NBS MEASUREMENT SERVICES: PHOTOMETRIC CALIBRATIONS

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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 250-15), NBS Measurement Services: Photometric Calibrations, by R. L. Booker and D. A. McSparron, is the fifteenth to be published in this new series of special publications. It covers the calibration of standards of luminous intensity, luminous flux, and color temperature (see test numbers 37010C-37160C 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

The National Bureau of Standards supplies calibrated standards of luminous intensity, luminous flux, and color temperature on a routine basis. The procedures, equipment, and techniques used to perform these calibrations as of July 1986 are described. Detailed estimates and procedures for determining uncertainties of the reported values are also presented.

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

TABLE OF CONTENTS

Appendix A - Detailed Procedures for a Luminous Intensity Calibration

TABLE OF CONTENTS (continued)

Appendix B - Detailed Procedures for a Routine Luminous Flux Calibration

TABLE OF CONTENTS (continued)

Appendix C - Detailed Procedures for a Routine Color Temperature Calibration

TABLE OF CONTENTS (continued)

Page

Appendix D - Reports of Calibration

Page

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Photometric calibration facilities at NBS were most recently described in 1972 [1]. The present document updates the 1972 Technical Note, particularly in the area of uncertainty estimates. Throughout this document uncertainties are estimated at the 3σ level. The specific calibrations described in this document are luminous intensity [candela], luminous flux [lumen] and color temperature [Kelvin]. These quantities are defined later in sections 1.3 and 4.1

Brief descriptions and prices for the individual standards and calibrations are listed in NBS Special Publication 250 [2] and its appendices (published semi-annually). Luminous intensity standards are listed in the SP 250 Appendix as items 37010C through 37070C (formerly items 7.7B through 7.7H), luminous flux standards as items 37080C through 37130C (formerly items 7.7I through 7.7M and item 7.72Q) and the color temperature standards as items 37140C through 37160C (formerly items 7.7N through 7.7P). Lamps are often calibrated for luminous intensity or luminous flux while operating at a specified color temperature. Operation at 2856 K (CIE* Source A) [3] is most often requested.

The material presented in this technical note is a description of photometric calibration facilities and procedures as they existed in July, 1986. Both the photometric bench and the color temperature apparatus will undergo modernization in the near future. In both cases, the measurement principles now in use are still valid and will remain the same. Changes to the color temperature apparatus will involve replacing the presently used Pritchard telephotometer with red- and blue- filtered silicon photodiodes permanently mounted to viewing ports on the sphere. The photometric bench

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*The CIE (Commission Internationale de L'Eclairage; International Commission on Illumination) is a voluntary standards organization devoted to international collaboration and exchange of information on illuminating engineering, radiometry, photometry, and colorimetry.

will be replaced with a modern high-quality rail and carriage system in a slightly different configuration. The $V(\lambda)$-corrected selenium barrier layer photocells will be replaced with $V(\lambda)$-corrected silicon photodiodes.

1.1 Photometry, Physical Photometry, and Radiometry

An understanding of the relationship among these three branches of science is fundamental to the application and use of the photometric standards provided by NBS. This topic is treated in a concise, but comprehensive manner in CIE Publication 18.2 [4]. The following discussion is intended to provide the reader with a brief overview of these relationships. The reader is urged to consult the literature and obtain a more comprehensive understanding.

Photometry deals with the measurement of optical radiation evaluated according to the visual effect it produces. Visual effects result from a processing of light stimuli by the human visual system - the eye, the optic nerve, and the more central visual parts of the brain. It is a very complex phenomenon and obviously of a subjective nature. Quantification of these visual efects depends on the choice of observer, the state of adaptation of the eye, the angular size and retinal location of the visual field, the intensity of the incident radiation, its wavelength, and other factors. In order to provide a convenient, precise, and reproducible basis of measurement for science and commerce, the CIE has adopted a number of conventions defining a standard observer. Use of these conventions allows one to relate a characterization of optical radiation in purely physical terms (radiometry) to the visual effects it produces, though only approximately. Objective measurements made incorporating these conventions and using physical detectors of optical radiation constitute the branch of science known as physical photometry.

According to the CIE conventions, a generalized radiometric quantity, $Q_{e,\lambda}$, is related to its analogous physical photometry quantity, Q_v, by an equation of the form:

$$Q_v = K_m \int Q_{e,\lambda} V(\lambda) d\lambda \qquad (1)$$

where $V(\lambda)$ is the photopic (light adapted) spectral response function for the "standard observer" of the CIE [4]. This function is shown by the curve in Figure 1. K_m is a coupling constant and fixing its value defines the physical photometry units in terms of the radiometric units. In 1977 the International Committee for Weights and Measures (CIPM) adopted a K_m value of 683 lumens/watt for monochromatic radiation at a wavelength of 555 nm. Note that implicit in the use of an integral in equation 1, is a convention of arithmetic additivity for photometric quantities, although such a law is obeyed imperfectly by actual observers.

Table 1 lists the quantities, units and symbols used in radiometry and photometry [4]. NBS supplies standards utilizing the conventions of physical photometry and based upon a radiometric standards chain. For the remainder of this document, the modifier physical will be dropped and the term photometry should be understood to mean physical photometry and its associated conventions.

1.2 Photometric Scale

The NBS photometric scales are derived from the NBS scale of spectral irradiance. Figure 2 shows the major steps in the derivation of this spectral irradiance scale from a blackbody operated at the temperature of freezing gold. Briefly, the gold point blackbody is used to realize the International Practical Temperature Scale (IPTS-68), which in turn is used to measure the temperature of a variable temperature blackbody (VTBB). The VTBB provides us with a scale of spectral radiance and this in turn provides the basis for the NBS scale of spectral irradiance. All of the steps in this chain have been documented in a series of calibration documents being published as supplements to SP 250 [5, 6, 7]. All of the measurements necessary for implementing the chain shown in Figure 2 are made on the NBS Facility for Automatic Spectroradiometric Calibrations (FASCAL). The NBS scale of spectral irradiance is maintained in a group of four 1000-watt quartz-halogen lamp working standards. Primary calibration of the photometric working standards is performed by making spectral irradiance measurements on FASCAL against these four quartz halogen lamps.

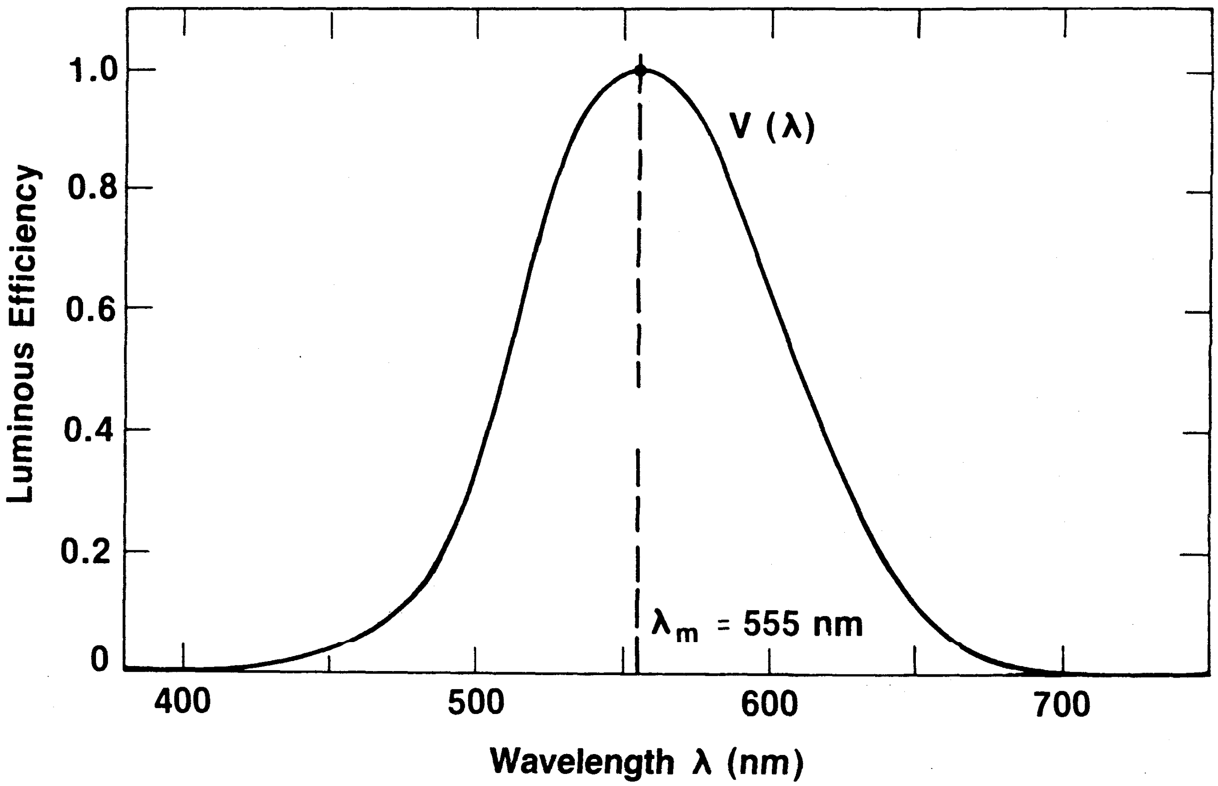


Figure 1. Spectral Luminous Efficiency Function V(λ) Defining the Standard Photopic Observer.

