NITED STATES
PARTMENT OF
MMERCE
BLICATION

NBS TECHNICAL NOTE 594-3

Optical Radiation Measurements:

Photometric Calibration Procedures

U.S.
PARTMENT
OF
COMMERCE
National
Bureau
of
Standards

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of a Center for Radiation Research, an Office of Measurement Services and the following divisions:

> Applied Mathematics—Electricity—Heat—Mechanics—Optical Physics—Linac Radiation[2]—Nuclear Radiation[2]—Applied Radiation[2]—Quantum Electronics[3]—Electromagnetics[3]—Time and Frequency[3]—Laboratory Astrophysics[3]—Cryogenics[3].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials and the following divisions:

> Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Reactor Radiation—Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute also monitors NBS engineering standards activities and provides liaison between NBS and national and international engineering standards bodies. The Institute consists of a Center for Building Technology and the following divisions and offices:

> Engineering Standards Services—Weights and Measures—Invention and Innovation—Product Evaluation Technology—Electronic Technology—Technical Analysis—Measurement Engineering—Fire Technology—Housing Technology[4]—Federal Building Technology[4]—Building Standards and Codes Services[4]—Building Environment[4]—Structures, Materials and Life Safety[4]—Technical Evaluation and Application[4].

THE CENTER FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

> Information Processing Standards—Computer Information—Computer Services—Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world, and directs the public information activities of the Bureau. The Office consists of the following organizational units:

> Office of Standard Reference Data—Office of Technical Information and Publications—Library—Office of International Relations.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Part of the Center for Radiation Research.

[3] Located at Boulder, Colorado 80302.

[4] Part of the Center for Building Technology.

Optical Radiation Measurements:

Photometric Calibration Procedures

Velma I. Burns

and

Donald A. McSparron

Heat Division
Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Peter G. Peterson, *Secretary*
NATIONAL BUREAU OF STANDARDS, Lawrence M. Kushner, *Acting Director*,
Issued November 1972

National Bureau of Standards Technical Note 594-3
Nat. Bur. Stand. (U.S.), Tech. Note 594-3, 35 pages (Nov. 1972)
CODEN: NBTNAE

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.46:594-3). Price 60cents.

