NBS Measurement Services:

Radiance Temperature Calibrations

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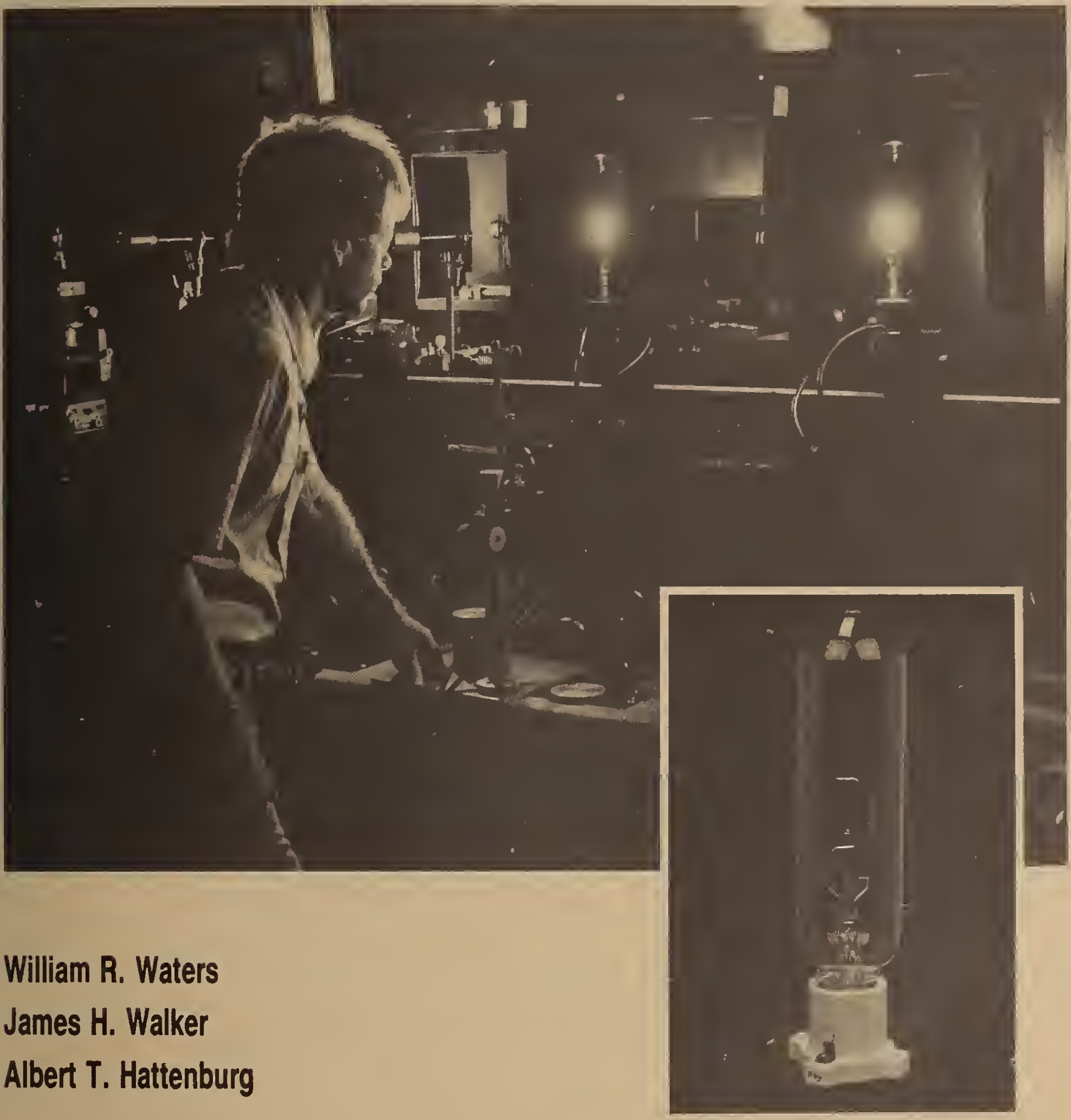

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U.S. Department of Commerce
National Bureau of Standards

Center for Radiation Research

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

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

NBS MEASUREMENT SERVICES: RADIANCE TEMPERATURE 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 250-7), NBS Measurement Services: Radiance Temperature Calibrations, by W. R. Waters, J. H. Walker, and A. T. Hattenburg, is the seventh to be published in this new series of special publications. It describes the measurement methods and instrumentation used in the realization and transfer of the International Practical Temperature Scale (IPTS-68) from 1073K to 2573K through spectral radiance calibrations of tungsten ribbon filament lamps (see test numbers 35010C-35060C 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.