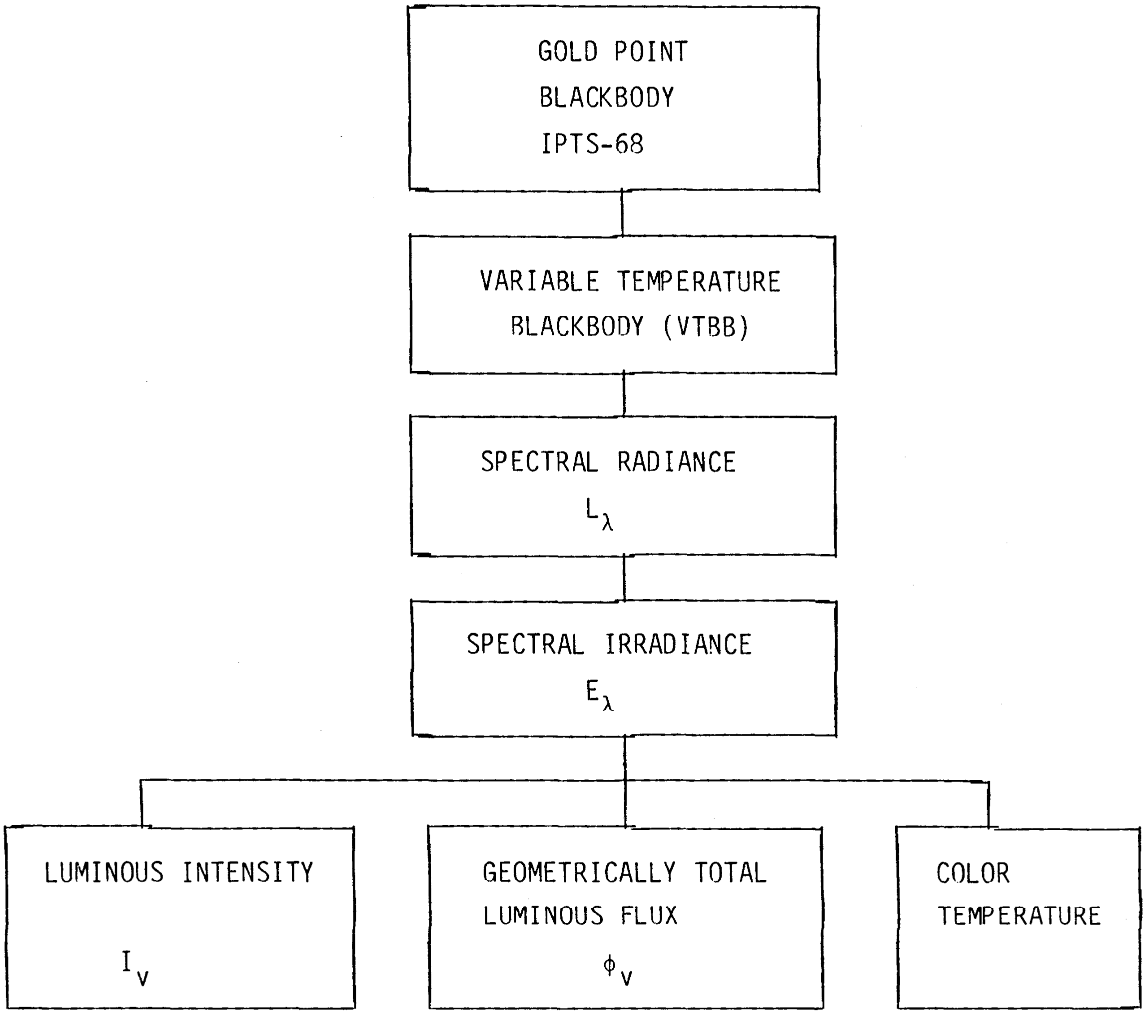
Table 1

Important Quantities, Units and Symbols used in Radiometry and Photometry

Radiometric Quantity	Unit	Photometric Quantity	Unit
radiant flux, radiant power (ϕ_e)	watt (W)	luminous flux (ϕ_v)	lumen (lm)
radiant intensity (I_e)	watt per steradian (W sr^{-1})	luminous intensity (I_v)	candela (cd)
radiance (L_e)	watt per square meter and per steradian (W m^{-2} sr^{-1})	luminance (L_v)	candela per square meter (cd m^{-2})
irradiance (E_e)	watt per square meter (W m^{-2})	illuminance (E_v)	lumen per square meter (lm m^{-2}), lux (lx)
radiant exitance (M_e)	watt per square meter (W m^{-2})	luminous exitance (M_v)	lumen per square meter (lm m^{-2})
distribution temperature	kelvin (K)		

Note: Should there be no possibility of confusion, the subscripts may be omitted from the symbols for the quantities. Also, when the spectral concentration of a radiometric quantity, such as radiance, is considered, it is designated by the same term preceded by the adjective spectral, and by the same symbol with the subscript λ; example, spectral radiance, L_λ.

Figure 2. Photometric Chain Showing Derivation of Photometric Scales From the Gold Point Blackbody



1.3 Photometric Quantities

The photometric quantities we are concerned with here are luminous intensity and luminous flux. Luminous intensity,

$$I_v = d\ \phi_v/d\omega \tag{2}$$

is the luminous flux per unit solid angle in the direction in question. For purposes of measurement, luminous intensity is defined by

$$I_v = K_m \int I_{e,\lambda}\ V(\lambda)\ d\lambda \tag{3}$$

and similarly for luminous flux,

$$\phi_v = K_m \int \phi_{e,\lambda}\ V(\lambda)\ d\lambda \tag{4}$$

where $I_{e,\lambda}$ and $\phi_{e,\lambda}$ are the spectral concentrations for radiant intensity and radiant flux.

An equivalent definition of luminous intensity makes use of the quantity illuminance E_v (see Table 1) which in the context of Figure 3, is simply defined as the quotient of the luminous flux $d\phi$ over the elementary area dA illuminated by the source. In this definition, we assume that the area dA is perpendicular to the direction (axis of cone) of illumination; thus,

$$E_v = \frac{d\phi_v}{dA} \tag{5}$$

Since $d\omega = \frac{dA}{r^2}$, we can substitute this and equation (5) back into equation (2) and obtain

$$E_V = \frac{Iv}{r^2} \tag{6}$$

In equations (3) and (4), $V(\lambda)$ is the spectral luminous efficiency function for the CIE standard photometric observer and K_m is the coupling constant previously discussed in section 1.1. Although $V(\lambda)$ is a psychophysical

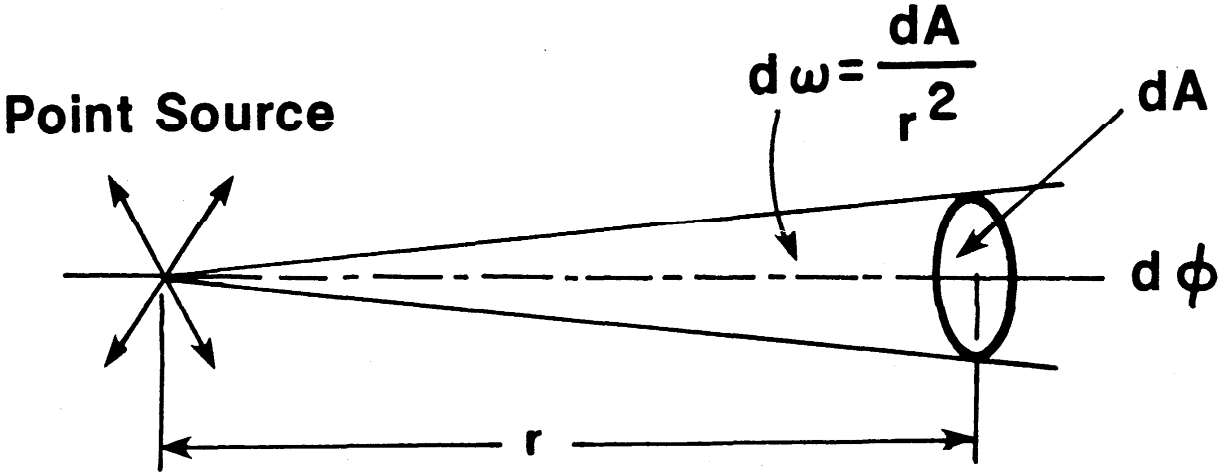


Figure 3. Concept of Luminous Intensity

function, its numerical weighting is fixed by international agreement and hence photometric measurements are physical measurements in the same sense as the measurement of analogous radiometric quantities. Table 1, produced from reference [4], shows the relationship between analogous radiometric and photometric quantities and units.

In principle, based on equation (1), it is also feasible to establish a radiometric/photometric scale that is based on the physics of silicon photodiodes instead of the physics of a gold-point blackbody. A detector-based scale of radiometry, in fact, is one of the goals of the NBS photodetector program. Procedures have been developed whereby "self-calibrating" silicon photodiodes are used to establish a detector-based scale [8] which compares quite well [9] with established source-based scales.

1.4 Safety

A 5mw helium-neon laser is occasionaly used for alignment of the photometric bench. An appropriate warning sign is displayed at the laboratory entrance. High current laboratory power supplies are used to power the higher wattage lamps. Appropriate precautions are used when working with these and other electrical laboratory equipment.

1.5 Acknowledgements

We express our appreciation to R. D. Saunders for his discussions assisting in the preparation of the uncertainty analyses and to R. L. Wilkinson for his assistance in the preparation of the detailed calibration procedures in Appendices A, B, and C.

2. LUMINOUS INTENSITY CALIBRATIONS

The luminous intensity of a source is the luminous flux emitted per solid angle. The unit of luminous intensity is the candela which is equal to one lumen per steradian. A source having a luminous intensity of 1 candela in all directions radiates luminous flux equal to 4 π lumens.

Inside-frosted lamp standards of luminous intensity are calibrated at the National Bureau of Standards by a substitution method on a calibrated horizontal bench photometer. The photometer is calibrated at the time of the measurements in terms of the unit of luminous intensity (candela) at approximately the color temperature of CIE standard illuminant A (2856 K-IPTS 68) as maintained at NBS. The luminous intensity scale is derived from the NBS spectral irradiance scale and is maintained in a group of nine 500-W inside-frosted lamps designated as the NBS 5612 groups.

The luminous intensity of these lamps was determined by measuring the spectral irradiance of each lamp on FASCAL, an automated high-accuracy spectroradiometer that serves as the transfer instrument, and then calculating the luminous intensity according to equation (3), with the spectral intensities $I_{e,\lambda}$ evaluated according to a radiometric form of equation (6). The measurements were performed at a distance of 1.5 meters. A complete set of measurements on the lamps in the 5612 group was performed in 1978 and again in 1984 with some measurement checks in between. Using the illuminance substitution method described in section 2.3.1, the luminous intensity scale was further transferred from the nine lamps in the NBS 5612 group to eight lamps which comprise the NBS 7796 group. The lamps in the NBS 7796 group are the working standards used in routine calibrations.

2.1 Test Lamp

2.1.1 Description

Gas-filled, inside-frosted lamp standards of luminous intensity are calibrated by NBS in 100-, 500-, and 1000-watt sizes. The corresponding luminous intensities are approximately 90, 700, and 1400 candelas. The 100- and 500-watt lamps have T-20 bulbs; the 1000-watt lamps have T-24 bulbs. They all have medium-bipost bases and C-13B filaments. The 100 watt lamps operate at 32 volts and the 1000-watt lamps operate at 120 volts; both types are designed to have approximately 1000 hours life. The 500-watt lamps are designed to have 500 hours life at 120 volts.

2.1.2 Preparation

The lamps are seasoned by operating them at design voltage (dc) for approximately 5% of their rated life and an identifying number is etched on each bulb.

2.1.3 Orientation

Test lamps are calibrated while operating base down on a horizontal bench photometer with the identifying number turned away from the detector. Lamp orientation is accomplished by aligning the lamp socket so that the lamp posts are held vertically, and the plane formed by the axes of the posts is perpendicular to the optic axis of the photometer. A special multi-pin jig and silhouette procedure has been developed for this alignment. The bottom of the lamp bulb is 10.16 cm below, and the lamp pins are equidistant from, the optic axis. Source-to-receiver distances are measured from the plane formed by the axes of the biposts to the sensitive surface of the detector.

The use of inside frosted instead of clear lamps greatly reduces the variation in luminous intensity that can result from small changes in the pitch orientation of the lamps [10]. In lamps that are issued to the public the luminous intensity of each lamp varies by less than 0.2% for (1) a ± 1.5° rotation about a horizontal axis intersecting the optic axis in the plane formed by the axes of the posts (pitch) and (2) a ±1.5° rotation about a vertical axis contained in the post plane and intersecting the optic axis (yaw).

2.1.4 Operation

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

2.2 Photometer

2.2.1 Detector and Amplifier

The photometer detector is a selenium barrier-layer photocell [11] equipped with a filter which modifies its spectral response to approximately match the CIE luminous efficiency function [3,12]. Measurements are usually made at a photocell illumination level of approximately 80 lux. The entire photosensitive surface is directly illuminated by the entire test or standard lamp, and no auxiliary optics are used. The photocell is fully illuminated during the 10 minute stabilization period of the lamps.

The detector photocurrent is measured with a unity gain operational amplifier (current to voltage converter) arranged in a typical closed loop configuration. Thus the photocell is operating into a near "zero-resistance" circuit (no voltage across the terminals of the photocell). A 5 1/2 digit voltmeter is used to measure the output of the operational amplifier.

