. Dimensions	described
99. Weight	described
100. Dimensions	described
101. Weight	described
102. Dimensions	described
103. Weight	described
104. Dimensions	described
105. Weight	described
106. Dimensions	described
107. Weight	described
108. Dimensions	described
109. Weight	described
110. Dimensions	described
111. Weight	described
112. Dimensions	described
113. Weight	described
114. Dimensions	described
115. Weight	described

FRONT VIEW

SIDE VIEW



ALIGNMENT JIG

FIGURE C-4

APPENDIX D

DATA REDUCTION AND QUALITY CONTROL

TABLE OF CONTENTS - APPENDIX D

	Page
A. Data Reduction.....	D-1
B. Quality Control.....	D-4

APPENDIX D

Data Reduction and Quality Control

A. Data Reduction

Test lamps are measured in groups of 12 in a statistically designed experiment against the four primary working standards (E_1 through E_4) which embody the NBS scale of spectral irradiance. For routine spectral irradiance calibrations, FASCAL is configured with four measuring positions, denoted P_1 through P_4 . A complete calibration of a group of test lamps (denoted T_1 through T_{12}) is performed in 16 measurement blocks, each block consisting of three test lamps and one standard lamp. Each block includes a comparison of the test and standard lamps at each of the 31 wavelengths at which values are reported. Table D-1 indicates the positions occupied by the standard and test lamps for each of the 16 blocks. Note that each test lamp is measured four times and that it is measured once against each of the primary working standards and once in each of the four measuring positions.

In analyzing the data from the calibration of a group of twelve test lamps, measured spectral irradiances for each test lamp are first computed according to the equation:

$$E_\lambda(TL) = f * (S_{TL}/S_{PWS}) * E_\lambda(PWS) \quad (1)$$

where:

$E_\lambda(TL)$ is the measured spectral irradiance of a test lamp,
 f is the linearity-range factor correction,

S_{TL}/S_{PWS} is the signal ratio of the test lamp-primary working standard comparison, and

$E_\lambda(PWS)$ is the assigned spectral irradiance of the primary working standard.

This equation is the same as Equation (14), Section IX of the main text. The assigned spectral irradiances of the primary working standard lamps, $E_\lambda(PWS)$, are corrected for drift according to Equation (10), Section VIII, before the computations indicated above are performed. Each block shown in Table D-1 yields three such equations at each of the 31 wavelengths of calibration. Thus the total experiment yields 48 measured spectral irradiances for test lamps at each wavelength.

In order to analyze the data to determine if systematic effects due to the particular standards used (departures from its assigned spectral irradiance) or due to the specific positions the lamps occupied during the measurements are present, a mathematical model of the experiment as a whole has been formulated. Each of the measured spectral irradiances is assumed to have resulted from an equation of the form:

$$E_\lambda(\text{TL-Measured}) = E_\lambda(\text{TL}) + Ax_1 + Bx_2 + Cx_3 + Dy_1 + Ey_2 + Fy_3 \quad (2)$$

where:

$E_\lambda(\text{TL})$ is the spectral irradiance due to the test lamp,
A, B, and C are coefficients that designate which standard lamp
is being used,

x_1 , x_2 , and x_3 are independent variables equal to the difference in measurements against standards E_2 and E_1 ($E_2 - E_1$), E_3 and E_1 ($E_3 - E_1$), and E_4 and E_1 ($E_4 - E_1$) respectively, D , E , and F are coefficients that designate which measuring position the test lamp is occupying, and y_1 , y_2 , and y_3 are independent variables equal to the difference in measurements made with the lamp in positions P_2 and P_1 ($P_2 - P_1$), P_3 and P_1 ($P_3 - P_1$), and P_4 and P_1 ($P_4 - P_1$) respectively.

As shown in Table D-2A, coefficient A assumes a value of +1 if standard lamp E_2 is being used, 0 if standard lamps E_3 or E_4 are being used, or -1 if standard lamp E_1 is being used. Similarly, coefficients B and C assume values of +1, 0, or -1 depending on the standard lamp in use. The position coefficients, D , E , and F , similarly assume values of +1, 0, or -1, depending on the position of the test lamp, as shown in Table D-2B. Note that the standard lamp coefficients are introduced as a difference between the given standard and one of the group taken as reference, E_1 . This procedure is equivalent to taking the mean of the four standards as the reference [$E_1 - E_{ave} = -(x_1 + x_2 + x_3)/4$]. This procedure is necessary, because in the self-contained experiment of the transfer calibration of test lamps against the primary working standards, there is no information or guarantee that all the working standards are not misassigned. Only differences between their assignments can be detected. Mathematically, it is necessary to avoid attempting to work with an indeterminant set

of equations. Similar arguments apply for the position coefficients.