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ABSTRACT: This report describes the measurement methods and instrumentation used in the realization and transfer of the International Practical Temperature Scale (IPTS-68) above the temperature of melting gold. The determination of the ratios of spectral radiance of tungsten-strip lamps to a gold-point blackbody at a wavelength of 654.6 nm is detailed. The response linearity, spectral responsivity, scattering error, and polarization properties of the instrumentation are described. The analysis of sources of error and estimates of uncertainty are presented. The assigned uncertainties (three standard deviations) in radiance temperature range from ±2°K at 2573°K to ±0.5°K at 1073°K.

KEY WORDS: calibrations; gold-point blackbody; radiance temperature; response linearity; standards; tungsten-strip lamps.

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I. INTRODUCTION

The National Bureau of Standards issues standards of radiance temperature calibrated in the range 800 to 2300°C on the International Practical Temperature Scale (IPTS-68). The standards are tungsten strip-filament lamps with cylindrical glass envelopes. The lamps are operated on direct current and require electrical power from about 10 amperes and 1 volt at 800°C to about 41 amperes and 12 volts at 2300°C. Uncertainties range from ±1/2 to +2°C. Visual optical pyrometers are calibrated in their design range, with larger uncertainties. The lamp standards and pyrometer calibrations are listed in NBS Special Publication 250 [1] as 35050C, 35060C, 35010C, 35020C, 35030C and 35040C (old numbers 7.4F, 7.4G, 7.4B, 7.4C, 7.4D, 7.4E) . Photoelectric pyrometers are accepted on a special test basis, under SP250 number 35070S (old number 7.4A).

II. BASIC THEORY (CALIBRATION DESIGN)

Temperatures above 1064.43°C (1337.58°K) are defined on the International Practical Temperature Scale of 1968 [2] in terms of the ratio of spectral radiances of two blackbody sources, one of which is maintained at the temperature of freezing gold (gold-point blackbody). Spectral radiance is the radiant power contained in a defined area, solid angle, and wavelength interval,

$$L_\lambda = d^3\Phi/dA\cdot\cos\theta\cdot d\omega\cdot d\lambda \qquad (1)$$

where L_λ is the spectral radiance, Φ is the radiant flux, A is the area, θ is the angle between the surface normal and the direction of propagation, ω is the solid angle about that direction, and λ is the wavelength. The relation between spectral radiance, wavelength and temperature is given by Planck's Law,

$$L_\lambda = c_1/\pi\cdot\lambda^5\cdot[\exp(c_2/\lambda\cdot T) - 1] \qquad (2)$$

where c_1 and c_2 are the first and second radiation constants, λ is the wavelength in vacuo, and T is the temperature. The defining equation for the IPTS above 1337.58°K is therefore

$$r = L_\lambda(T)/L_\lambda(T_{Au}) = [\exp(c_2/\lambda\cdot T_{Au}) - 1)]/[\exp(c_2/\lambda\cdot T) -1] \qquad (3)$$

where $L_\lambda(T)$ and $L_\lambda(T_{Au})$ are the spectral radiances of the two blackbodies at temperatures T and T_{Au}, T_{Au} is the temperature of freezing gold defined as 1337.58°K, r is their ratio, and c_2 is defined as 1.4388 cm-°K. In principle, a measurement of the ratio at a discrete wavelength with a linear response instrument yields the value of T.

In practice, the radiance temperature scale is realized with an instrument of finite bandpass, and an integral form of Eqn. 2 must be used.

$$r = \int L_\lambda(T)\cdot R_\lambda\cdot d\lambda \;/\; \int L_\lambda(T_{Au})\cdot R_\lambda\cdot d\lambda \qquad (4)$$

where R_λ is the spectral responsivity of the instrument and includes the spectral transmittance of the wavelength-limiting element (e.g., interference filter or monochromator), the spectral transmittance of all other optical elements, and the spectral responsivity of the detector. A determination of R_λ allows a calculation of T from Eqns. 2 and 4. Determination of the ratio for a range of values provides a temperature scale over the corresponding temperature range.