2.2.2 Optical Bench

All measurements are made on a 4.5-meter optical bench. The optical bench is housed in an enclosure 61 cm wide and 117 cm high. The enclosure is covered with black "suedine" cloth on all four sides. The optic axis is 38 cm above the bench and is located approximately 69 cm from the bottom, 48 cm from the top, and 30.5 cm from the sides of the enclosure. Source-to-receiver distances of 1.3 to 4.2 meters are typically used. For the 100- and 500-watt lamp sizes, a baffle with an aperture 7.6 cm wide and 17.8 cm high is placed 25 cm from the plane of the biposts and centered with respect to the lamp bulb. For the 1000-watt test lamps, this baffle aperture is 10 cm wide and 23 cm high. Additional baffles are placed between the source and the detector to screen the detector from any directly reflected light. A small baffle is also attached directly to the lamp support to shield the detector from light reflected off the socket. Light emitted by the lamp in the direction away from the receiver is absorbed with a light trap placed 40 cm behind the lamp.

2.3 Calibration Procedure

2.3.1 Photometer Calibration

The photometer is calibrated, at the time of the measurements, in terms of the illuminance produced at the detector by each of a group of 500-watt lamps of the same type and construction as the test lamps. These working standards are periodically compared with a group of 9 similar lamps (NBS 5612 group) which represents the unit of luminous intensity at approximately the color temperature of CIE standard illuminant A (2856 K-IPTS 68) as maintained at NBS.

An illuminance substitution method is used for the measurements. Source-to-detector distances (photometric distances) are chosen to produce approximately equal illuminances at the detector and thus avoid any need for linearity corrections. 500-watt lamps are calibrated at a photometric distance of 3 meters for both standards and test lamps. This produces approximately 80 lux at the photocell. When calibrating 100-watt lamps the photometer is calibrated with the 500-watt working standard at a photometric distance of 3 meters and again with a distance of 4.17 meters (approximately 40 lux). The test lamps are then measured at two distances, one distance to produce approximately 80 lux and another distance to produce approximately 40 lux. The 1000-watt lamps are measured at 4.17 meters with the photometer calibrated with the 500-watt working standards at a distance of 2.9 meters. Detailed procedures for luminous intensity calibrations are given in Appendix A.

2.4 Measurement Schedule

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

2.5 Data Reduction

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

2.6 Uncertainty

The lineage of the prime luminous intensity reference lamp group (NBS 5612 group) is shown in Figure 2. The uncertainties (3σ) associated with this chain through the calibration of a test lamp for spectral irradiance have been documented elsewhere [7]. Table 2 is an expanded version of the uncertainty table in reference [7] specifically applicable to the spectral irradiance calibration of the luminous intensity reference group. The last column in Table 2, headed $V(\lambda)$ weighted, is a photometric weighting of the radiometric uncertainties according to equation (3). Note that the actual experiment utilized the alternative definition of luminous intensity, equation (6). Note also that, since these measurements were performed immediately following a spectral irradiance scale realization, the time drift model error normally associated with the use of the four working standard spectral irradiance lamps is not applicable and therefore not included in Table 2. The values listed under IV in Table 2 are taken as the uncertainty of the prime luminous intensity reference lamp group. In the buildup of the uncertainty terms shown in Table 2, the factors in the physical models [6, 12] enter multiplicatively with one exception. This exception is exponential in form and has a value of approximately 1.00 in the range of interest. Hence, the summing of relative percents in quadrature is justified.

Table 2. Uncertainty Estimates (%, 3σ) for the Spectral Irradiance and Photometric Scales at the Time of the Photometric Scale Realization.

	400 nm	450 nm	500 nm	555 nm	600 nm	654.6 nm	700 nm	V(λ) Weighted
I. NBS SPECTRAL RADIANCE SCALE								
a. Absolute error (with respect to SI Units)	0.92	0.82	0.73	0.66	0.61	0.56	0.54	0.65
b. NBS long term reproducibility	0.46	0.40	0.35	0.32	0.29	0.28	0.29	0.32
II. NBS SPECTRAL IRRADIANCE SCALE								
a. Systematic errors	0.21	0.19	0.18	0.16	0.16	0.15	0.14	0.16
b. Random errors (3 σ precision)	0.07	0.07	0.07	0.07	0.06	0.06	0.07	0.07
III. TRANSFER CALIBRATION OF A TEST LAMP								
a. Systematic errors	0.26	0.24	0.22	0.20	0.19	0.18	0.17	0.20
b. Random errors (3 σ precision)	0.20	0.20	0.20	0.15	0.15	0.15	0.20	0.15
IV. UNCERTAINTY OF REPORTED VALUES								
a. With respect to SI units	1.00	0.90	0.81	0.72	0.68	0.62	0.62	0.71
b. NBS long term reproducibility	0.60	0.55	0.49	0.45	0.42	0.40	0.42	0.44

IVa is a quadrature combination of items Ia, II and III.

IVb is a quadrature combination of items Ib, II and III.

Two additional measurements enter into the uncertainty calculation for an individual test lamp: the substitution calibration of the working standards group, NBS 7796 group, and the substitution calibration of the test lamp against the working group. Each of these experiments involves a direct comparison of essentially identical lamps. The only systematic error that could affect the results would come from the spectral response of the detector. In principle, if the sources are identical in spectral distribution, no error occurs, no matter what the properties of the detector are. In practice, the detector is approximately matched to the V(λ) curve and systematic errors are assumed to be neglible. Each of these experiments is also subject to the random variations of the measurements. A study was conducted on 124 measurements of 36, 500-watt lamps and 80 measurements on 20, 100-watt lamps. This study yielded a pooled estimate of the standard deviation of a single measurement of 0.3%. Since it is customary to make three measurements of a test lamp, an allowance of ± 0.5% is made for the random variation of the measurements on a test lamp (three times the standard deviation of the mean of three measurements). Similarly for the eight lamps of the working standards group, the appropriate random uncertainty is the precision associated with the group mean, 0.2%. Examination of this data base also revealed occasional non-random changes in light output. Usually these changes were of the order of 0.2-0.3%, though a few were as large as 1%. Presumably these changes were due to shorting in the filament coil structure. In order to allow for possible discrete changes in lamp output, an additional uncertainty of 0.5% (1/2 the largest observed change) is assigned. Table 3 sumarizes these various uncertainties for an individual test lamp.

In 1968-70, an international intercomparison of the candela at the color temperature of CIE illuminant A showed a range of 1.7% among the eight participating national standardizing laboratories including NBS [13]. Preliminary results from an international intercomparison in 1984-86 show a similar range. These results are consistent with the ± 1.0% uncertainty estimated for the NBS calibrations as shown in Table 3.

2.6.1 Precautions

Lamps supplied to other laboratories as standards of luminous intensity

Table 3

Uncertainties (3σ) Associated with the NBS Scale of Luminous Intensity

I. Uncertainty of the Calibration of the Reference Lamp Group (NBS 5612 Group)	
a. With respect to SI units	0.7%
b. NBS long term reproducibility	0.4%
II. Transfer Calibration of the NBS Working Group	
a. Random uncertainty of the mean of the eight lamps (3σ)	0.2%
III. Substitution Calibration of a Test Lamp	
a. Random uncertainty (3σ)	0.5%
b. Nonrandom shifts	0.5%
IV. Total Uncertainty of a Reported Value	
a. With respect to SI Units (a quadrature combination of items I_a, II, and III.)	1.0%
b. NBS long term reproducibility (a quadrature combination of items I_b, II, and III.)	0.8%

represent the unit of luminous intensity (candela) as maintained at the National Bureau of Standards. They are expensive laboratory equipment and deserve the utmost care in handling and use.

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

1. The lamps should be turned on and off slowly (15-30 seconds). The lamp should not be moved while lighted.

2. In order to prolong the useful life of the lamps, it is recommended that they be used sparingly and great care taken so that at no time will the current appreciably exceed the value stated in the report. For general use, working standards should be prepared by calibrating them relative to the lamps supplied by NBS. When a laboratory procures standard lamps from NBS it is well to obtain at least three such lamps in order to be able to detect any changes that may occur.

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

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

5. Baffle aperture edges should be very thin or beveled so as not to reflect light to the detector. It is of little use to coat baffle edges with black paint or black cloth, since most flat surfaces reflect light reaching them at large angles of incidence regardless of whether or not they are blackened.

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

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

$$\frac{dI_v}{I_v} = 6.25 \frac{di}{i} \tag{7}$$

where I_v is the luminous intensity and i is the lamp current [14,15]. Thus a current measurement accuracy of at least 0.032% is required if it is not to affect the luminous intensity by more than a factor of 0.2%.

3. LUMINOUS FLUX CALIBRATIONS

Radiant flux [ϕ_e] is radiant energy per unit time. Luminous flux is radiant flux weighted with the photopic luminous efficiency function V(λ), which is defined in a way that limits our concern to the visible spectrum. When the geometrically total flux (in lumens) of a lamp is known, then the luminous efficacy of the lamp in lumens/watt is easily determined. Lamps are rated in this manner throughout the lighting industry and light fixtures are evaluated according to the fraction of a lamp's flux output that they direct to a task or a surface.

The fundamental method of determining the total luminous flux emitted by a source is to measure the luminous intensity in a large number of directions distributed in space about the source, and then integrate the measured luminous intensity over the solid angle of 4π steradians. A practical method is to measure the illuminance from the source at points on the surface of an imaginary sphere. Large source-to-detector path lengths are not necessary when deriving the lumen (total flux) from illuminance, rather than intensity measurements, and it is not necessary that the source be at the center of the sphere [16]. Since the detector can be brought significantly closer to the source, there will be a greater sampling of the surface surrounding the source for the same number of measurements taken. National standardizing laboratories use a goniophotometer, consisting of a photometer which can be rotated about the source, to measure directional light distribution characteristics.

A theoretically equivalent procedure is to mount the light source on a goniometer which allows the source to be rotated about its horizontal and vertical axes. The illuminance is measured by a single fixed detector. This method is generally not used by standardizing laboratories because it introduces uncertainties due to changing the orientation of the operating lamp.

Once a scale of total luminous flux has been established, a more convenient way to transfer calibrate other lamps is by means of a substitution method using an integrating sphere. According to the theory of the integrating sphere [17], the reflected flux reaching any point on the sphere wall is directly proportional to the total flux of a source within the sphere. Since it is only the reflected flux that is proportional, it is necessary to baffle the source to prevent direct light from reaching the detector. The baffling is a perturbation to the sphere theory. In routine substitution measurements, baffles and lamp mounting hardware are left in place in the sphere and their effects approximately null out. However, the lamps themselves (standards and test lamps) and their sockets may differ in self-absorption, and corrections for these effects may be necessary.

In June, 1980, the group of opal-bulb lamps (NBS 526 Group) that serves as the primary NBS reference standard of luminous flux was recalibrated in accord with the 1979 international redefinition of photometric units [18], using the goniometric distribution of the lamps. This calibration was then transferred, using the substitution method, to three working groups, consisting of lamps ranging from 100 to 500 watts. The 1980 substitution calibration of the working group lamps is described here, and the luminous flux scale realization is summarized briefly. Lamps calibrated for issuance to the public are measured against the working group in a manner similar to the calibration of the working groups against the NBS primary reference standards.

For miniature lamps, luminous flux scales are derived from the 100-watt working group (NBS 3158 group) by substitution methods in integrating sphere photometers. The present scale, realized in this manner, was first issued in 1974 and was re-determined in 1981/82.

3.1 Test Lamps

Two general types of incandescent lamps, large lamps and miniature lamps, are calibrated for issuance to the public. Lamps are seasoned at rated voltage for 4% of their rated life before calibration and each bears an identifying number etched on the neck of the bulb. Lamps are usually supplied by NBS but may be submitted by the user. The so-called large lamps are general-purpose, inside-frosted lamps ranging from 25 to 500 watts. The clear-bulbed, miniature lamps range from about 1.25 to 29 watts.