Preface

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

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

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

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

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

TABLE OF CONTENTS

Photometric Calibration Procedures

Velma I. Burns and Donald A. McSparron

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

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

1. Introduction

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

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

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

---

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

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

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

2.1 Test Lamps

Description

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

Preparation

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

Orientation

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

---

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

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

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

Operation

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

2.2 Photometer

Detector and Amplifier

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

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

Optical Bench

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

---

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

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

2.3 Calibration Procedure

Photometer Calibration

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

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

Measurement Schedule

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

Data Reduction

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

2.4 Discussion

Uncertainty

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Precautions

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

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

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

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

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

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

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

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

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

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

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

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

2.5 References

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

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

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

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

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

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

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

3. Color Temperature

3.1 Description of Calibration of Incandescent Lamp Standards of Color Temperature

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

3.1.1 The NBS Color Temperature Scale

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

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

---

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

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

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

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

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

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

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

3.1.2 Test Lamps

Description

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

Preparation

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

Orientation

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

Operation

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

3.1.3 The NBS Color Temperature Comparator

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

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

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

3.1.4 Calibration Procedure

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

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

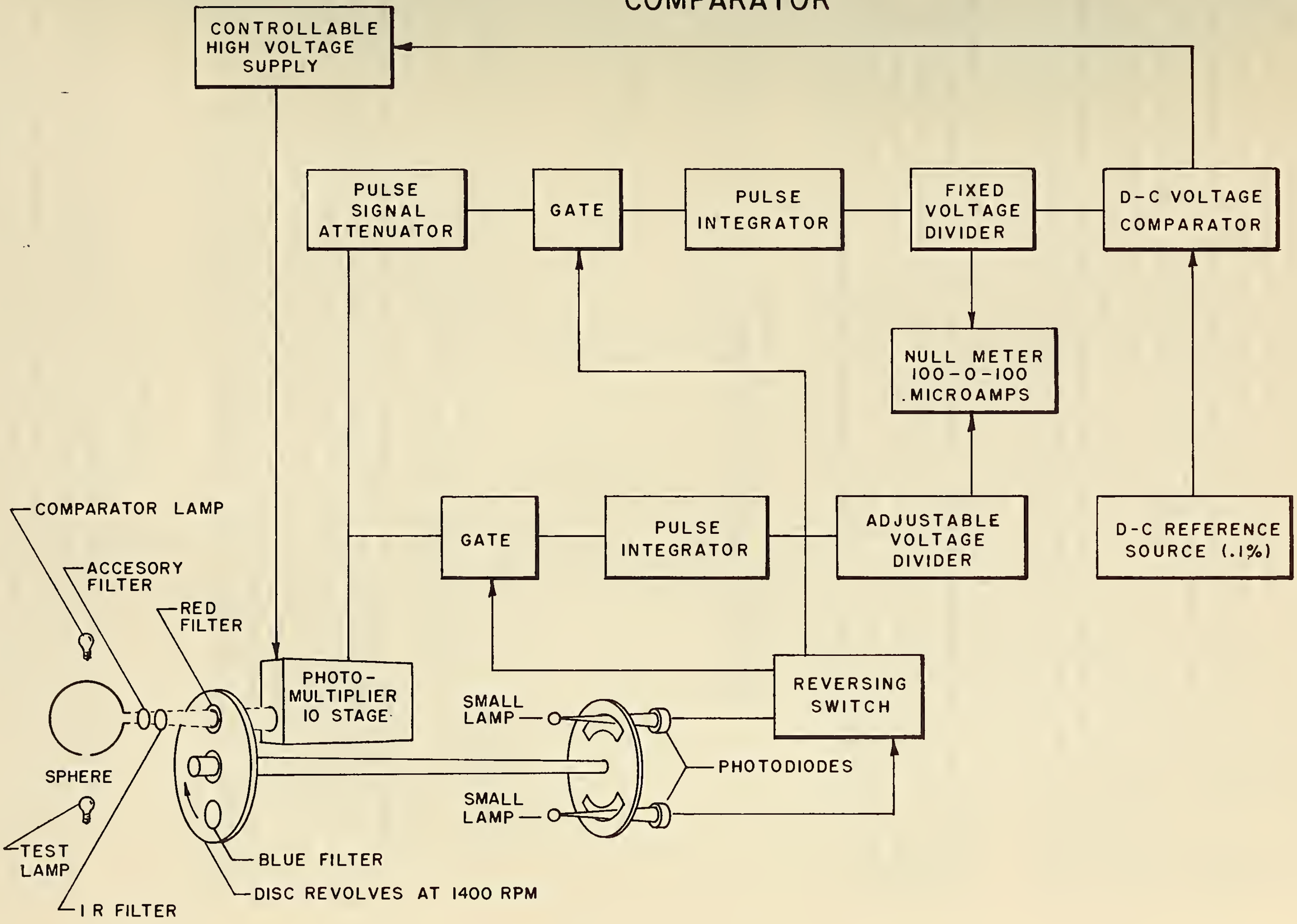
Typically nine test lamps are run at one time. The entire calibration procedure, including calibration of the comparator against each member of the working standard group, is repeated three times on successive half days. In order to check for possible shelf effects (drifts that occur while the lamp remains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

3.1.5 Uncertainty

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

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

NBS BLUE-RED COLOR TEMPERATURE COMPARATOR



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

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

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

*Temperature based on IPTS-48.

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

3.1.6 Discussion

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

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

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

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

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

5. Differentiation of equation 2 yields:

$$di = (B + 2CT_c)\ dT_c \qquad (3)$$

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

3.1.7 References

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

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

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

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

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

[6] D. B. Judd, The 1949 Scale of Color Temperature, J. Res. Nat. Bur. Stand., 44, January 1950.

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

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

[9] Comité Consultatif de Photométrie, 6^{e} Session (1965), Annexe 7, p. 47.

3.2 Inside-Frosted Lamp Standards of Color Temperature

Inside-frosted incandescent lamp standards of color temperature at 2856 K are calibrated at the National Bureau of Standards by a substitution method in accord with the procedures described in Section 3.1, "Description of Calibration of Incandescent Lamp Standards of Color Temperature". For inside-frosted lamps, the exact procedure used differs from the previously described procedure only in the type of lamp calibrated and the standards used for the comparison.

3.2.1 Test Lamps

The test lamps and their preparation are described in Section 2.1, "Description of Calibration of Inside-Frosted Lamp Standards of Luminous Intensity". The test lamps are calibrated while burning base down with the identifying number turned away from the comparator. Lamp orientation is accomplished by aligning the lamp socket so that the lamp posts are held vertically with the plane formed by the axes of the posts perpendicular to the optical axis of the comparator. The light center of the lamp is on, and the lamp pins are equidistant from the optical axis of the comparator (see calibration report for specific light center lengths).