The radiance temperature scale is typically maintained and disseminated on tungsten-strip lamps, which possess a repeatable current vs radiance-temperature relationship not available in present variable-temperature blackbodies. Realization of the scale with these lamps and a gold-point blackbody is also practical, and is the typical procedure followed by standards laboratories [3]. This scale is valid only for the wavelength of realization, since the spectral distributions of the lamps are not known functions. Traditionally the wavelength of realization has been near 650 nm, a convenient region for visual optical pyrometers. At NBS, a spectroradiometer system is presently being used and a wavelength of 654.6 nm (wavelength of a thorium spectral line) has been chosen. This method requires that the instrument relative spectral responsivity function extend only over a small spectral range, or is known accurately enough to determine the wavelength at which the integrands of Eqn. 3 have the same ratio as the integrals.

III. MEASUREMENT APPARATUS

Until 1984, radiance temperature calibrations were performed on the NBS Photoelectric Pyrometer [4]. Component failure on this instrument led to the transfer of the measurements to the Facility for Automated Spectroradiometric Measurements (FASCAL) pending development and characterization of a new photoelectric pyrometer (see section VIII). FASCAL, which is also used for spectral radiance [5,6] and spectral irradiance [7] calibrations, is the instrument described in this report. A block diagram of the system is shown in Figure 1.

1. Gold-point Blackbody

The Gold-point Blackbody (GPBB) is a horizontal graphite cylinder with a small viewing hole (diameter 1 mm) at one end, and a conical cavity at the other. The cylinder is surrounded by 0.99999 pure gold, and the crucible containing the gold is surrounded by heating coils and an insulated case. The construction and characterization of the GPBB have been detailed in prior reports [4]. The estimated emissivity is 0.9999. The duration of a melt or freeze plateau is approximately 5 minutes, and the time delay between these observation periods is about 5 minutes.

2. Lamp Sources

Tungsten-strip filament lamps are used both in the realization of the radiance temperature scale and as secondary standards for scale