25-watt inside-frosted, vacuum, tungsten lamps and 60-, 100-, 200-, and 500-watt inside-frosted, gas filled, tungsten lamps are calibrated for issuance as luminous flux standards. The corresponding values of luminous flux are approximately 270, 870, 1600, 3300, and 10,000 lumens. The 25- and 60-watt lamps have A-19 bulbs, the 100-watt an A-21, the 200-watt a PS-30, and the 500 watt has a PS-35 bulb. All of the lamps have medium screw bases, except the 500-watt which has a mogul screw base.

Miniature lamps are also calibrated for issuance to the public. Miniature lamps currently issued to the public are part of a stock resulting from a 1981-82 calibration of 6 types of miniature lamps ranging in total flux output from 6 to 400 lumens. Electrical leads covered with white insulation are soldered to the base of each lamp. The lamp types and their approximate operating characteristics are listed in Table 4. Lamps submitted by users for calibration must be of the types listed in Table 4.

Table 4. Operating Characteristics of Miniature Lamp Standards of Luminous Flux

Lamp Type	Current (set)	Voltage	Approximate Color Temp.	Nominal Luminous Flux	
	(amperes)	(volts)	(kelvins)	(lumens)	(MSCP)
1183	5.80	5.0	2950	400	32
1183	5.55	4.7	2856	300	24
1133	3.50	5.3	2856	220	18
87	1.80	6.1	2856	130	10
81	1.00	6.1	2856	66	5.2
63	0.63	7.4	2750	44	3.5
51	0.197	6.3	2400	6	0.5

3.2 Sphere Photometers

There are two integrating spheres used for the luminous flux measurements; one with a diameter of 2 meters and one with a diameter of 0.76 meters. The 2-meter sphere is coated with powdered barium sulfate, prepared by mixing 95% ethyl alcohol with reagent grade barium sulfate, and then spraying the resulting suspension onto the sphere wall. The alcohol evaporates leaving a pure barium sulfate coating. About 30 coats are necessary to produce the required thickness of 1 to 2 millimeters. A 7.6-centimeter diameter observation port is located in the sphere wall. The 0.76-meter diameter sphere is coated with a commercial sphere paint made of a mixture of magnesium carbonate, latex, and mineral spirits. A 4.3-centimeter diameter observation port is located in the sphere wall.

The observation ports in both spheres are fitted with white diffusing plastic filters (Plexiglas color W2447 Rohm and Haas white) mounted flush with the inside sphere walls. Baffles, coated with the commercial sphere paint, are placed between the lamps and the observation ports. In both spheres, lamps are located at the nominal center of the sphere. When measuring lamps up to 500 watts in the 2 meter sphere, the baffle used is a 20 cm disk, located 0.55 meters from the observation port. For special measurements of higher wattage lamps, a baffle 45 cm in diameter is used. In the 0.76 meter sphere, a rectangular baffle is used, 6 cm by 7.6 cm, placed 0.24 meters from the observation port.

Because of the selective spectral reflectances of the sphere coatings and selective spectral transmittances of the windows, pale blue filters are inserted adjacent to the windows in both spheres. Each pale blue filter was selected from a set of Corning 5900 filters of graded color temperature altering power. The net spectral effect of the sphere reflectance, window transmittance and the blue filter is that the relative spectral distribution of the flux arriving at the detector is approximately the same as that leaving the lamp. The proper filter is determined just before a series of calibrations is started. Typical corrections are 350 K for the 2 meter sphere and 500 K for the 0.76 meter sphere.

Selenium, barrier-layer photocells [11] (Weston model 856 YYLSV) are used with the spheres. Each is equipped with a filter to correct its spectral response to approximately match the CIE luminous efficiency function. The photocells are mounted in the tubes fitted to the windows of the spheres. The tubes are coated on the inside with a non-glossy black paint. The current produced by the photocells is converted into an amplified voltage signal by a unity-gain operational amplifier used with closed loop feedback. Thus the photocells operate into a zero-resistance circuit [11], with negligible voltage across the terminals. A 5 1/2 digit voltmeter is used to measure the output of the operational amplifier.

3.3 Standards

A group of five 300-watt opal-bulb lamps (the NBS 536 group) operating at a color temperature of approximately 2720 K serves as the primary NBS reference standard of luminous flux. For the June 1980 work, the international redefinition of the photometric units agreed to in 1979 [18] was implemented by performing a complete recalibration of the primary NBS reference group in terms of the NBS scale of spectral irradiance [7]. The relative goniometric distribution of the light produced by each of the five lamps of the NBS 526 group was measured at five wavelengths within the visible spectrum. These distribution measurements yielded the ratio of the geometrically total spectral flux emitted by the lamp to the flux emitted in a single "reference" direction. The flux emitted in the reference direction was measured in terms of the NBS scale of spectral irradiance. The total luminous flux emitted by each lamp was then computed from equation (4). The mean assignment of the primary NBS reference group was shifted 0.25% by this measurement from the assignment of the previously maintained scale, which had been based on the platinum point blackbody definition of the candela.

The NBS working standards are periodically recalibrated in the 2-meter sphere photometer by comparing them in six runs, using the three photocells mentioned above, with the 300 watt opal-bulb lamps. The NBS working standards are listed in Table 5. Each of the three groups of standards consists of six lamps.

Table 5. NBS Working Standards of Luminous Flux.

Lamp Group Designation	Nominal Wattage	Bulb	Filament	Approx. Color Temp.	Lumens (Group Mean)
NBS 162	500	PS 35 clear gas-filled	C-7	2800K	6426
NBS 6807	200	PS 30 frosted gas-filled	C-9	2900K	3252
NBS 3158	100	A-21 frosted gas-filled	C-9	2900K	1637

In the 1981-82 calibrations, flux assignments for the miniature lamp working standards groups were derived from the primary flux standards (NBS 526 group) in several steps. In the first step, the six lamps in the NBS 3158 group were compared directly against the primary flux group in the 2-meter sphere. This group was then compared in the 2-meter sphere with a group of ten type 1183 lamps operated at the two levels listed in Table 4. The type 1183 group, operated at 32 mean spherical candlepower (MSCP = $\phi_v/4\pi$)), was then used in the 0.76-meter sphere to calibrate the group of type 1133 lamps. In turn, the type 1133 lamps were used in the 0.76-meter sphere as standards to calibrate the other working groups listed in Table 4.

3.4 Calibration Procedures - Working Standards

Prior to a calibration run, each group of working standards and test lamps is divided into subgroups so that measurements can be spaced throughout the day in a balanced distribution and thus average out any linear drifts in the measurement process. Each comparison of working standard and test lamps is performed on three different days using different photodetectors. Electrical measurements are made with an integrating digital voltmeter and/or a potentiometer to an accuracy of 0.02% or better. Power is applied slowly to the lamps, taking at least 15 seconds to reach the desired current. The lamps are allowed to warm up at least 5 minutes in the closed sphere. All lamps are set at their assigned currents, and the operating voltage is read at the time their light output is recorded. Detailed procedures for a routine luminous flux calibration are given in Appendix B.

At the conclusion of one day's measurements, a photometer calibration factor is calculated for each working standard lamp in the run by dividing the value of the flux assigned to the lamp by the corresponding signal from the photocell. The average calibration factor for all standards in that day's run is then calculated. The uncorrected luminous flux for each test lamp is computed by multiplying this average calibration factor by the signal from the photocell when illuminated by the test lamp. These uncorrected flux values are converted into measured flux values by correcting for the differences between the working standards and test lamps' self-absorption in the sphere photometers [19], and for the nonlinearity of the particular photocell being used.

In order to determine the correction due to lamp absorption in the 2-meter sphere, a 200-watt lamp is placed at the bottom of the sphere. Light from the 200-watt lamp is baffled from the sphere window and from unlit lamps placed in turn at the center of the sphere. Readings are taken of the detector output when each of the unlit working standards is in the sphere and again when the unlit test lamps are in the center of the sphere. The correction is the ratio of the average reading taken with each group of working standards to the average reading of the test lamps being measured. Corrections are typically 1% or less.

Similar measurements are made in the 0.76-meter sphere using a 28-volt, 40-watt, partially-silvered-bulb lamp near the bottom of the sphere. The corrections for absorption in the 0.76-meter sphere relative to the type 1133 lamps are typically a few tenths of a percent.

For each of the three selenium photocells used in these calibrations, the deviation from linearity of the response of the detection system is determined. The determination is made on a horizontal-bar photometer by an inverse-square method. The test photocell is mounted on the bar at a known distance from a stable, clear-bulb, monoplane straight-wire filament lamp. The filament is approximately 2 centimeters square. (The use of a planar filament lamp avoids any invalidation of isotropic assumption implicit in the inverse square law that can occur with, for instance, a helical - coil filament lamp when different portions of the rear of the coiled filament are obscured by the front portions as the source-to-detector distance is varied [20]). The photocell is moved along the bar and its response noted at various distances from the lamp. The deviation of the response from that expected by applying the inverse-square law is attributed to the nonlinearity of the detection system. Illuminance levels ranging approximately from 3 lux to 800 lux are produced at distances ranging from 0.75 to 4.17 meters. Maximum deviations from linearity for the three detectors are typically a few percent or less.

The measured luminous flux values for all lamps in a group, averaged over the three measurements, constitute the assigned value of the luminous flux attached to that group.

3.5 Calibration Procedures - Test Lamps

Test Lamps for issuance to the public are calibrated in groups of ten to twenty. Three measurements, one on each of three days, are made on each lamp in the group. Each lamp is placed in the sphere and allowed to warm up at its designated current or voltage for ten minutes when using the 2-meter sphere and five minutes when using the 0.76 meter sphere. Then measurements of voltage, current, and luminous flux are made. The lamps are measured in the following order: two standards, one-half of the test lamps, two standards, the other half of the test lamps, and the remaining two standards. The three photocells described earlier are used, one on each of the three days. Test lamps in the 2-meter sphere are compared to the standards which are closest in luminous flux. Corrections for the nonlinearity of the photocell and difference in absorption are applied. When miniature lamps are calibrated in the 0.76-meter sphere, no corrections for lamp absorption or system non-linearity are necessary since the miniature working standards and test lamps are of the same type and have nearly the same light output.

Lamps are calibrated base up in the 2-meter sphere and base down in the 0.76-meter sphere. All lamps are operated on dc electrical power with the center contact at positive (+) potential. Typical calibration reports for both large lamps and miniature lamps are shown in Appendix D.

3.6 Uncertainties- Large Lamps

The uncertainty of the primary reference group (the 300-watt opal lamps) is made up of two components: the uncertainty of the measurement of each lamp's goniometric distribution, and the uncertainty of the radiometric measurement of its spectral irradiance. A thorough analysis of the errors of both processes has been done. Based on repeated measurements, the uncertainty due to goniometric distribution is 0.3 % (range of measurements, equivalent to 3σ). The uncertainty of the spectral irradiance transfer, including the uncertainty in the radiometric scale, is 0.7% as shown in Table 2. Comments on this uncertainty estimate were presented in section 2.6.

The uncertainty of transfer from the primary reference flux group to the NBS working standards may be divided into three parts, those uncertainties due to: (1) geometric effects, i.e., the presence of objects, such as the lamp, its support, and the baffle, in the sphere and their geometrical arrangement; (2) spectral effects, i.e., differences in the spectral distribution of the lamps being compared or a difference between the spectral response of the detector being used in the CIE spectral luminous efficiency function; and (3) random variations of the measurements. While a detailed analysis of the geometric effects has not been made, differences as large as 1% have been observed when using the sphere geometry described above compared to a very different geometry requiring more objects in the sphere during the measurements. An allowance of 1% has therefore been made for geometric sources of error.