3.2.2 The NBS Color Temperature Scale for Inside-Frosted Lamps

Three inside-frosted, 500-watt incandescent working lamp standards of color temperature have been calibrated at 2856 K and are maintained by NBS. These lamps (NBS 9171, NBS 9172, and NBS 9173) are of the same type as described above. Initial calibration of these lamps was performed spectroradiometrically against the 500-watt, clear-bulb working standards of color temperature (NBS 1926, NBS 1927, and NBS 7875). The spectroradiometer used for this calibration [1] determined the ratios of the spectral radiant powers of the test and standard lamps at every 10 nm from 380 nm to 760 nm with a spectral bandpass of 5 nm. The data reduction assumed that the relative spectral power distribution of the clear-bulb standards was the same as the relative power distribution of a Planckian radiator. The relative spectral power distribution of the inside-frosted lamps thus determined was used to compute their chromaticity coordinates. The procedure described by Kelly [2] was then used to compute the correlated color temperature of the inside-frosted lamps.

3.2.3 References

[1] D. A. McSparron, K. Mohan, R. C. Raybold, R. D. Saunders, and E. F. Zalewski, Spectroradiometry and Conventional Photometry An Interlaboratory Comparison, Nat. Bur. Stand. (U.S.) Tech Note 559, pp. 5-12, November 1970.

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

4. Description of the Calibration of Incandescent Lamps for Luminous Flux

In response to several requests from the users of luminous flux standards, the National Bureau of Standards has calibrated a group of general-purpose incandescent lamps. The lamps range in size from 10 watts to 1000 watts and are approximately 120-volt, base-up burning lamps. They were calibrated in a 2-meter integrating sphere photometer.

4.1 Test Lamps

The lamps to be calibrated were submitted by the users and were stated to have been properly seasoned before submission. Each lamp bears an identifying number etched on the bulb.

4.2 Sphere Photometer

The lamps were calibrated while burning base up in the center of a 2-meter integrating sphere photometer. The sphere is coated with Burch sphere paint. A 7.6-centimeter diameter observation port is located in the sphere wall and is covered with a white diffusing plastic (Plexiglas, color W2447 Rohm and Haas white) flush with the sphere wall. A baffle, also coated with Burch sphere paint is placed between the lamp and the window, 0.55 meters from the window. When measuring 10-watt to 500-watt lamps, the baffle used was a circular disk 17.5 centimeters in diameter. When measuring the 750-watt and 1000-watt lamps, the baffle was shaped roughly like a projection of the lamp and was 15 centimeters by 23 centimeters.

Because of the somewhat selective spectral reflectance of the sphere coating and transmittance of the window, a blue filter is inserted adjacent to the window. The blue filter was selected from a set of filters of graded color temperature altering power, so that the net spectral effect of the sphere reflectance, window transmittance and the blue filter is that the spectral distribution of the flux arriving at the detector is approximately the same as that leaving the lamp. In order to select the proper filter, a lamp was operated at 2856 K color temperature in the sphere. The filter was then selected such that light from the lamp operating in the sphere and transmitted through the window and filter had a color temperature of 2856 K. The proper filter was determined just before this test was started (about four months after the sphere was painted). The correction at that time was approximately 640 K. The correction was determined again after about half of the data had been taken (three months later) and the correction needed was approximately 700 K (a change of about 60 K). At the conclusion of the test the correction needed was still 700 K.

A selenium barrier layer photocell [1] (Weston model 856) equipped with a filter to correct its spectral response to approximately match the CIE luminous efficiency function [2] is placed in a brass tube fitted to the window. The brass tube is coated on the inside with mat black paint. The photocell photocurrent is measured with an operational amplifier (current to voltage converter) arragned in a typical closed-loop configuration. Thus the photocell is operating into a near zero resistance circuit (no voltage across the terminals of the photocell). A five-place digital voltmeter is used to measure the output of the operational amplifier.

Three selenium photocells were used in this test and the deviation from linearity of the response of the detection system with each photocell was determined. This determination was made on a horizontal bar photometer by an inverse square method. The photocell was mounted on the bar at a known distance from a stable monoplane straight-wire filament lamp. The filament was approximately 2 centimeters square. The photocell was moved along the bar and its response noted at various distances from the lamp. The deviation of the response from that which one would expect by applying the inverse square law was attributed to the nonlinearity of the detection system. Distances used were 0.63 meters to 4.17 meters. The lamp was operated at two voltages in order to cover the desired range within these distances. For illuminance at the detector of 3 lux to 800 lux, maximum deviations from linearity for two of the detectors were -4.5% and for the third detector the maximum deviation from linearity was +6.5%.