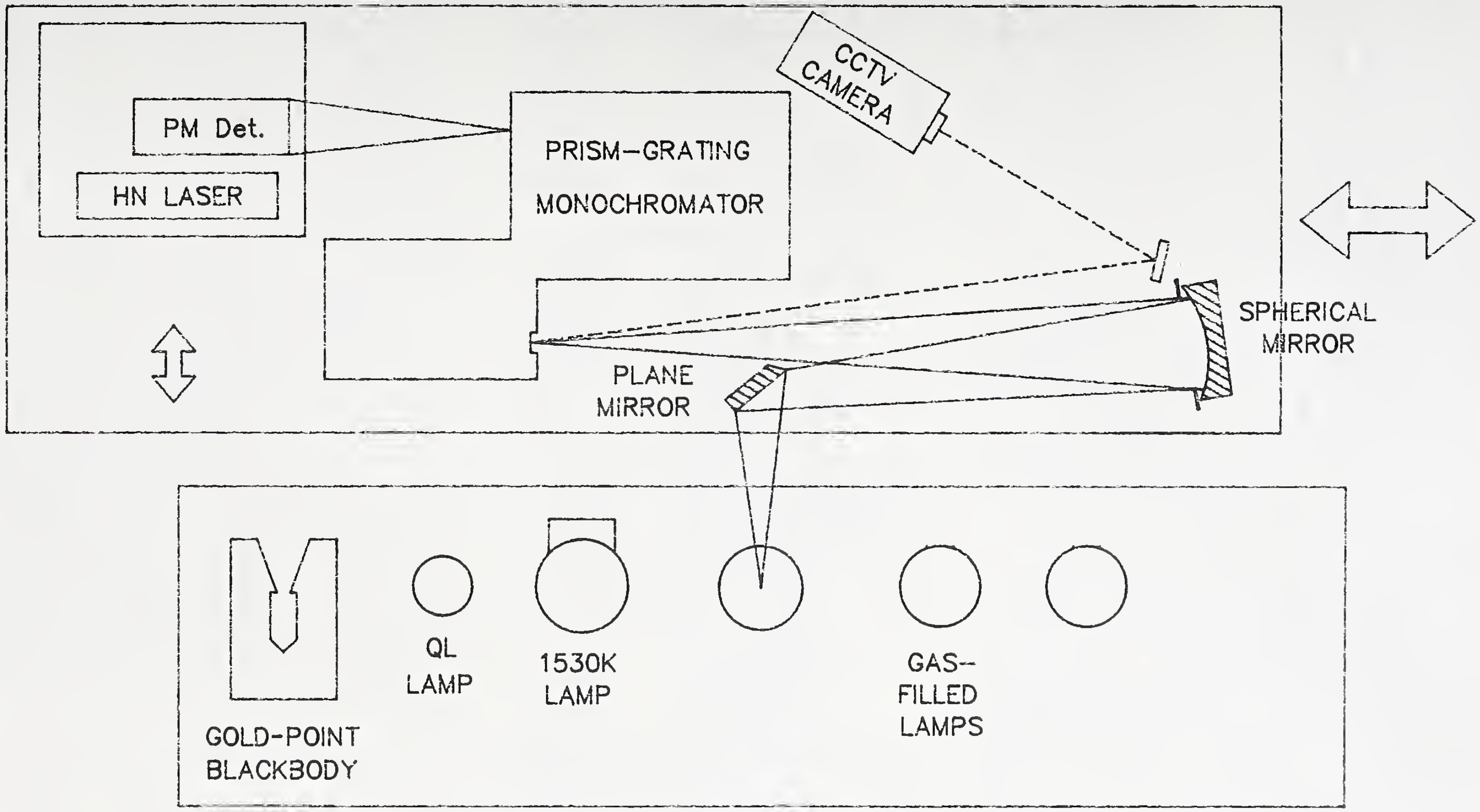

FIGURE 1. FASCAL Radiance Temperature Measurement

dissemination. Each filament has a small notch in one edge, about midway along its length, to aid in determination of the filament portion to be calibrated (target area). A small mark is placed on the rear of the lamp envelope to permit reproducible angular positioning. The lamps are rigidly fastened in source mounts which allow translation along, and rotation about, three mutually perpendicular axes. These motions are required for precise alignment and for radiometric scans in translation and rotation. The lamps are operated on direct current, provided by stabilized (0.005% regulation) power supplies. Current measurements are provided with the aid of manganin shunts (0.01 or 0.001 ohms) and a 5-1/2 digit voltmeter.

a. Vacuum Lamps. Vacuum tungsten-strip lamps of the Quinn-Lee type [8,9] are used in the scale realization. One lamp is operated at a single current to produce a spectral radiance equal to that of the gold-point blackbody at 654.6 nm. A second lamp is operated at a single current to produce a spectral radiance of about eight times that of the gold-point blackbody at 654.6 nm (about 1530°K radiance temperature). Both lamps are stable to better than 0.02% over two hundred hours when operated under these single-level conditions.

b. Gas-filled Lamps. Gas-filled tungsten-strip lamps are calibrated as secondary standards for dissemination of the radiance temperature scale. Prior to calibration, the lamps are annealed at a radiance temperature of 2350°C for 2 hours on direct current. Each lamp is examined for the variations in spectral radiance with angle of emission, while set at a radiance temperature of 1700°C. The lamp orientation is chosen to minimize variations in spectral radiance with rotation, and an alignment arrow is then etched on the rear of the envelope. The amount and orientation of polarization effects are also determined. Lamps selected for calibration display a degree of polarization of 0.005 or less. Appendix A shows a typical calibration report and accompanying descriptive material which provide a table of radiance temperature versus current, degree of lamp polarization, estimated uncertainties, and precautions regarding lamp operation.

3. Spectroradiometer

a. Fore-optics. Sources are imaged with unit magnification at the entrance slit of the monochromator by the two front-surface aluminized mirrors shown in figure 1. The mirror surfaces are stripped and recoated at intervals to reduce signal loss due to oxidation. The plane mirror directs the beam to the spherical mirror (radius of curvature 1220 mm) along a line about 1.5 degrees from the spherical mirror axis. The spherical mirror focuses the beam onto a mirror-surfaced mask, placed immediately in front of the entrance slit. The mask is engraved with horizontal and vertical scales with 0.1 mm divisions, and is viewed at high magnification by either a telescope or a video camera to allow for precise positioning of the sources. The mask determines the height of the system field stop (source target area). The entrance slit determines the width. The stop dimensions are 0.8 mm high by 0.6 mm wide for the scale realization and transfer. The system aperture stop is located within the monochromator.

b. Monochromator. A prism-grating double monochromator is employed to minimize spectral scattering and avoid multiple orders. The dispersion is about 4 nm/mm at the 654.6 nm wavelength setting. The entrance aperture (solid angle) is rectangular in shape, with a vertical angle of 0.125 radians and a horizontal angle of 0.0625 radians. The wavelength setting is calibrated against a spectral line standard (thorium) and is repeatable to within 0.05 nm. The entrance, intermediate, and exit slits are adjustable from 0.01 to 3.0 mm as a unit, resulting in a nearly triangular-shaped spectral responsivity function.

c. Detector. For the radiance temperature determinations an end-on 11-stage photomultiplier with quartz window and S-20 spectral response is placed behind the exit slit. The detector is cooled to 258°K with a thermoelectric cooler. The anode current is amplified and converted to a 0-10 volt signal by a programmable amplifier. In order to ensure linearity of response, the current is normally restricted to a maximum of 500 nanoamperes by selection of appropriate applied voltage for the photomultiplier. The signal is fed to a 5 1/2 digit voltmeter, capable of integration times ranging from one second to several minutes. To facilitate alignment of optics or sources, a He-Ne laser is placed at the detector position, so that its beam passes through the monochromator and fore-optics in the reverse direction.