The uncertainties due to spectral effects have been determined from calculations based on measurements of the relative spectral characteristics of the integrating sphere, of the photopically corrected photodetector, and of the standard and test lamps. The spectral throughput of the integrating sphere was determined from measurements of the relative spectral distribution of the light produced by a lamp operating in the sphere, compared to the relative spectral distribution of the light produced by the same lamp operating outside of the sphere. The relative spectral response for a "true" photopically corrected detector is used in the calculation, and contrasted with the "actual" response of the detectors [21]. The calculations were made for conditions where the test lamps operated at color temperatures of 2700 K to 3000 K, compared to a flux standard operated at a color temperature of 2856 K. Under NBS working conditions, the combined effect of all these factors would yield an uncertainty due to spectral effects that would not exceed 0.4%.

For random variations, the standard deviation computed from 138 measurements (six measurements on each of the five or six lamps in each of the three groups of working standards plus the opal reference standards) is 0.14%. The uncertainty assigned for the random variations is three times the standard deviation of the mean of the six measurements on each lamp or 0.2%. The three uncertainties (geometric, spectral, and random) combined in quadrature give an uncertainty of 1.1% for the NBS working standards relative to the primary reference group.

The uncertainty of the transfer from the NBS working standard to test lamps supplied to other laboratories depends on the size and operating color temperature of the test lamps relative to the standard group used to calibrate them. For test lamps of sizes and color temperatures differing from those of the working standards, the uncertainties of the transfer from NBS working standards to test lamps are the same as for the transfer from the primary group; 1.0% for geometric differences, and 0.4% for spectral differences. In addition there is a random variation in the transfer to a test lamp that applies to all lamps. This is computed as three times the standard deviation of the mean of the three measurements made of each of the test lamps and is 0.4%.

The uncertainty due to all suspected errors associated with a reported value for a lamp standard of luminous flux, is given by combining in quadrature the uncertainties of the primary reference group, the uncertainties of the NBS working standards relative to the primary reference group, the uncertainty of the transfer to the test lamp when that lamp is not similar to the working standards, and the random error typical of the lamps calibrated. Therefore the combined total uncertainty of the assigned value for a lamp ranges from 1.4% to 1.8% depending on similarity to the working standards.

The uncertainties for large lamp luminous flux calibrations are summarized in Table 6.

3.7 Uncertainties - Miniature Lamps

The estimated uncertainties in the calibration of the NBS primary reference group (the NBS 526 group), the transfer of the scale to the 100-watt working group (the NBS 3158 group), which served as the starting point for the calibration of the miniature lamps, and the calibration of a test lamp against this working group have just been described. The uncertainty of the calibration of a test lamp, in this case the type 1183 miniature lamp working group, against the 100-watt working group was estimated to be 1.8% relative to SI units, and 1.6% relative to the NBS primary group. Additional contributions to the uncertainty associated with the calibration of a miniature test lamp result from: the transfer from the 2-meter sphere to the 0.76-meter sphere; absorption and linearity corrections; geometrical and spectral differences between the standards and the test lamps; and random errors in the operation of the lamps and the measurement of their luminous flux.

An estimate of the possible error encountered in transferring calibrations from the 2-meter sphere to the 0.76-meter sphere was taken from the measurements made on the type 1183 and type 1133 lamp groups. These groups were measured in both spheres and the relative assignments shifted by 0.7%. This observed difference is believed to be due to differing geometrical distributions of the luminous flux from the lamps and/or uncertainties in the absorption corrections. An allowance of 0.7% is taken as the uncertainty due to these factors.

No detailed analysis of the uncertainties due to spectral differences has been made. For the gas-filled lamps, no allowance is made for the uncertainty

Table 6. Uncertainties (3σ) Associated with Large Lamps Calibrated for Luminous Flux

1. Uncertainty of primary reference group:		
a. Uncertainty of distribution measurements	0.3%	
b. Uncertainty in spectral irradiance scale and in transfer to luminous flux group	0.7%	
Total Uncertainty of NBS primary Reference Group		0.8%
2. Uncertainty of NBS Working Standards relative to primary reference group:		
a. Geometric differences	1.0%	
b. Spectral differences	0.4%	
c. Random variations (3σ)	0.2%	
Total uncertainty of working standards relative to NBS primary reference group (a, b, c combined in quadrature)		1.1%
3. Uncertainty for lamps differing in size or color temperature from those of working standards:		
a. Geometrical differences		1.0%
b. Spectral differences		0.4%
4. Random variation in transfer from working standard to test lamp (3σ):		0.4%
<u>Total Uncertainty of Test Lamp</u>		
1. Lamps the same size and color temperature as the working standards:		
a. Relative to SI - combine 1, 2, and 4 in quadrature		1.4%
b. Relative to NBS - combine 2 and 4 in quadrature		1.2%
2. Lamps of sizes or color temperatures different from that of the working standards:		
a. Relative to SI - combine 1, 2, 3, and 4 in quadrature		1.8%
b. Relative to NBS - combine 2, 3, and 4 in quadrature		1.6%

due to the differences in spectral distribution since the lamps were operating at approximately the same color temperature. Differences in the spectral distribution are therefore small. For the type 51 vacuum lamps an allowance of 2% is taken as a "best guess" estimate for the uncertainty due to spectral differences. In 1974, measurements were made both with photopically corrected selenium cells and with photopically corrected silicon cells. A difference of 2% was observed depending on the type of cell used. The present measurements are limited to photopically corrected selenium cells, but it is interesting to note that the observed shift in the assignment to the NBS type 51 working group was also approximately 2%.

For random variations, including the uncertainty in the linearity corrections, a statistical analysis of the measured luminous flux values was performed. Using the data from the 1981/82 calibration of the NBS working lamp groups, the deviations from mean assignment were computed for each lamp (99 degrees of freedom). Then the standard deviations were pooled to give an overall estimate of the precision of the measurements for the working groups. This analysis resulted in an estimate of 0.3% for the random variations in deriving the assignments for the NBS working miniature groups.

The uncertainty due to random variations in the transfer calibration of a test lamp was obtained by pooling the observed variation in the measurements over all test lamps (80 degrees of freedom). The pooled estimate of the standard deviation was 0.15%. An allowance of 0.3% (three times the standard deviation of the mean of the three measurements made on each test lamp) is made for the uncertainty due to this source.

The uncertainty due to all suspected errors associated with a reported value for a lamp standard of luminous flux is obtained by combining in quadrature the uncertainties in the measurement chain that generated the value. Table 7 summarizes these uncertainties.

3.8 Care and Use

Lamps supplied to other laboratories as standards of luminous flux represent the unit of luminous flux (lumen) as maintained at the National

Table 7

Uncertainties (3σ) Associated with Miniature Lamps Calibrated for Luminous Flux

1. Uncertainty of NBS 100-watt working standards	
a. Relative to SI	1.8%
b. Relative to NBS	1.6%
2. Uncertainty in transfer of scales from measurements in the 2-meter sphere to measurements in the 0.7-meter sphere	0.7%
3. Random errors in the transfer to the NBS miniature lamps working standards (3σ)	
a. Type 1183 lamps vs. NBS 100 W lamps	0.3%
b. Type 1133 lamps vs. type 1183 lamps	0.3%
c. Type 87, 81, 63, and 51 lamps vs. type 1133 lamps	0.3%
4. Random errors in the substitution calibration of test lamps	0.3%
5. Uncertainty due to spectral differences (type 51 lamps only)	2.0%

Total Uncertainty of Test Lamps

Lamp Type	Quadrature Combination of Items	Relative to SI	Relative to NBS
1183	1, 2, 3a, & 4	2.0%	1.8%
1133	1, 2, 3a, 3b, & 4	2.0%	1.8%
87, 81 & 63	1, 2, 3a, 3b, 3c, & 4	2.0%	1.8%
51	1, 2, 3a, 3b, 3c, 4 & 5	2.8%	2.7%

Bureau of Standards with the best precision now available. They are expensive laboratory equipment and deserve the utmost care in handling and use.

In addition to some obvious precautions, such as keeping the lamps clean and avoiding mechanical shock to the filament, the following are a few precautions which should be followed. Precautions 1 through 7 apply to both large lamps and miniature lamps.

1. The electrical power to the lamps at turn on or turn off should be increased or decreased gradually, taking at least 15 seconds to reach the specified electrical operating points.

2. In order to prolong the useful life of the lamps as standards, it is recommended that they be used sparingly and great care should be taken so that at no time will the current through the lamp appreciably exceed the value stated in the report. For general use, working standards should be prepared by calibrating them relative to the lamp standards supplied by NBS. When a laboratory procures standard lamps from NBS, it is well to obtain at least three such lamps in order to be able to detect any changes that may occur.

3. A baffle should be used between the lamp and the observation window. The baffle should be as small as possible but large enough to prevent any light from the lamp reaching the window without undergoing at least one reflection. The baffle surface should have the same reflectance properties as the sphere wall.

4. The variation of luminous flux of a tungsten filament lamp is approximately related to the variation in its current by the equation [14,15]:

$$\frac{d\phi}{\phi} = K \frac{di}{i} \tag{8}$$

where ϕ is the luminous flux, i is the lamp current and K is 6.25 for gas-filled lamps and 6.05 for vacuum lamps. Thus a current measurement accuracy of at least 0.032% is required if the uncertainty in the luminous flux is to be no greater than 0.2% due to the electric current uncertainty.

5. Some detectors are not linear in their response. Detectors of a single type made by a single manufacture sometimes differ significantly in this respect. If lamps of different flux outputs are to be compared, the response of the detector should be studied to determine its departure from linearity.

6. Most sphere coatings are somewhat spectrally selective in reflectance. Diffusing windows commonly used in spheres also have spectrally selective transmittances. Corrections should be made when comparing lamps operating at different color temperatures. In addition to this, a detector whose spectral response agrees with the CIE luminous efficiency function should be used.

7. Lamps of different physical size and blackening absorb different amounts of flux reflected to them by the sphere wall. The amount of flux absorbed also varies with the size of the sphere being used and with the reflectance of its coating. Therefore, when lamps of different physical size, bulb material and/or blackening are being compared, corrections for the lamp absorption should be made. The absorption correction should be determined in the sphere in which the comparison is made.

8. The coated wire leads on the miniature lamps should be left attached to the lamp. If they are removed, the voltage measured across the lamp will not be the reported value.

4. COLOR TEMPERATURE CALIBRATIONS

Incandescent lamp color temperature standards are calibrated at NBS using a red-blue ratio substitution method. The basic instrumentation consists of a 20-cm diameter integrating sphere and a commercially-available telephotometer. The color temperature instrument is calibrated at the time of the measurement in terms of the color temperature scale maintained by NBS.

4.1 The NBS Color Temperature Scale

NBS has established and maintains a scale of color temperature. Careful distinctions should be made between the concept of color temperature and the related concepts of radiance temperature, correlated color temperature, and distribution temperature. Radiance temperature is defined as the "temperature of the full radiator for which the radiance at the specified wavelength has the same spectral concentration as for the radiator considered" [22]. Color temperature is defined as the "temperature of the full radiator which emits radiation of the same chromaticity as the radiation considered" [22]. That is, the test source and the full radiator (i.e. blackbody) have the same appearance to a human observer. Note particularly that the corresponding relative spectral power distributions are not necessarily identical or even similar. If the test source and the corresponding blackbody have identical relative spectral power distributions in the spectral region of interest, the correct designation is distribution temperature [22]. If one wishes to assign a "temperature" to describe a source whose appearance, and hence whose relative spectral power distribution, is markedly different from a blackbody, such as a fluorescent lamp, the correct designation is correlated color temperature [22]. Mathematical procedures are available for determining the correlated color temperature of any source [23]. In applying the values of color temperature reported by NBS, the user should bear these distinctions in mind. Particular care should be exercised in utilizing the widespread practice of treating color temperature values as synonymous with distribution temperatures.