4.3 Standards

A group of six 300-watt opal bulb lamps (Group NBS 526) operating at a color temperature of approximately 2720 K serves as the NBS standard of luminous flux. The lamps were calibrated by measuring their luminous intensity distributions relative to their luminous intensity in a single direction. The luminous intensity in the single direction was measured by comparison with the NBS standard of luminous intensity. The total luminous flux was then determined by integrating this luminous intensity with respect to angle of view. This work was done about 30 years ago and some check measurements were made about 14 years ago and about 5 years ago. The lamps are used very infrequently to calibrate NBS working standards.

The NBS working standards were recalibrated at the start of this test by comparing them in six runs, using four photocells (the three photocells mentioned above and one silicon photodiode), with the 300-watt opal-bulb lamps. The NBS working standards are listed in the following table. Each group of standards consists of six lamps.

Lamp Group Designation	Nominal Wattage	Bulb	Filament	Approximate Color Temperature	Lumens
NBS 162	500	PS 35 clear gas-filled	C-7	2800 K	6440
NBS 6807	200	PS 30 frosted gas-filled	C-9	2900 K	3260
NBS 3158	100	A-21 frosted gas-filled	C-9	2900 K	1641
BS 5470	60	S 21 clear vacuum	Squirrel Cage	2450 K	446

Corrections for nonlinearity of the detection system were applied. These corrections varied between -0.58% and +1.25%. In addition, corrections for the difference in the lamp absorption between the opal-bulb lamps and the working standards were determined and applied. In order to determine the correction due to lamp absorption, a 200-watt lamp was placed at the bottom of the sphere and held at constant voltage. Light from the 200-watt lamp was baffled from the sphere window and from unlighted lamps placed in turn at the center of the sphere. Readings were made of the detector output when each of the opal-bulb lamps (unlighted) was in the socket at the center of the sphere and again when each of the working standards (unlighted) was in the socket at the center of the sphere. The correction is the ratio of the average reading taken with each group of working standards to the average reading taken with the opal-bulb lamps in the sphere. For these lamps the corrections varied between -0.16% and -0.32%.

4.4 Calibration of the Test Lamps

The test lamps were calibrated in groups of approximately twenty. Three measurements were made on each lamp in the group, one on each of three days. Each lamp was placed in the sphere and allowed to operate at its designated current or voltage for ten minutes before measurements of voltage, current, and luminous flux were made. The lamps were measured in the following order: 2 standards, one half of the test lamps, 2 standards, the other half of the test lamps, and the remaining two standards. The lamps submitted by any single laboratory were distributed throughout the group and not measured successively. The three photocells described above were used, one on each of the three days. Test lamps were compared with standards which were closest to them in wattage. Corrections for the non-linearity of the photocell were applied. These corrections were greatest for the 10-watt lamps. For one photocell the correction was as high as 2.4%. Corrections for the difference in absorption were determined by the same method as described for the calibration of the working standards. Absorption corrections ranged from +0.66% to -0.07%.

4.5 Uncertainties

The geometrically total luminous flux output of the prime reference group (the six 300-watt opal-bulb lamps) was obtained by measuring the luminous intensity of the lamps in a large number of directions relative to the intensity in a reference direction (distribution photometry). Determination of the luminous intensity of the lamp in this reference direction, together with integration of these relative intensity measurements then allowed computation of the total luminous flux output of the lamps. Distribution measurements were made three times, twice in 1938 and once in 1958, on three different instruments. No detailed error estimates were made for these measurements. In the absence of more fundamental error estimates, the maximum observed range among the three sets of measurements, for any member of the prime reference group, will be taken as the estimate of the uncertainty of the distribution photometry measurements. This range is 0.7%.*