4. Control and Data Acquisition System

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

The system is directed by a microcomputer and a high-speed disk system for program and data storage. A modular interface controller [10] provides the link between instruments and computer. All measurement signals are multiplexed into the digital voltmeter through the interface scanner, and the instruments are remotely programmed and controlled through interface modules. All instrument settings and signal outputs are printed and stored on disk for later analysis. The spectroradiometer (fore-optics, monochromator, and detector) and a closed-circuit TV camera are mounted on a carriage. The carriage can be positioned by remote command along a linear track, to align the spectroradiometer with one of the sources mounted at fixed stations along the track. The average move time between stations is a few seconds, and positions are repeatable to about 0.1 mm. The TV camera presents a highly magnified image of the monochromator entrance slit mask to displays at the spectroradiometer and at the operator console, for initial source alignment and subsequent monitoring.

IV. MEASUREMENT OF INSTRUMENT AND SOURCE PARAMETERS

1. Spectral Responsivity Function

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

The responsivity factor is obtained by spectrally scanning a continuous source standard of spectral radiance with narrow (0.1 mm) slits. To determine the slit-scattering function, an integrating sphere irradiated by a krypton or argon laser is spectrally scanned by the spectroradiometer, with the slit widths set at the 0.6 mm width used in the scale realization and transfer. The plot of the output signal versus wavelength is the mirror image of the plot of the slit-scattering function versus wavelength [11]. For a 647 nm krypton laser, the function is nearly triangular in shape with a width at half-height of 2.2 nm. Relative to the peak value, the measured values decrease to about 10^{-3} at 3 nm, 10^{-4} at 15 nm, and 10^{-7} at 70 nm from the central wavelength. At 150 nm from the central wavelength, the value decreases to 10^{-8} in the short-wavelength wing and to 10^{-9} in the long-wavelength wing. Scans with 488 and 514 nm (argon), and 676 nm (krypton) yield similar results. These values were confirmed over the central and near wings portion of the function by measurements with the direct method, using a dye laser tuned through a series of wavelengths with the spectroradiometer set at a fixed wavelength [10]. Since the function changes very slowly with wavelength in the visible region, the measurement at 647 nm yields the slit-scattering function at 654.6 nm.

2. Linearity of Response

The degree of linearity of the spectroradiometer response is determined with an automated beam conjoiner [13]. A beam from a constant source is split into two branches, whose fluxes are independently attenuated or blocked before recombination and further attenuation. The flux contribution from both branches is equal to the sum of the fluxes from each branch when measured separately (additivity). The device provides ninety-six levels of flux ranging over a factor of about five hundred. The levels are presented in random order to avoid systematic errors, and are interspersed with twenty-nine zero flux levels. A microcomputer controls the attenuating filters and records the filter positions and radiometer signals. The data is least-squares fitted to a polynomial response function, to determine a correction factor by which the radiometer output signal must be multiplied to obtain a quantity proportional to radiant flux.

The measured instrument response is linear to within ±0.2% for a range of photomultiplier anode currents from 1 to 500 nanoamperes. For currents much less than 1 nanoampere, the signal is limited by noise. For currents greater than one microampere, the linearity correction increases rapidly, rising to 3% at 7 microamperes. The anode current is restricted to less than 500 nanoamperes during measurements by selection of appropriate photomultiplier tube voltage. Correction factors for the amplifier ranges are determined from measurement of a known electrical current and combined with the linearity correction factor.

3. Polarization

The polarization properties of the spectroradiometer and the gas-filled lamps are measured with the aid of dichroic (linear) polarizers positioned in motorized rotating mounts. The sheet polarizer properties and those of the spectroradiometer are determined in an initial set of experiments, using an illuminated integrating sphere as a source of unpolarized radiation. The characterized polarizer and spectroradiometer are then used to measure the polarization properties of the lamp sources.