Applying this model to the set of measurements shown in Table D-1 gives a set of 48 equations in 18 unknowns -- the spectral irradiances of the twelve test lamps, the three standard lamp coefficients, and the three position coefficients. At each of the 31 wavelengths for which values are measured, the 48 simultaneous equations are solved by least squares methods. The results of this fitting process give the best value of spectral irradiance for each test lamp (equal to the mean of the four measured values -- a feature of the design shown in Table D-1), an estimate of the precision of transfer (the standard deviation of the spectral irradiance coefficients), an estimate of the consistency of the four primary working standards, and an estimate of any effects associated with the measuring positions. The estimate of the precision of transfer is entered into the uncertainty estimate for a test lamp at the 3σ level for the mean of the four measurements (line III-b of Table V, in the main document).

B. Quality Control

The statistical information obtained from the least squares fitting process is the key tool in the quality control of the measurement process. An assumption of this form of data analysis is that all parameters, spectral irradiance of the test and standard lamps, position effects, standard lamp effects, equipment sensitivity, alignment procedures, etc., are constant over the course of the measurements. The validity of this

assumption can be assessed from an examination of the residuals of the least squares fits with statistical tests for randomness. Although occasionally a block has shown unacceptable residuals, repeat measurements of this specific block have always brought the data into agreement. Presumably the occasional observance of a large residual is due to a miss set alignment or electrical operating point for the test lamp.

A further assumption of this form of data analysis is that the test lamps form a homogeneous population, i.e., the variability (standard deviation) is a uniform characteristic of the group as a whole, not of an individual lamp. Again the randomness of the residuals of the least squares fits demonstrates the validity of this assumption.

The standard lamp coefficients are essentially a measure of the departure of the primary working standards from their assigned drift equations. In the course of using the primary working standards it is usual to observe a gradual deterioration of the agreement among the four standards. When the range of the disagreement reaches about 75% of the uncertainty with respect to the estimated NBS long term reproducibility, a primary recalibration of the working standards is indicated. In the meantime, it lends confidence to the measurements that the standards agree to the sub 1% level when they are drifting at vastly different rates as shown in Table D-3.

The position coefficients are essentially a measure of the differing stray light conditions at the four measuring positions. In the data taken to date, the position coefficients have never

exceeded 0.4% and only rarely are they statistically significant. Introduction of these coefficients in the additive form given in Equation 2 assumes that the source of stray light is independent from the lamp being measured. An equally plausible assumption would be that the source of the stray light is the lamp itself, i.e. unwanted reflections from the lamp surrounds are reaching the measuring instrument. In this case the stray radiation would presumably be proportional to the spectral irradiance of the lamp. It can be shown that the additive model used is an adequate approximation to the proportional case if the stray radiation effects are small. As noted above, the effects observed are small and the additive model is therefore believed to be adequate.

One further quality control technique is used in these measurements. It has been noted that test lamps are measured in groups of 12. Usually two of these test lamps are in-house "check standards". These check standards serve two functions. First, since they are measured repeatedly and thus have a history that can be compared with the present measurements, they insure that the computer controlled measurements, data acquisition, and data reduction are continuing to function properly. They also guard against certain forms of gross error, for instance a reversal of the electrical operating polarity of the standard lamps would produce about a 4% shift in their values in the visible and would readily be detected as an anomaly in the measured value of the check lamps. The second major function of the check standards is to act as backups to the primary working standards. Since their history and drift behavior are well

established, they can replace a primary working standard should one burn out or become unstable. The alternative, an emergency primary calibration of a new lamp, would cause unacceptable delays to the ongoing calibration program.