The uncertainties associated with the direct substitution comparison of the luminous intensities of two identical inside-frosted lamps have been discussed in section 2.4 [3]. For this type of direct substitution transfer the uncertainty assigned is 4.1% relative to SI (individual components combined in quadrature). For the luminous intensity determination on the prime reference flux group, an additional uncertainty must be allowed because of the difference between the luminous intensity standard lamps and the flux standard lamps. Specific differences that will affect the measurements are: (1) the different physical sizes of the lamps (23 cm long, PS-40 bulbs for the flux lamps versus 17.8 cm long, T-20 bulbs for the luminous intensity standards); (2) different spectral distributions (2720 K for the flux lamps versus 2856 K for the luminous intensity standards); and (3) inability to repeat the alignment of the flux lamps due to inadequate reference positions on the lamps. Inverse square law considerations lead to an estimate of 0.5% for the uncertainty introduced by the differing physical sizes of the lamps. Spectral differences of the magnitude encountered here have been observed to produce differences of up to 0.25% in other similar luminous intensity measurements. Finally, misalignment, particularly a systematic difference in alignment between the distribution photometers and the photometers used for the luminous intensity determinations might produce an error of 0.25% (based on a study of the distribution curves and an estimated ability to align the lamps to ±2°). It is unlikely that these uncertainties would have the same sign and therefore, they are combined in quadrature. This results in an uncertainty relative to SI of 4.2%.

---

*The uncertainties being discussed are listed in the table on page 25.

The uncertainty of transfer from the prime reference flux group to the NBS working standards may be divided into three parts, those uncertainties due to: (1) geometric effects; i.e., the presence of objects, such as the lamp, its support, and the baffle, in the sphere and their geometrical arrangement; (2) spectral effects, i.e., differences in the spectral distribution of the lamps being compared or a difference between the spectral response of the detector being used and the CIE spectral luminous efficiency function; and (3) random variations of the measurements. No detailed analysis of the geometric and spectral effects have been made. However, regarding the geometric effects, differences as large as 1% have been observed when using a sphere geometry described above compared to a very different geometry requiring more objects in the sphere during the measurements. An allowance of 1% has been made for this source of error. Uncertainties due to the spectral effects have not been extensively evaluated. An allowance of 1% is the best guess estimate for these. For random variations, the standard deviation of a single measurement obtained from a population of 144 measurements (6 measurements on each of the 6 lamps on each of the 4 groups of working standards) was 0.14%. The uncertainty assigned for the random variations was three times the standard deviation of the mean of the 6 measurements on each lamp or 0.2%. These uncertainties combined in quadrature give an uncertainty of 1.4% relative to the prime reference group and when combined in quadrature with the SI uncertainty of the prime reference group yield 4.4%.

The uncertainty of the transfer from the NBS working standards to test lamps supplied to other laboratories depends on the size and operating color temperature of the test lamps relative to the standard group used to calibrate them. For the test lamps which are the same size and color temperature as the standards used, the uncertainty is estimated from the random variations. This was computed as three times the standard deviation of the mean of the three measurements made of each of the test lamps and is 0.4%. For the uncertainty of the transfer from NBS working standards to test lamps of other sizes and color temperatures, additional uncertainties as large as 1.0% for geometric differences and 1.0% for spectral differences must be included. Combining these in quadrature results in an uncertainty of 1.5%.

The total uncertainties of the test lamps relative to SI or to the NBS prime reference group are obtained by combining in quadrature either the above 0.4% or 1.5% with the 4.4% or the 1.4% referred to above and listed in the table. The resulting SI total uncertainty is 4.4% to 4.7% and the total uncertainty relative to the prime reference group is 1.5% to 2.0%. The specific value depends on the relative size and color temperature of the test lamps and the NBS working standard lamps used to calibrate them.

TABLE OF UNCERTAINTIES

Uncertainty of the Prime Reference Group

Uncertainty of the distribution measurements	0.7%	
Uncertainty of the NBS luminous intensity scale relative to SI (individual uncertainties combined in quadrature)	4.1%	
Additional uncertainty of the luminous intensity transfer because of:		
(1) different physical sizes of the lamps	0.5%	
(2) spectral differences	0.5%	
(3) alignment of flux lamps	0.25%	
Total uncertainty relative to SI		4.2%

Uncertainty of the NBS Working Standards

Uncertainty of the transfer from the prime reference group because of:		
(1) geometric differences	1.0%	
(2) spectral differences	1.0%	
(3) random variations	0.2%	
Total uncertainty relative to the NBS prime reference group		1.4%
Total uncertainty relative to SI		4.4%

Uncertainty of the Test Lamps

Uncertainty of the transfer from the NBS working standards		
(1) for lamps of the same size and color temperature as the working standards	0.4%	
(2) for lamps of other sizes and color temperatures	1.5%	
Total uncertainty relative to SI	4.4% to	4.7%*
Total uncertainty relative to the NBS prime reference group	1.5% to	2.0%
Total uncertainty relative to the NBS working standards	0.4% to	1.5%

*depending on the relative size and color temperature of the test lamps and the NBS working standard lamps used to calibrate them.