The determination of spectroradiometer and sheet polarizer properties consists of spectral radiance measurements of the sphere source alone, with a pair of similar polarizers interposed in the beam and set at a number of angular positions (rotations about the optic axis), and with each polarizer individually placed in the beam at the same angular positions. In order to account for departure from ideal behavior, a Mueller transmittance matrix [14] containing six parameters is assumed for the sheet polarizers. Circular polarization is assumed to be negligible. The spectroradiometer polarization direction is determined in a preliminary experiment and chosen as the polarization reference direction, leaving only the degree of polarization to be determined for the instrument. Our measurements provide about 200 equations involving ten unknowns, whose values are then obtained by a non-linear least-squares solution.

The sphere source is replaced by the lamp source whose properties are to be measured using a characterized sheet polarizer and spectroradiometer. Measurements are made with the lamp alone and with the polarizer set at the same angular positions as before. This results in 25 equations involving the two source unknowns, whose values are obtained by a least-squares solution. The polarization of the lamp source is specified by the direction of maximum linear polarization γ, and the degree of polarization

$$p = (L_{max} - L_{min}) / (L_{max} + L_{min}) \qquad (5)$$

where L_{max} and L_{min} are the maximum and minimum readings of a polarization- indifferent radiometer when an ideal linear polarizer is rotated in the source beam. The factor (see App. B) required to reduce the signal ratio of Eqn. 4 to a value which would be obtained with a polarization-indifferent radiometer is

$$(1 + Bp_1)^{-1}$$

where $p_1 = p\cdot\cos 2\gamma$ and B is the spectroradiometer polarizance (degree of linear polarization introduced by the spectroradiometer). For the spectroradiometer employed here, the measured polarizance is 0.26 at 654.6 nm. The degree of polarization of a typical lamp selected for calibration is about 0.003. The uncertainty in the radiometer polarizance B is estimated as ±0.0005, and the lamp polarization uncertainties are estimated as ±0.002 (uncertainties are stated at the three standard deviations level). A more detailed description of the measurement process and data analysis is given in Appendix B.

4. Size of Source

The "size of source" effect (signal contribution due to flux which originates outside the target area and is scattered into the measured beam by the fore-optics) is determined by observing the signal from a 0.6 by 0.8 mm segment of a uniform diffuse source, and noting the change in signal when the surrounding area of the source is changed by placing various masks on the diffuse source. The masks expose source areas which closely approximate the radiant areas of the lamp and blackbody sources used in the scale realization and transfer. As a check, the effect is also evaluated by observing changes in the near-zero signal from a "black hole" (an absorbing cavity slightly larger than the 0.6 by 0.8 mm field stop) as the various surrounding area masks are positioned. The observed differences are used to apply a correction to the signals observed in source comparisons. The measured effect varies from 0.04% to 0.1% at 654.6 nm depending upon the elapsed time since the last mirror recoating.

V. PROCESS OF REALIZATION AND TRANSFER

The process of realization and transfer consists of three steps, all carried out at a wavelength of 654.6 nm. In step one, the gold-point spectral radiance is transferred to a Quinn-Lee vacuum lamp. In step two, a second vacuum lamp at about 1530°K radiance temperature (about eight times the gold-point spectral radiance) is compared to the first vacuum lamp. In step three, the second lamp is compared to the test lamp. After resetting the test lamp current, step three is repeated for each desired radiance temperature. If the vacuum lamps remain constant between observations, the product of the signal ratios from the three comparisons is the signal ratio of the test lamp to the GPBB. With appropriate corrections for size of source and polarization, the spectral radiance and thus the radiance temperature of the test lamp can be evaluated from eqns. 4 and 2. The polarization and the spectral radiance distributions over ω, A, and λ of the vacuum lamps are of no concern here, since the lamps serve only to reproduce the spectroradiometer signal between comparisons. The only requirement is that the vacuum lamp parameters remain constant between comparisons with the gold-point blackbody (GPBB) and with the test lamp. This is satisfied by the constant-current operation of the stable (0.02% per 200 hours) vacuum lamps. Comparison with the GPBB is performed about every 50 to 100 hours of lamp operation, and the vacuum lamps are compared with each other weekly during experiments. The use of the first vacuum lamp avoids the inconvenience of manipulating the GPBB through its melting and freezing point cycles and provides a continuous measure of gold-point radiance. It also increases the number of experiments allowed between maintenance or replacement of the gold-point furnace. The use of the second vacuum lamp keeps all signal ratios within the linear response region of the spectroradiometer (i.e., within the 1 to 500 nanoampere range of anode current).

Appendix C provides a detailed description of the routine calibration process.