The NBS scale of color temperature was first established in 1934 [24] by visual comparison of monoplane, coiled tungsten filament, incandescent lamps with three melting point blackbodies: platinum at 2045 K, rhodium at 2236 K, and iridium at 2720 K. The nine lamps thus calibrated (three at each temperature) were then used to calibrate three working standard lamps across the color temperature range. An empirical approach was adopted for interpolating between the three fixed temperature points. Taking advantage of the cavity effect due to filament coiling, pyrometric determinations of the radiance temperature were made at a position on the inside of a single turn of the coiled filament. It was observed that the differences between the radiance temperatures so determined and the color temperatures of the lamp as a whole were a smoothly varying function of the voltage applied to the lamp. Pyrometric determinations of the radiance temperatures of three different coil turns of the test lamps yielded consistent color temperature values for the interpolated region. Further, from this data it was empirically determined that an equation relating the color temperature (T_C) and the applied voltage (V), of the form

$$T_C = A + B\ (V)^{1/2} \tag{9}$$

was adequate to express all of the data within the estimated uncertainties. The 1934 color temperature scale was also extrapolated up to 3200 K and down to 1500 K. Sources with known color temperatures in the extrapolated regions were produced by modifying incandescent lamp outputs (assumed to be sources whose distribution temperatures equalled their color temperatures) with blue and amber filters whose spectral transmittances had been measured. Incandescent lamps and associated equations of the form of eq. (7) have been used since 1934 to maintain the NBS color temperature scale. The scale has been adjusted twice, in 1949 [25] and in 1970 [26], to take account of changes in the International Practical Temperature Scale.

The present scale of color temperature has been transferred to a number of clear bulb incandescent working standard lamps that are used in the actual calibration of color temperature standards for issuance to the public. Lamps BS 9021, BS 9022, and NBS 9341 are used in the range 2000-2600 K; and lamps NBS 1923, 1924, and 1925 are used in the range 2300-2900 K. With the exception of lamp NBS 9341, these working standards were calibrated by visual comparison with the lamps used to originally establish the scale in 1934.

These calibrations have since been validated by checks against the NBS spectral irradiance scale. Lamp NBS 9341 was calibrated from spectral irradiance measurements.

In addition, lamps NBS 9098, 9099, 9166, 9246, 10155, and 10423 are used in the range 2600-3200 K. These lamps were calibrated from spectral irradiance data obtained with a high accuracy spectroradiometer. Using the procedure described by Kelly [23], chromaticity coordinates were computed for these lamps, converted to u, v space, and correlated color temperatures determined at a number of currents.

Once spectral irradiance data are used to establish the color temperature calibration at fixed points, it is convenient and straightforward to interpolate and extrapolate the calibrations to other color temperatures. Empirical equations of the form

$$I = A + BT_C + CT_C^2 \tag{10}$$

relating the color temperature T_C and current I through the lamp, were used to establish the scale in increments of 1 K throughout each lamp's range.

In addition to the clear lamps just described, which collectively comprise the color temperature scale over the range 2000-3200 K, three inside-frosted lamps, NBS 9171, 9172 and 9173, are used at 2856 K (CIE Source A) to calibrate inside-frosted test lamps at that color temperature. Initial calibration of these lamps was performed spectroradiometrically against the 500-watt, clear-bulb working standards of color temperature. The spectroradiometer used for this calibration [27] determined the ratios of the spectral radiant powers of the frosted and clear lamps at every 10 nm from 380 nm to 760 nm with a spectral bandpass of 5 nm. The data reductions assumed that the relative spectral power distribution of the clear-bulb standards was the same as the relative power distribution of a Planckian radiator. The relative spectral power distribution of the inside-frosted lamps thus determined was used to compute their chromaticity coordinates. The procedure described by Kelly [23] was then used to compute the correlated color temperature of the inside-frosted lamps.

4.2 Test Lamps

Clear airway beacon lamps are issued by NBS as color temperature standards in the range 2000-3000 K. These nominally 500 watt, 120 volt lamps have clear T-20 bulbs, C-13B filaments, medium bipost bases, with a rated life of 500 hours at 120 volts.

At present, inside frosted lamps are issued as color temperature standards at a single color temperature only, 2856 K. The physical characteristics of these lamps are the same as the clear lamps except for the frosting.

4.2.1 Preparation

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

4.2.2 Orientation

Test lamps are calibrated while operating base down with the etched identifying number turned away from the comparator. The clear lamps are aligned so that their planar filaments are centered on a perpendicular to the optical axis of the entrance aperture of the collecting sphere of the color temperature comparator.

Orientation of the inside frosted lamps is accomplished by aligning the lamp socket so that the lamp posts are held vertically with the plane formed by the axes of the posts perpendicular to the optical axis of the comparator. The light center of the lamp is on, and the lamp pins are equidistant from this optical axis.

4.2.3 Operation

All measurements are made with the lamps operating on dc power. Electrical measurements are made with a digital voltmeter to an accuracy of

0.02%. After positioning and alignment, the lamp is slowly (15-30 seconds) brought up to approximately the required electrical operating point and allowed to stabilize for at least 10 minutes before measurements are made. Measurements are then made of the current through the lamp and the potential drop across the pins of the bipost base necessary to produce a color match to a comparison source.

4.3 Color Temperature Apparatus

Numerous devices based on the red/blue ratio principle have been described in the literature [28]. The present apparatus has not been optimized, and will be modernized in the near future (see Introduction). It has, however, been shown to possess adequate sensitivity and precision. The standard deviation computed on the basis of repeated measurements of the same color temperature on the same test lamp ranges from about 3.5 K at 3000 K to about 8.0 K at 2000 K.

The present interim apparatus consists of a 20-cm diameter integrating sphere and a Pritchard model 1980 telephotometer. The integrating sphere is coated with a commercial sphere paint made of a mixture of magnesium carbonate, latex, and mineral spirits. A single light source is typically located 70 cm from the 7.5 cm diameter sphere opening. Both the sphere and light source are located in a rectangular light-tight enclosure. A baffle is located between the source and sphere, 25 cm from the sphere. There is a 2.5 cm aperture opening in the baffle that allows for viewing of the entire lamp.

Measurements are made based on the red-to-blue ratio principle [28]. The lamp is powered by three, 60-volt power supplies connected in series. The telephotometer is used with its own internal broad-band red and blue filters and is equipped with a close-up lens focused at the plane of the 3-cm diameter viewing port of the sphere. A 3-cm diameter black tube is attached to the sphere and extends 7 cm to the lens of the telephotometer.

Radiation collected in the sphere is measured separately through the red and blue filters and the ratio of these signals is determined. A sufficiently dense neutral density filter must be used to prevent saturation of the photomultiplier. Once the particular internal neutral density filter is selected, it remains in position for both the red and blue measurements. The sphere-telephotometer apparatus has been used for color temperature calibrations in the range 2000 K to 3000 K. The use of accessory color compensating filters at the extreme ends of this range is not necessary.

Equality of two red-to-blue ratios is interpreted to mean equality in color temperature. Since the measurement involves the inference of a visual property of the test source (chromaticty match to the standards) from the measurement of a different physical property, severe requirements are placed on the test and standard sources. Specifically, their relative spectral power distributions must be identical throughout the entire visible region of the spectrum. Only test lamps substantially identical to the working color temperature standard lamps are calibrated by this method.

4.4 Calibration Procedure

A simple substitution procedure is used to calibrate lamps for color temperature on the sphere-telephotometer apparatus. At the beginning of each calibration run, the proper internal neutral density filter is selected and the telephotometer is calibrated in turn against each lamp of the relevant working group.

Each lamp of the working standard group is placed in the measuring position and allowed to operate for 10 minutes at the current required for the desired color temperature. Separate measurements with the red and blue filters in place are recorded and the red-to-blue ratio determined. After each lamp of the working group is measured, the test lamp is placed in the measurement position and, after warm-up, red and blue measurements are made while adjusting the current of the test lamp to bracket the red-to-blue ratio average of the working standard lamps. A linear interpolation between the high and low currents determines the test lamp current corresponding to the target R/B ratio. The entire procedure is repeated two more times. The three current values thus determined for the test lamp are averaged to find the final reported calibration value. Detailed procedures for a routine color temperature calibration are given in Appendix C. A typical calibration report is shown in Appendix D.

4.5 Uncertainty

The NBS color temperature scale is based on the NBS spectral irradiance scale. The uncertainties associated with the spectral irradiance scale have been presented in Table 2. Color temperature is a parameter related to spectral quality (relative spectral distribution) of the optical radiation considered. The uncertainties associated with the NBS working lamp standards of color temperature have been estimated by the following procedure. Wavelengths of 650 nm and 450 nm were choosen as representative of red and blue components of the lamp spectrum. The red-to-blue ratio (R/B ratio) was computed for blackbodies at the temperatures of interest. The R/B ratio was altered by the percentage uncertainties given in Table 2 (uncertainty with respect to SI). Computations were performed for the +red, -blue case and the -red, +blue case. The resultant shift in blackbody temperature in K is taken as the uncertainty associated with the NBS working standards. This computation has the nature of a limit-of-error calculation and thus is approximately a 3σ error. These results are listed in the systematic uncertainty column in Table 8.

The present NBS color temperature comparator is an interim apparatus, as discussed in section 1, and has not been extensively characterized. Further, the data base acquired on this instrument is extremely limited. The transfer precision of the instrument has been estimated from the data acquired on five lamps measured over the range 2000 - 3000 K. Each lamp was measured three times at four color temperatures in this range. Pooled estimates of the standard deviation of a single measurement at each color temperature were computed. The uncertainty asigned to the transfer calibration of a test lamp is taken as three times the standard deviation of the mean of three measurements. Table 8 summarizes these uncertainties.

4.6 Discussion

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

Table 8. Color Temperature Uncertainties (3σ)

Color Temp K	Systematic Uncertainty K	Transfer Precision (3σ) K	Total Uncertainty (Quadrature) K
2000	7.0	8.0	10.5
2400	9.0	8.0	12.0
2600	10.0	4.5	11.0
2856	12.5	3.5	13.0
3000	14.0	3.5	14.5

1. The lamps should be turned on and off slowly (15-30 seconds). The lamp should not be moved while lighted.

2. In order to prolong the useful life of the lamps, it is recommended that they be used sparingly, and great care should be taken so that at no time will the current appreciably exceed the value stated in the report. For general use, working standards should be prepared by calibrating them relative to the lamps supplied by NBS. When a laboratory procures standard lamps from NBS it is well to obtain at least three such lamps in order to be able to detect changes that may occur.

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

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

5. Differentiation of equation (10) yields:

$$dI = (B + 2CT_C)\ dT_C \qquad (11)$$

Typical values of the constants A, B, and C in eq. (11) for the airway beacon lamps of the type 500T20/13 are $A = -.45$, $B = 1.0 \times 10^{-3}$, and $C = 1.4 \times 10^{-7}$. Evaluating eq. (11) in the range 2000 K to 3000 K, shows that the sensitivity of the current setting ranges from 0.0016 to 0.0018 amps/K. Since these lamps typically draw about 4 amps at 2856 K, a current setting accuracy of at least 0.1% is required if the color temperature of the lamp is not to be affected by more than 2 K.