Table D-1

Measurement Design for Type FEL Spectral Irradiance Standards

Block	Position			
	P ₁	P ₂	P ₃	P ₄
1	E-1	T-1	T-2	T-3
2	T-4	E-1	T-5	T-6
3	T-7	T-8	E-1	T-9
4	T-10	T-11	T-12	E-1
5	E-2	T-4	T-7	T-10
6	T-1	E-2	T-8	T-11
7	T-2	T-5	E-2	T-12
8	T-3	T-6	T-9	E-2
9	E-3	T-12	T-6	T-8
10	T-9	E-3	T-10	T-2
11	T-11	T-3	E-3	T-4
12	T-5	T-7	T-1	E-3
13	E-4	T-9	T-11	T-5
14	T-12	E-4	T-3	T-7
15	T-6	T-10	E-4	T-1
16	T-8	T-2	T-4	E-4

Table D-2A
Standard Lamp Coefficients

Standard Lamp	A	B	C
E_1	-1	-1	-1
E_2	1	0	0
E_3	0	1	0
E_4	0	0	1

Table D-2B
Position Coefficients

Position (Test Lamp)	D	E	F
P_1	-1	-1	-1
P_2	1	0	0
P_3	0	1	0
P_4	0	0	1

Table D-3
Standard Lamp Drift Rates
 (Percent change per 100 burning hours)

Wavelength (nm)	Lamp			
	1	2	3	4
250	0.5	4.3	4.0	4.8
350	0.45	3.4	2.9	3.35
450	0.4	2.9	2.3	2.55
555	0.4	2.55	1.9	2.0
654.6	0.4	2.35	1.6	1.65
800	0.4	2.1	1.35	1.3
1300	0.35	1.7	0.8	0.65
1600	0.35	1.6	0.75	0.5

APPENDIX E

DEUTERIUM LAMP STANDARDS OF SPECTRAL IRRADIANCE - 1986

TABLE OF CONTENTS - APPENDIX E

	Page
A. Material.....	E-1
B. Method of Calibration.....	E-1
C. Lamp Orientation and Operation.....	E-2
D. Uncertainty.....	E-4
References.....	E-6

Appendix E

Deuterium Lamp Standards of Spectral Irradiance

1986

A. Material

Modified, commercially available deuterium lamps as shown in Figure E-1 are supplied by NBS for this calibration. Each lamp has been seasoned for 100 hours at 300 mA dc. The lamp is oriented so that changes of $\pm 1^\circ$ about this aligned position yield a minimum change in its radiation field at 250 nm (see paragraph C below). The lamp is then potted in a medium bipost base.

B. Method of Calibration

The deuterium lamps are calibrated on the Facility for Automated Spectroradiometric Calibrations (FASCAL) [1]. Spectral irradiance measurements are made at 10 nm intervals from 200 nm to 350 nm. For the spectral region from 250 nm to 350 nm, modified type FEL quartz-halogen lamps are used as transfer standards. Primary working standards E3 and E4 [1] and special working standards WS-13 and WS-14 are used. For the spectral region from 200 nm to 240 nm, deuterium lamp working standards D1339, D1345, D1347 and, D1373 are used. The relative spectral distribution of the flux from these deuterium lamp working standards has been assigned from transfer measurements based on the NBS spectral irradiance scale for the vacuum ultraviolet [2]. For each calibration run, the relative spectral distribution curve of the deuterium lamp working standards is normalized to the type FEL standards at 250 nm and these normalized values are

transferred to the test lamps. Test lamps are measured in groups of twelve against all eight of the working standards over a period eight days. Normally at least two check standards (lamps that have been previously measured, but are treated as unknown test lamps in the data reduction) are included in the group of test lamps.

C. Lamp Orientation and Operation

Deuterium lamp standards are mounted vertically with the base down and orientated so that the optical axis of the spectroradiometer passes perpendicularly through a plane defined by the front surfaces of the lamp base posts. Orientation of this plane is set in pitch and yaw to within $\pm 0.1^\circ$. The optical axis also passes midway between the posts and 9.5 cm above the bottom of the posts. The defined plane is set 50.0 cm from the entrance aperture of the spectroradiometer. Typically the radiation field varies 2% or less for rotations of $\pm 1^\circ$ from the aligned position.