VI. DATA ANALYSIS AND UNCERTAINTIES

1. Temperature Values

The signal ratio of the test lamp to the GPBB is obtained from the product of the signal ratios measured in the first vacuum lamp comparison with the GPBB, the second (1530°K) vacuum lamp comparison to the first, and the test lamp comparisons to the second lamp. The ratio is then multiplied by correction factors to account for the size-of-source disparity, polarization error, and departure from linear response where appropriate. An estimated test lamp radiance temperature is then calculated from the ratio of Planck functions for two blackbodies which have the same signal ratio (one blackbody at the gold-point), using 654.6 nm as the wavelength. This temperature can then be used to determine by iteration the exact temperature which will satisfy Eqn. 4. For the spectral responsivity function of this spectroradiometer, this exact temperature differs from the estimated temperature obtained from the Planck ratio by an amount which is small (less than 0.2°K) and is a simple function of the temperature. Therefore, to avoid the repetitive iteration process, the temperature calculated from the Planck ratio is corrected to the desired Eqn. 4 value by this known difference.

2. Uncertainties

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

In order to examine the contributions of the various errors to the uncertainty in radiance temperature, an approximate equation for the complete measurement process can be developed by using the Wien approximation to Eqn. 2,

$$L_\lambda \simeq (c_1/\pi)\cdot\lambda^{-5}\cdot\exp(-c_2/\lambda\cdot T) \qquad (6)$$

to express the spectral radiance of a blackbody. With this approximation, Eqn. 3 becomes

$$r = \exp(c_2/\lambda \cdot T_{Au})/\exp(c_2/\lambda \cdot T) = \exp[(c_2/\lambda) \cdot (1/T_{Au} - 1/T)] \qquad (7)$$

Solving for T, and expressing r in terms of the measured ratios and their correction factors, we can express the complete measurement process as

$$T = \left[(1/T_{Au}) - (\lambda/c_2) \cdot \ln[s \cdot d \cdot f \cdot M_0 \cdot M_1 \cdot M_2/(1+B \cdot p_1)] \right]^{-1} \qquad (8)$$

where the definitions of the quantities and their estimated 3σ uncertainties are:

M_0, signal ratio GPBB vs. first vacuum lamp (0.12%)
M_1, signal ratio first vacuum lamp vs. 1530°K lamp (0.12%)
M_2, signal ratio 1530°K lamp to test lamp (0.2-0.5%)
s, size-of source correction for GPBB vs. test lamp (0.1%)
d, correction for test lamp drift during calibration (0.1%)
f, linearity-range factor correction (0.04-0.1%)
T_{Au}, IPTS-68 temperature of freezing gold (0.4°K)
c_2, second radiation constant (0.00014 cm·°K)
B, spectroradiometer polarizance (0.05%)
p_1, lamp polarization component (0.2%)
λ, wavelength setting at 654.6 nm (0.15 nm)

Radiance temperature uncertainties due to the factors of Eqn. 8 are obtained from the partial derivative with respect to those factors and the estimated uncertainty in the factor (propagation of error). Thus the calculated uncertainty in radiance temperature at the 2300°C (2573.15°K) point due to the 0.4°K uncertainty in T_{Au} is

$$\Delta T = (2573.15/1337.58)^2 \cdot (0.4)$$

or 1.48°K. Differences between errors calculated by Eqn. 8 and those calculated by the exact Planck equation are negligible. Note that for the wavelength λ this process yields the error due to inserting the wrong wavelength in the calculation, not the error due to incorrect wavelength setting.

In addition to the factors which appear explicitly in this relation, uncertainties in the ratios M_0, M_1, and M_2 arise from errors in the wavelength setting λ, in the current measurements of the vacuum (0.2 ma) and gas-filled (2 ma) lamps, in the alignment of lamps and in the measured spectral responsivity function. The uncertainties in the ratios due to wavelength setting and current are assessed by measurement of the change in signal ratio when varying these quantities. The effect upon the signal ratios due to the uncertainty in the measured spectral responsivity function is determined by solving Eqn. 4 for a range of $R(\lambda_0,\lambda)$ values, using the known spectral radiance distribution of the GPBB and an approximate test lamp distribution derived from spectral scans of such lamps. The radiance temperature uncertainties due to these factors are then deduced from the ratio uncertainties as before. The uncertainties in signal ratio, wavelength setting, lamp currents and lamp alignment are considered random errors; the remaining errors are systematics.