REFERENCES

1. V.I. Burns and D.A. McSparron, Photometric Calibration Procedures, NBS Technical Note 594-3, November 1972.

2. G.A. Uriano, et al, Editors, NBS Calibration Services Users Guide 1986-1988, NBS Special Publication 250, July, 1986.

3. CIE Publication #15, Colorimetry, 1971. (See note below)

4. CIE Publication #18.2, The Basis of Physical Photometry, 1983. (See not below)
   See also: F.E. Nicodemus, H.J. Kostkowski, and A.T. Hattenburg, Self-Study Manual on Optical Radiation Measurements, Chapter 1, NBS Technical Note 910-1, March 1976.

5. W.R. Waters, J.H. Walker, and A.T. Hattenburg, NBS Measurement Services: Radiance Temperature Calibrations, NBS Special Publication 250-7.

6. J.H. Walker, R.D. Saunders, and A.T. Hattenburg, NBS Measurement Services: Spectral Radiance Calibrations, NBS Special Publication 250-1, January, 1987.

7. J.H. Walker and D.A. McSparron, NBS Measurement Services: Spectral Irradiance Calibrations, NBS Special Publication 250-20.

NOTE: In the U.S., CIE documents can be purchased by contacting the office of

Dr. K.D. Mielenz, Secretary
USNC-CIE
National Bureau of Standards
Room B306, Metrology Building 220
Gaithersburg, MD 20899
Telephone Number (301) 975-2316

8. See, for instance: C.G. Hughes III, Silicon Photodiode Absolute Spectral Response Self-Calibration Using A Filtered Tungsten Source, Appl. Opt. 21, 2129 (1982).
R.L. Booker and J. Geist, Induced Junction (Inversion Layer) Photodiode Self-Calibration, Appl. Opt. 23, 1940 (1984).
J. Geist, E.F. Zalewski, and A.R. Schaefer, Spectral Response Self-Calibration and Interpolation of Silicon Photodiodes, Appl. Opt. 19, 3795 (1980).

9. See, for instance: E.F. Zalewski and W.K. Gladden, Absolute Spectral Irradiance Measurements Based on the Predicted Quantum Efficiency of a Silicon Photodiode, Optica Pura y Aplicada, 17, 133 (1984).
L.P. Boivin, Calibration of Incandescent Lamps for Spectral Irradiance by means of Absolute Radiometers, Appl. Opt. 19, 2771 (1980).

10. E. Zalewski, et al, Photometric Instrumention and Research (1970 to 1971) NBS Technical Note 594-2, pp. 29, 32, 33, September 1972.

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

12. See, for instance: G. Wyzecki and W.S. Stiles, Color Science: Concepts and Methods, Quantitive Data and Formulae, 2nd edition, John Wiley and Sons, New York, N.Y., 1982

13. J. Bonhoure, Rapport sur la Cinquieme Comparaison des etalons nationaux d'intersite et de flux lumineux (1969), p. 86, 7th session of the Consultative Committee on Photometry (CCP), 1971.

14. J.W.T. Walsh, Photometry, Dover Publications, Inc., 180 Varick Street, New York, N.Y., 1965.

15. A. Kingslake, Applied Optics and Optical Engineering, Academic Press, New York, N.Y., 1965.

16. A.R. Schaefer and K. Mohan, A New Gonioradiometer for Total Flux Measurements, J. Illum. Engr. Soc. 3, 349, 1974.

17. See, for instance: R. Ulbricht, ETZ 21, 595 (1900).
E. Rosa and A. Taylor, Sci. Papers NBS p. 447, 281 (1922).
D. Goebel, Generalized Integrating Sphere Theory, Appl. Opt. 6. 125, 1967.

18. P. Giacomo, Metrologia 16, p. 55-61 (1980), News from the BIPM. This article reports the actions of the 16th Conference Generale des Poids et Measures.

19. IES Lighting Handbook, Reference Volume (1981), J.E. Kaufman, Editor, Section 4, Measurement of Light and Other Radiant Energy.

20. F.E. Nicodemus, Self-Study Manual on Optical Radiation Measurements, Chapter 4, NBS Technical Note 910-2, Feb. 1978.

21. E.H. Eberhardt, Source - Detector Spectral Matching Factors, Appl. Opt. 7, 2037, 1968.

22. CIE Publication #17, International Lighting Vocabulary, 3rd Edition, 1970.

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

24. H.T. Wensel, D.B. Judd, and W.F. Roeser, Establishment of a Scale of Color Temperature, Bur. of Stand. J. Res., 12, pp. 527-536, May 1934.

25. D.B.Judd, the 1949 Scale of Color Temperature, J. Res. Nat. Bur. Stand., 44, January 1950.

26. Color Temperature, Luminous Efficacy and the International Practical Temperature Scale of 1968, Nat. Bur. Stand. Technical News Bulletin, pp. 206-207, 54, No. 9, September 1970.

27. D.A. McSparron, et al, Spectroradiometry and Conventional Photometry, An Interlaboratory Comparison, pp. 5-12, NBS Technical Note, November 1970.

28. See for instance: J.S. Preston, Phys. Soc., Proc. 47, 1935, p. 1012. H.G. W. Harding, Phys. Soc., Proc. 63, 1950, p. 685. J. Sci. Inst., 29, 1952, p. 145. W.J. Brown, J. Sci. Inst., 31, 1954, p. 469.

APPENDIX A

DETAILED PROCEDURES FOR A LUMINOUS INTENSITY CALIBRATION

TABLE OF CONTENTS - APPENDIX A

Detailed Procedures for a Luminous Intensity Calibration

1. Introduction

This procedure describes the luminous intensity calibration of a single 1000-W, inside-frosted lamp. A single lamp is used to illustrate the procedure; in actual practice a group of test lamps would be calibrated.

2. Lamps

2.1 Test Lamp

The test lamp is a 1000-W, inside-frosted, medium bipost lamp with a T-24 bulb. The lamp has been seasoned at rated voltage for approximately 5% of its rated life and has an identifying NBS number etched on the bulb.

2.2 Working Standards

The working standards are the eight 500-W lamps in the NBS 7796 group. They are also inside-frosted, medium bipost lamps, but have a T-20 bulb.

3. Measurement Preparation

3.1 Detector Alignment

Mount the first selenium cell on the detector carriage. Bring the carriage up to the shadowgraph. Remove the aperture mask from the detector. Turn on the shadowgraph light source and align the detector to the zero position on the shadowgraph grid. Note the carriage position on the bar. Replace the aperture mask and move the detector carriage back 2.9 m.

3.2 Lamp Alignment

Put the lamp mount back on the bar. Mount the alignment jig in the lamp mount. Using the alignment jig and the shadowgraph, adjust the height using the cross hairs corresponding to a 4" light center height. Then using the pitch and rotation adjustments, orient the alignment jig so that it is perpendicular to the centerline extending between the center of the detector and the light center. Set the zero position. Cover the shadowgraph grid with the black cloth. Position the baffles as described in section 2.2.2 of the text. Remove the jig and put in the 1st working standard.

3.3 Shunt Box

The electrical measurement circuitry includes a shunt box in series with the lamp. Shunt values must be selected that are greater than the operating current of the working standards or test lamp. Since the 1000-W lamp draws approximately 7.7A, use the 15 A shunt.

3.4 Volt Box

The electrical measurement circuitry includes a volt box in parallel with the lamp. Put the volt box setting on 150 volts.

3.5 Lamp Connections

Make electrical connections to the lamp. Turn on the power supplies with the coarse control turned all the way down. Slowly increase the power until the current is about 1/2 the set value. Let the power supplies and measurement circuitry warm up in this fashion for a short period. During the warm-up period, prepare the run cards.

4. Run Cards

4.1 Working Standards

Three separate run cards are prepared, one corresponding to each selenium cell detector. List the working standards, operating current, shunt value, operational amplifier setting, the source to detector distance, and the bar marking for the detector and source carriages. Reverse the sequence of the working standards on the second run card.

4.2 Test Lamp

Prepare a lamp card for each test lamp. List test number, (if applicable), lamp number, lamp description and current value.

5. Measurements

5.1 Working Standards

Slowly bring the first working standard up to the calibration set current and set the timer for 7 minutes. When timer goes off check current setting, and then record current, voltage, and detector output. Slowly power down the lamp, remove, and repeat for next three working standard lamps.

5.2 Test Lamp

Increase the source-detector distance to 4.17 meters and re-position the baffles. Mount the 1000-W test lamp, warm-up for 7 minutes, and record current, voltage, and detector output.

5.3 Remaining Working Standards

Decrease the source-detector distance to 2.9 m and run the 4 remaining working standards.

5.4 Remaining Measurement Runs

Measurements runs must be repeated with the other two selenium cells. Each detector must be aligned as described in section 3.1 of this appendix.

6. Data Reduction

6.1 Calibration Factor

Divide the assigned luminous intensity value for each working standard by the corresponding measured detector output from the first run. This yields a K-factor in candelas/volt for each working standard. Average the eight K-factors. Multiply the average K-factor by the measured detector output for each working standard. This yields the measured luminous intensity of each working standard for this run in candelas.

6.2 Quality Control Factor

Determine the difference between the assigned output and the measured output for each of the working standards. The sum of the positive differences should equal the sum of the negative differences (allowing for rounding). Neglecting signage, sum the differences. Divide the sum of the differences by the number of working standards to get the average difference. Divide the average difference by the average of the assigned values for the working standards, and multiply by 100 to convert to percent. The resulting so-called "delta" is used as an internal quality control check and should be less than 0.5%.

6.3 Test Lamp Luminous Intensity Value

Multiply the average K-factor in (cd/v) by $(4.17/2.9)^2$ to correct for distance. Multiply the distance-corrected average K-factor by the detector output for the test lamp, thereby producing the luminous intensity of the test lamp in candelas.

6.4 Final Value

Repeat steps 6.1 through 6.3 for the 2nd and 3rd runs. Average the three luminous intensity values to determine the final reported calibration value. Also report the corresponding average current and voltage of the test lamp.

APPENDIX B

DETAILED PROCEDURES FOR A ROUTINE LUMINOUS FLUX CALIBRATION

TABLE OF CONTENTS - APPENDIX B

Detailed Procedures for a Routine Luminous Flux Calibration

1. Introduction

In order to clarify the detailed procedures for a luminous flux calibration, the example which follows is limited to the calibration of a single 200-W lamp. In actual practice, it is likely that more than one lamp would be calibrated.

2. Lamps

2.1 Test Lamp

The test lamp is a 200-W general purpose, inside-frosted, incandescent lamp having a medium-screw base and a PS-30 bulb. The lamp has been seasoned at rated voltage for 4% of its rated life and has an identifying NBS number etched on the neck of the bulb. The customer will usually request the measurement at a specific current, voltage, or color temperature.

2.2 Working Standards

The working standards are the six 200-W lamps in the NBS 6807 group. They are identical to the test lamp, which makes unnecessary any measurements to correct for differences in bulb absorption.

3. Run Card Preparation

3.1 Working Standards

Prepare three run cards, one corresponding to each of the three selenium cells. Label each card as to run number and cell number. On each card, list the calibration current and corresponding luminous flux for each of the working standards. The sequence of the six working standards is the same for the 1st and 3rd cards but is reversed for the 2nd card.

3.2 Test Lamp

Prepare a lamp card for the test lamp. Information on this card should include the lamp designation (NBS number), size of the lamp, type base of the lamp, test number from the NBS test folder, and corresponding run numbers from the run cards for the working standards.

4. Measurement Preparation

4.1 Shunt Box

The measurement electrical circuitry includes a shunt box in series with the lamp. Select a shunt value greater than the operating current of the working standards or test lamp. For the 200-W luminous flux lamps, the 3.0 A shunt is the proper one. (approximately twice the lamp current).

4.2 Volt Box

The measurement circuitry includes a volt box in parallel with the lamp. Put the volt box setting on 150 v.