The electrical circuit for operating the deuterium lamp is shown in Figure E-2. The heater filament power is supplied by a dc power supply (10 V, 1.2 A). The blue-tipped white lead from the lamp is connected to the positive terminal of the filament power supply and the black-tipped white lead is connected to the negative terminal. The main dc power supply is a 500 V, 300 mA constant current power supply (0.1% current regulation preferred). Because most power supplies cannot react fast enough to maintain a constant arc, a ballast resistor (1000 Ω , 100 W) is recommended in the positive lead from the power supply to the

lamp anode (red-tipped white lead). A current measuring instrument is connected in series with the cathode of the lamp (black-tipped white lead) and the negative or ground side of the main power supply.

In order to start the lamp, the filament is first heated for 10-60 seconds at 10 V. The 500 V is then applied to the lamp - striking the arc. If the lamp is of the type L 1128 (issued by NBS prior to 1986), the heater supply should then be turned off. If the lamp is of the type L 1627, then the heater voltage should be reduced to 7.0 ± 0.5 V and left on. The lamp should be allowed to stabilize for 15 to 20 minutes before spectral irradiance measurement are made. If the lamp is turned off, it should be allowed to cool back to room temperature (25°C) before restarting.

The lamp should be operated in a relatively open region that allows for normal air circulation. A confined region, such as a lamp housing, may change the cooling patterns and hence the gas pressure of the arc. This in turn will affect the calibration (flux output) of the lamp. The same precaution applies to forced air cooling of the lamp. Ozone production within a confined region could also be a problem. One can check for the presence of ozone by fanning the air in front of the lamp and observing if the measured output at 250 nm increases. Temperature coefficients are not measured for individual lamps. However, it has been observed that for lamps of this type, changes of a few degrees from room temperature (25°C) introduce changes in the flux output of less than 1%.

D. Uncertainty

The uncertainty of the quartz-halogen spectral irradiance standards [1] and the vacuum ultraviolet spectral irradiance scale [2,3] have been documented in the references cited. The uncertainty of the transfer measurements described here is dominated by the variability of the test deuterium lamps. About half of the tested deuterium lamps exhibit a standard deviation of a single measurement of about 1% at all wavelengths. The other half are more variable, with the worst having a standard deviation of a single measurement of 5% with some indication of a bistable behavior. In order to allow for the worst case situation, the uncertainty of the transfer calibration is taken to be 4.5% (three times the standard deviation of the mean of four measurements on a lamp having a standard deviation of a single measurement of 5%). Table E-1 summarizes these uncertainties.

Occasionally deuterium lamps have been observed to shift by as much as 25% after storage for two to three months. Therefore it is strongly recommended that deuterium lamp standards be compared to a modified type FEL quartz-halogen standard over the spectral range 250 nm to 300 nm each time the deuterium lamp is used. The interchangeability of these standards (same base, orientation, and calibration distance) makes it convenient to perform such a comparison.

Although deuterium lamps occasionally exhibit bistable behavior and/or discrete shifts in the absolute level of their output, the relative spectral distribution of their output has remained constant to about 1%. It has been estimated [2,3] that the uncertainty in the relative spectral irradiance distribution (the ratio of the spectral irradiance at any two wavelengths in the region 200 nm to 350 nm) is 1% plus 0.02% times the nm difference between the two wavelengths.

References

1. Walker, J. H., Saunders, R. D., Jackson, J. K., and McSparron, D. A., Spectral Irradiance Calibrations at NBS, NBS Special Publication 250-20 (This document)
2. Klose, J. Z., and Bridges, J. M., Radiometric Calibrations of Portable Sources in the Vacuum Ultraviolet, NBS Special Publication 250-3.
3. Saunders, R. D., Ott, W. R., and Bridges, J. M., Spectral Irradiance Standard for the Ultraviolet: the Deuterium Lamp, Appl.Opt. 17, pp. 593-600, Feb. 15, 1978.

Table E-1
Deuterium Lamp Uncertainty Estimates (3σ)

	Wavelength			
	200 nm	210 nm	250 nm	350 nm
Vacuum Ultraviolet E_λ Scale	6%	6%	-----	-----
Quartz-Halogen* E_λ Scale	-----	-----	1.5%	1.1%
Transfer Calibration of a Test Lamp	4.5%	4.5%	4.5%	4.5%
Total Uncertainty (Quadrature Combination)	7.5%	7.5%	5%	5%

* Values taken from Table IV, in the main document.