NBS participated in the fifth international intercomparison of national standards of luminous flux in 1969. The results of this intercomparison [4] showed the NBS luminous flux standards to be 0.7% above world mean. However, later investigations have shown that the technique used for calibrating the lamps for this intercomparison resulted in the assignment of luminous flux values which were low by 0.6% relative to the technique used in the present test. Thus the values assigned to the lamps calibrated at this time are estimated to be higher than world mean by 1.3%.

The NBS 200-watt group of working standards (group NBS 6807) and 200-watt lamps of the same type which have been submitted for calibration several times appear to be drifting in luminous flux output relative to lamps of other sizes and relative to the NBS prime reference group (approximately 1% since 1962). Therefore, these lamps should be checked frequently.

4.6 Care and Handling

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

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

1. The lamps should be turned on and off slowly (15-30 seconds), and great care should be taken so that at no time will the current through a lamp appreciably exceed the value stated in the report.

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

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

4. The variation of luminous flux of a tungsten filament lamp is approximately related to the variation in its current by the formula: [5,6]

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

where ϕ is the luminous flux, i is the lamp current and K is 6.25 for gas-filled lamps and 6.05 for vacuum lamps. Thus a current measurement accuracy of at least 0.032% is required if it is not to affect the luminous flux to greater than 0.2%.

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

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

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

8. When comparing lamps which are nearly identical in physical size, absorption, luminous flux, and color temperature, the corrections listed above in 5, 6, and 7 may not be significant.

4.7 References

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

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

[3] National Bureau of Standards, Technical News Bulletin, p. 44, (February 1972).

[4] Bureau International des Poids et Mesures, Rapport Sur La Cinquieme Comparaison des Etalons Nationaux D'Intensite et de Flux Lumineux (1969).

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

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

FORM NBS-114A (1-71)

U.S. DEPT. OF COMM.
BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO. NBS TN-594-3

2. Gov't Accession No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE

OPTICAL RADIATION MEASUREMENTS:
Photometric Calibration Procedures

5. Publication Date November 1972

6. Performing Organization Code

7. AUTHOR(S) Velma I. Burns and Donald A. McSparron

8. Performing Organization

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address

Same as No. 9.

13. Type of Report & Period Covered Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

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

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

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

Calibration procedures; color temperature; luminous flux; luminous intensity; photometry; uncertainty.

18. AVAILABILITY STATEMENT

☒ UNLIMITED.

☐ FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NTIS.

19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED

21. NO. OF PAGES 35

22. Price .60¢

USCOMM-DC 66244-P71

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts. Includes listings of other NBS papers as issued.

Published in two sections, available separately:

- **Physics and Chemistry**

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $9.50; $2.25 additional for foreign mailing.

- **Mathematical Sciences**

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $5.00; $1.25 additional for foreign mailing.

TECHNICAL NEWS BULLETIN

The best single source of information concerning the Bureau's measurement, research, developmental, cooperative, and publication activities, this monthly publication is designed for the industry-oriented individual whose daily work involves intimate contact with science and technology—*for engineers, chemists, physicists, research managers, product-development managers, and company executives.* Includes listing of all NBS papers as issued. Annual subscription: Domestic, $3.00; $1.00 additional for foreign mailing.

Bibliographic Subscription Services

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau: Cryogenic Data Center Current Awareness Service (weekly), Liquefied Natural Gas (quarterly), Superconducting Devices and Materials (quarterly), and Electromagnetic Metrology Current Awareness Service (monthly). Available only from NBS Boulder Laboratories. Ordering and cost information may be obtained from the Program Information Office, National Bureau of Standards, Boulder, Colorado 80302.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality, and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other-agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

Consumer Information Series. Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

CATALOGS OF NBS PUBLICATIONS

NBS Special Publication 305, Publications of the NBS. 1966-1967. When ordering, include Catalog No. C13.10:305. Price $2.00; 50 cents additional for foreign mailing.

NBS Special Publication 305, Supplement 1, Publications of the NBS, 1968-1969. When ordering, include Catalog No. C13.10:305/Suppl. 1. Price $4.50; $1.25 additional for foreign mailing.

NBS Special Publication 305, Supplement 2, Publications of the NBS, 1970. When ordering, include Catalog No. C13.10:305/Suppl. 2. Price $3.25; 85 cents additional for foreign mailing.

Order NBS publications (except Bibliographic Subscription Services) from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
215