4.3 Detector

Mount one of the cells in the tube extending from the sphere window. Do not lock the detector in place. Connect the detector to the operational amplifier.

4.4 Lamp Connections

Open sphere and mount the appropriate base/lamp holder in the sphere (medium-screw for the 200-W lamps). Put in 1st lamp of the 6807 group and close the sphere. Complete connections to power supply. Turn on the power supplies with the coarse control turned all the way down. Slowly increase the power until the set current is reached. Set the timer for 7 minutes.

4.5 Final adjustments

Determine final position of detector cell in the tube (distance from diffusing window). The cell must not be saturated and should operate at 80-90% of full scale. Leave the cell in this position for the remainder of the run. Determine the final range on the operational amplifier.

5. Measurements

5.1 Data-Taking

When the timer goes off, recheck the current set. Rotate the input selector switch so the DVM reads the op amp. Set the DVM controls to take an average of 10-30 readings of the op amp output. Record this data on the run card. Rotate the switch and record the lamp voltage. Slowly power down the lamp. Turn off the power supplies. Open the sphere. Remove the lamp and replace with the next lamp in the 6807 group. Close the sphere. Turn on the power supplies. Slowly power up the lamp and set the timer. In this manner, run 1/2 of the working standards.

5.2 Test Lamp

Put the test lamp in the sphere. Slowly increase the power. When the electrical operating point is reached, set the timer. When the timer goes off, use the integrating DVM to take an average of 10-30 readings and record the current, voltage, and op amp reading. Power down the lamp, turn off the power supplies, open the sphere, and remove the test lamp.

5.3 Remaining Working Standards

Run the three remaining working standards. This completes the 1st measurement run.

5.4 Remaining Measurements

Take out the 1st detector cell and insert the 2nd cell. Perform the 2nd measurement run. This procedure will be the same as the first run, except the sequence of the working standards is reversed. A 3rd run is performed with the remaining detector cell, in the same sequence as the 1st run.

6. Data Reduction

6.1 Calibration Factors

Divide the assigned flux value for each working standard by the measured detector output from the 1st run. This yields a K-factor in lumens/volt for each working standard lamp; check for drift. Average the six K-factors. Multiply the measured detector output for each working standard by the average K-factor. This yields the measured lumen output of each lamp for this run.

6.2 Quality Control Factor

Determine the difference between the assigned output and the measured output for each of the working standards. The sum of the positive differences should equal the sum of the negative differences (allowing for rounding). Neglecting signage, sum the differences. Divide the sum of the differences by the number of working standards to get the average difference. Divide the average difference by the average of the assigned values for the working standards, and multiply by 100 to convert to percent. The resulting so-called "delta" is used as an internal quality control check and should be less than 0.5%.

6.3 Test Lamp Luminous Flux Value

Multiply the detector output from the test lamp by the average K-factor from the 1st run producing a lumen output value for the test lamp.

6.4 Final Value

Repeat Steps 6.1 through 6.3 for the 2nd and 3rd runs. Average the three computed lumen output values. This is the final reported calibration value. Also report the average current and voltage of the lamp.

APPENDIX C

DETAILED PROCEDURES FOR A ROUTINE COLOR TEMPERATURE CALIBRATION

TABLE OF CONTENTS - APPENDIX C

Detailed Procedures for a Routine Color Temperature Calibration

1. Introduction

The example chosen here is the color temperature calibration at 2856 K of an inside-frosted luminous intensity standard, which is a commonly requested calibration. A color temperature standard, per se, would be a clear lamp.

2. Lamps

2.1 Test Lamp

The test lamp is a 500-W, inside-frosted, medium bipost lamp. The lamp has been seasoned at rated voltage for 4% of its rated life and has an identifying NBS number etched on the bulb.

2.2 Working Standards

The working standards are the three lamps of the NBS 9171 group. They are identical to the test lamp.

3. Preparation of Run Cards

3.1 Working Standards

A single run card is prepared for each color temperature listing all the working standards on that card. All 3 runs will be recorded on the single card. List the color temperature, assigned current sets for each lamp, and note the fixed shunt value.

3.2 Test Lamp

Describe lamps, note color temperature, identifying NBS number, and test number if appropriate.

4. Measurement Preparation

4.1 Photometer

The telephotometer is warmed-up overnight prior to color temperature calibrations.

4.2 Alignment

Install 1st working standard and note carriage position on bench. Turn on lamp at reduced current. Adjust mounting height of lamp so that the filament center is at the same height as the center of the sphere opening. Bring lamp up to assigned current and set timer for 7 minutes.

4.3 Photometer Sensitivity Adjustments

Select a combination of ND-filter and aperture setting that does not saturate the photomultiplier tube. A typical setting is ND-2 with a 1° aperture setting.

5. Measurements

5.1 Working Standards

Measure and record signal levels through both the R and B filters. Power down the lamp. Repeat procedures for other two working standards. Compute the R/B ratio for each working standard and then average these 3 values. This average R/B ratio then becomes the target for the test lamp.

5.2 Test Lamp

Mount the test lamp and warm-up for 7 minutes at the estimated calibration voltage. Find two currents where R/B is approximately 5% above and below the target R/B ratio. Also record the voltages. Repeat the above procedures for 2 more runs with the working standards and the test lamp.

6. Data Reduction

6.1 Test Lamp

For each run, do a linear interpolation between the high and low currents and find the current corresponding to the target R/B ratio. Final voltage is determined in the same manner. Average the currents from each of the three runs. This is reported as the calibration current for 2856 K and will be the set current for the subsequent luminous intensity calibration (if any). The average voltage is also reported.

APPENDIX D
REPORTS OF CALIBRATION

TABLE OF CONTENTS - APPENDIX D

Note:

The "enclosed descriptions" referred to in these Reports of Calibration are earlier descriptions of the Calibration procedures and have been superceded by the present document.

FORM NBS-443
(REV. 11-[illegible])

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
Gaithersburg, MD 20899

REPORT OF CALIBRATION

for
Luminous Intensity
of
Three 500-Watt Inside-Frosted Lamps
Supplied to:

(See your Purchase Order No. G53488, dated April 16, 1985)

1. Material

Three 500-watt lamps were calibarated for luminous intensity. The lamps have C-13B filaments in T-20 inside-frosted bulbs with medium bipost bases. The lamp designations listed below are etched on the bulbs.

2. Calibration

The lamps were calibrated for luminous intensity in accordance with the enclosed description* of the calibration of inside-frosted lamp standards of luminous intensity. Note especially paragraphs I-C and I-D which describe the orientation and operation of the test lamps. The photometric distance used for this calibaration was 3 meters.

3. Results

Lamp No.	Direct Current (amperes)	Voltage (volts)	Luminous Intensity (candelas)
NBS 10499	3.900	108.87	676
NBS 10500	3.900	109.34	720
NBS 10501	3.900	108.72	703

Prepared by:	Approved by:
Ronald L. Wilkinson	Donald A McSparron
Ronald L. Wilkinson	Donald A. McSparron
Radiometric Physics Division	Radiometric Physics Division
Center for Radiation Research	Center for Radiation Research

NBS Test No.: 534/
Date: January 7, 1986

Page 1 of 1

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*The enclosed description referred to above includes an uncertainty estimate that has been updated in the present document. See Table 2 of the present document for the updated uncertainty values.

FORM NBS-443
(REV. 11-85)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
Gaithersburg, MD 20899

REPORT OF CALIBRATION

for
Luminous Flux
of
One 200-Watt General-Purpose Lamp

Supplied to:

(See your purchase order number LY-3842 dated September 25, 1985.)

1. Material

One 200-watt general-purpose incandescent lamp was calibrated for luminous flux. The lamp designation listed below is etched on the bulb.

2. Calibration

The lamp was calibrated in a two-meter integrating sphere in accordance with the enclosed description "Calibration of Incandescent Lamps for Luminous Flux". The values reported below are based on the NBS scale of spectral irradiance in agreement with the international redefinition of the photometric units in 1979. Values reported on this scale are 0.25% less than those reported on the previous NBS flux scale. This shift is less than the uncertainty associated with the reported luminous flux values. The uncertainty is discussed in Section V and summarized in the final table of the enclosed description.

NBS Test No.: 534/
Date: March 13, 1986

Page 1 of 2

REPORT OF CALIBRATION

Lamp No.	Set Direct Current (amperes)	Voltage (volts)	Luminous Flux (lumens)
NBS10279	1.645	119.81	3485

Prepared by:

Ronald L. Wilkinson

Ronald L. Wilkinson
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Approved by:

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FORM NBS-443
(REV. 11-65)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
Gaithersburg, MD 20899

REPORT OF CALIBRATION

for

Luminous Flux

of

Ten Miniature Lamps

Submitted by:

(See your Purchase Order Number 1344-122-2535 dated January 29, 1986.)

1. Material

Ten minature incandescent lamps were calibrated for luminous flux. The lamp designations listed below are scribed on the lamp bases.

2. Calibration

The lamps were calibrated in a 0.76-meter integrating sphere in accordance with the enclosed description "Calibration of Miniature Lamps for Luminous Flux - 1982". The values reported below are based on the NBS scale of spectral irradiance in agreement with the international redefinition of the photometric units in 1979. Values reported on this scale are 0.25% less than those reported on the previous NBS flux scale. This shift is less than the uncertainty associated with the reported luminous flux values. The uncertainty is discussed in Section VII and summarized in Table 2 of the enclosed description.

NBS Test No.: 534/
Date: March 10, 1986

REPORT OF CALIBRATION

Lamp No.	Direct Current (Amperes-Set)	Voltage (volts)	Luminous Flux (lumens)
NBS 9876	5.800	4.868	405.1
NBS 9878	5.800	4.946	435.5
NBS 9883	5.800	4.999	431.9
NBS 9815	1.000	6.279	69.77
NBS 9816	1.000	6.217	67.90
NBS 9817	1.000	6.317	70.45
NBS 9546	0.197	6.158	6.23
NBS 9548	0.197	6.488	7.43
NBS 9565	0.197	6.035	5.78
NBS 9566	0.197	6.882	6.87

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NBS Test No.: 534/
Date: March 10, 1986

Page 2 of 2

FORM NBS-443
(REV. 11-68)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
Gaithersburg, MD 20899

REPORT OF CALIBRATION
for
Color Temperature
of
One 500-Watt Lamp
Supplied to:

(See your purchase order number 1511 dated July 23, 1985.)

1. Material

One 500-watt airway beacon lamp was calibrated for color temperature. The lamp has a C-13B filament in a clear T-20 bulb with a medium bipost base. The lamp designation listed below is etched on the bulb.

2. Calibration

The lamp was calibrated in accordance with the enclosed description* of the calibration of incandescent lamp standards of color temperature. The currents through the lamp required to produce color temperatures of 2000 K, 2400 K, 2856 K, and 3000 K were determined. The coefficients of the color temperature equation result from a least squares fit of the measured data points to a second order polynomial.

3. Results

Lamp No.	Direct Current (amperes)	Voltage (volts)	Color Temperature (IPTS 1968) (kelvins)
NBS10496	2.460	43.21	2000
	3.228	71.21	2400
	4.152	112.76	2856
	4.463	128.46	3000

NBS Test No.: 534/
Date: December 24, 1985

Page 1 of 2

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*The enclosed description referred to above includes an uncertainty estimate that has been updated in the present document. See Table 8 of the present document for the updated uncertainty values.

The coefficients from the least squares fit to the equation

$$I = A + BT_c + CT_c^2$$

in which I is the current through the lamp in amperes, and T_c is the color temperature in kelvins, are:

$$A = -0.6819$$

$$B = 1.2851 \times 10^{-3}$$

$$C = 1.4305 \times 10^{-7}$$

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