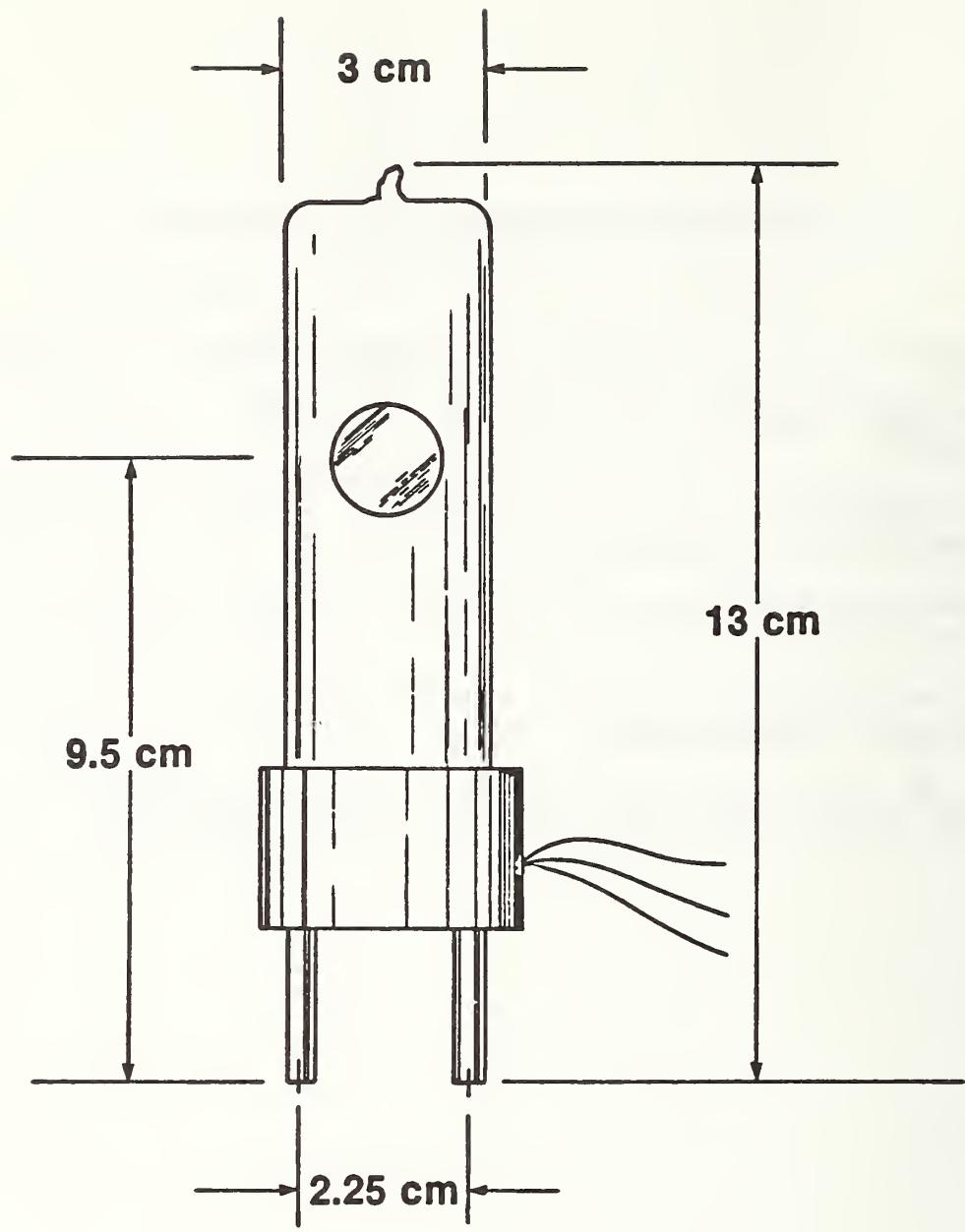


FIGURE E-1 DEUTERIUM LAMP STANDARD

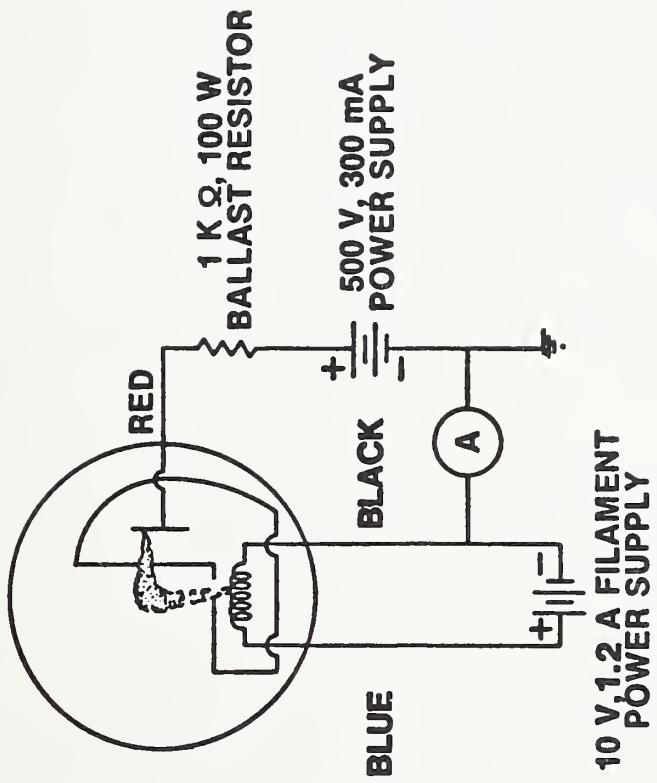


FIGURE E-2 ELECTRICAL CIRCUIT FOR
OPERATING DEUTERIUM LAMPS - 1986
Type L 1627

APPENDIX F

SPECTRAL IRRADIANCE

DEUTERIUM LAMP

REPORT OF CALIBRATION

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

Gaithersburg, MD 20899

REPORT OF CALIBRATION

off

One Deuterium Lamp Standard of Spectral Irradiance

Supplied to:

1. Material

One deuterium lamp potted in a black anodized medium bipost base has been supplied by the National Bureau of Standards for this calibration. The lamp designation RA-000 is painted on the ceramic insulator located on the side of the lamp anode shield.

2. Calibration

The lamp was calibrated using the equipment and procedures described in Appendix E of the enclosed NBS Special Publication 250-20, "Spectral Irradiance Calibrations at NBS", Walker, J. H., Saunders, R. D., Jackson, J. K., and McSparron, D. A., (1987). Note particularly paragraph C of this appendix which describes the orientation and operation of a test lamp.

3. Results

The results of this test are given in the attached Table 1. See also paragraph D of Appendix E for a discussion of the uncertainty of the reported values.

Prepared by:

Approved by:

John K. Jackson
Radiometric Physics Division
Center for Radiation Research

Donald A. McSparron
Radiometric Physics Division
Center for Radiation Research

NBS Test No.: 534/

Date:

Page 1 of 2

REPORT OF CALIBRATION

TABLE 1

Spectral Irradiance (W/cm^3) at 50.0 cm from Lamp RA-000 for a current of 300 mA dc when operated as described in paragraph C in Appendix E of the enclosed NBS Special Publication 250-20.

Wavelength (nm)	Lamp No. RA-000 (W/cm^3)
200	0.490
210	0.470
220	0.450
230	0.420
240	0.390
250	0.330
260	0.280
270	0.240
280	0.200
290	0.170
300	0.150
310	0.130
320	0.110
330	0.100
340	0.080
350	0.070

NBS Test No.: 534/
Date:

Page 2 of 2

<p>U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)</p>				1. PUBLICATION OR REPORT NO. NBS/SP-250/20	2. Performing Organ. Report No.	3. Publication Date September 1987
<p>4. TITLE AND SUBTITLE NBS Measurement Services: Spectral Irradiance Calibrations</p>						
<p>5. AUTHOR(S) J. H. Walker, R. D. Saunders, J. K. Jackson, D. A. McSparron</p>						
<p>6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions) NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE Gaithersburg, MD 20899</p>				7. Contract/Grant No. 8. Type of Report & Period Covered Final		
<p>9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)</p>						
<p>SAME</p>						
<p>10. SUPPLEMENTARY NOTES</p> <p>Library of Congress Catalog Card Number: 87-619862</p> <p><input type="checkbox"/> Document describes a computer program; SF-185, FIPS Software Summary, is attached.</p>						
<p>11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)</p> <p>This report describes the measurement methods and instrumentation used in realization and transfer of the NBS scale of spectral irradiance. The basic measurement equation for the irradiance realization is derived. The spectral responsivity function, linearity of response, and "size of source effect" of the spectroradiometer are described. The analysis of sources of error and estimates of uncertainty are described. The assigned uncertainties (3-sigma level) in spectral irradiance range from 2.2% at 250 nm to 1.0% at 654.6 nm to 6.5% at 2400 nm.</p>						
<p>12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)</p> <p>blackbody; calibrations; radiometry; response linearity; slit-scattering function; spectral irradiance; standards</p>						
<p>13. AVAILABILITY</p> <p><input checked="" type="checkbox"/> Unlimited <input type="checkbox"/> For Official Distribution. Do Not Release to NTIS <input checked="" type="checkbox"/> Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. <input type="checkbox"/> Order From National Technical Information Service (NTIS), Springfield, VA. 22161</p>				14. NO. OF PRINTED PAGES 102 15. Price		

PUBLICATIONS IN THE SP 250 SERIES ON NBS MEASUREMENT SERVICES

- SP 250-1 Spectral Radiance Calibrations
J. H. Walker, R. D. Saunders, and
A. T. Hattenburg
- SP 250-2 Far Ultraviolet Detector Standards
L. R. Canfield and N. Swanson
- SP 250-3 Radiometric Standards in the Vacuum
Ultraviolet
J. Z. Klose and J. M. Bridges
- SP 250-4 Fricke Dosimetry in High-Energy
Electron Beams
C. G. Soares, E. L. Bright, and M. Ehrlich
- SP 250-5 Alpha-Particle Calibrations
J. M. R. Hutchinson
- SP 250-6 Regular Spectral Transmittance
K. L. Eckerle, J. J. Hsia, K. D. Mielenz,
and V. R. Weldner
- SP 250-7 Radiance Temperature Calibrations
W. R. Waters, J. H. Walker, and
A. T. Hattenburg
- SP 250-8 Spectral Reflectance
V. R. Weldner and J. J. Hsia
- SP 250-9 Calibration of Beta-Particle-Emitting
Ophthalmic Applicators
J. S. Pruitt
- SP 250-10 Radioactivity Calibrations with the "4π"
Gamma Ionization Chamber, and Other
Radioactivity Calibration Capabilities
J. M. Calhoun
- SP 250-11 Dosimetry for High-Dose Applications
J. C. Humphreys, D. Hocken, and
W. L. McLaughlin
- SP 250-12 Neutron Personnel Dosimetry
R. B. Schwartz
- SP 250-13 Activation Foil Irradiation with Californium
Fission Sources
G. P. Lamaze and J. A. Grundl
- SP 250-14 Activation Foil Irradiation by Reactor Cavity
Fission Sources
G. P. Lamaze and J. A. Grundl
- SP 250-15 Photometric Calibrations
R. L. Booker and D. A. McSparron
- SP 250-16 Calibration of X-Ray and Gamma-Ray
Measuring Instruments
P. J. Lampertl, T. P. Loftus, and R. Loevinger
- SP 250-17 The NBS Photodetector Spectral Response
Calibration Transfer Program
E. F. Zalewski
- SP 250-18 Neutron Source Strength Calibrations
E. D. McGarry and E. W. Boswell
- SP 250-19 Calibration of Gamma-Ray-Emitting
Brachytherapy Sources
J. T. Weaver, T. P. Loftus, and R. Loevinger
- SP 250-20 Spectral Irradiance Calibrations
J. H. Walker, R. D. Saunders, J. K. Jackson,
and D. A. McSparron
- SP 250-21 Calibration of Beta-Particle
Radiation Instrumentation
M. Ehrlich, J. S. Pruitt, and C. G. Soares
- SP 250-22 Platinum Resistance Thermometer
Calibrations
B. W. Mangum
- SP 250-23 Liquid-in-Glass Thermometer
Calibration Service
J. A. Wise
- SP 250-24 Standard Cell Calibrations
B. Field
- SP 250-25 Calibration Service for Inductive
Voltage Dividers
A. O. McCoubrey

U.S. Department of Commerce
National Bureau of Standards
Gaithersburg, MD 20899

Official Business
Penalty for Private Use \$300