Table I summarizes the uncertainties obtained by this process. The calculated uncertainties in degrees are tabulated for a number of temperatures over the calibration range. The individual values are combined in quadrature to yield the combined uncertainty for each temperature. Issued calibration reports (see Appendix A) include a similar table of uncertainties, with errors grouped for the convenience of the user. These uncertainties apply to the reported values at the conclusion of the calibration.

3. Quality Control

The calibrations resulting from this process are derived in principle from a complete realization of the radiance temperature scale, and therefore are not dependent upon the maintenance of in-house standards. In practice, the realization often omits the GPBB comparison and relies upon the value of gold-point spectral radiance which is maintained on the stable Quinn-Lee vacuum lamp. The long-term record of this lamp's comparison with the GPBB (each 50-100 hours of operation) is monitored to detect any deviation from normal. The ratio of the second vacuum lamp (at 1530°K) to the gold-point lamp is monitored throughout the calibration process in order to detect any change in either vacuum lamp.

The radiance temperature values of those lamps which have a prior calibration (a common occurrence) are compared to the values of earlier calibrations in order to disclose any apparent shifts in the scale. Recalibration of a few lamps which are retained at NBS for the realization of other radiometric or photometric scales provide further checks on scale stability. The calibration report is carefully reviewed by a party who was not involved in producing the values.

VII. OPTICAL PYROMETER CALIBRATIONS

Visual optical pyrometers of suitable quality are calibrated on the IPTS against the calibrated lamp standards of radiance temperature described in this report. For calibration points above 2300°C, the transmittance of the high range filters (absorbing glasses) of the pyrometers are measured, and the calibration point is calculated from this transmittance and the low range (no filter) calibration. Calibration values are checked against a few observations on a variable temperature blackbody in those cases where the effective wavelength of the pyrometer is not within normal bounds. A detailed treatment of visual optical pyrometry is given in NBS Monograph 41 [15]. Photoelectric pyrometers are occasionally accepted as a special test. Because such instruments and their calibration requirements vary widely, the measurement procedures are determined at the time of test acceptance.

TABLE I

Summary of Estimated Uncertainties in Degrees C

Source of Uncertainty	Temperature (°C)				
	800	1100	1400	1800	2300
Signal Ratio M_0 (r)	0.06	0.10	0.15	0.23	0.36
Signal Ratio M_1 (r)	0.06	0.10	0.15	0.23	0.36
Signal Ratio M_2 (r)	0.27	0.27	0.28	0.37	0.67
Size of Source (s)	0.05	0.09	0.13	0.20	0.30
Lamp Drift (s)	0.05	0.09	0.13	0.20	0.30
Linearity (s)	0.05	0.03	0.05	0.13	0.30
Temperature Freezing Gold (s)	0.26	0.42	0.62	0.96	1.48
Second Radiation Constant (s)	0.02	0.0	0.04	0.11	0.22
Polarization (s)	0.04	0.06	0.09	0.14	0.21
Wavelength Setting (r)	0.08	0.05	0.08	0.20	0.44
Vacuum Lamp Current (r)	0.05	0.08	0.13	0.18	0.29
Test Lamp Current (r)	0.29	0.18	0.12	0.09	0.07
Spectral Responsivity (s)	0.03	0.01	0.0	0.02	0.03
Lamp Alignment (r)	0.13	0.21	0.32	0.49	0.76
Total estimated 3σ uncertainty on Thermodynamic Scale (square root of sum of squares)	0.5	0.6	0.8	1.3	2.0

Note: Random errors denoted by (r), systematic by (s).

VIII. PHOTOELECTRIC PYROMETER DEVELOPMENT

The radiance temperature calibrations described in this report were previously performed by the NBS Photoelectric Pyrometer [4]. This instrument employed refractive optics, an extended-red photomultiplier detector, interference filters which restricted the spectral bandpass to about 10 nm, a small internal tungsten filament lamp which served as the reference source, and a set of composite filters (absorbing glasses) to extend the range to high temperatures. A new version of this instrument is now under development, and will assume the role of realizing the IPTS above the gold-point and performing the radiance temperature calibrations.

The new pyrometer also employs refractive optics and an extended-red photomultiplier detector, but differs from the earlier version in three critical respects. The bandpass is restricted to about 1 nm. In lieu of the internal pyrometer lamp, more stable external vacuum tungsten-strip lamps are used to reproduce small multiples of the gold-point spectral radiance. The detector is operated under measured linear conditions to realize higher multiples of the gold-point spectral radiance, so that the absorbing glass filters are no longer required. The measurement process is similar to that described in this report. A schematic diagram is shown in Figure 2.

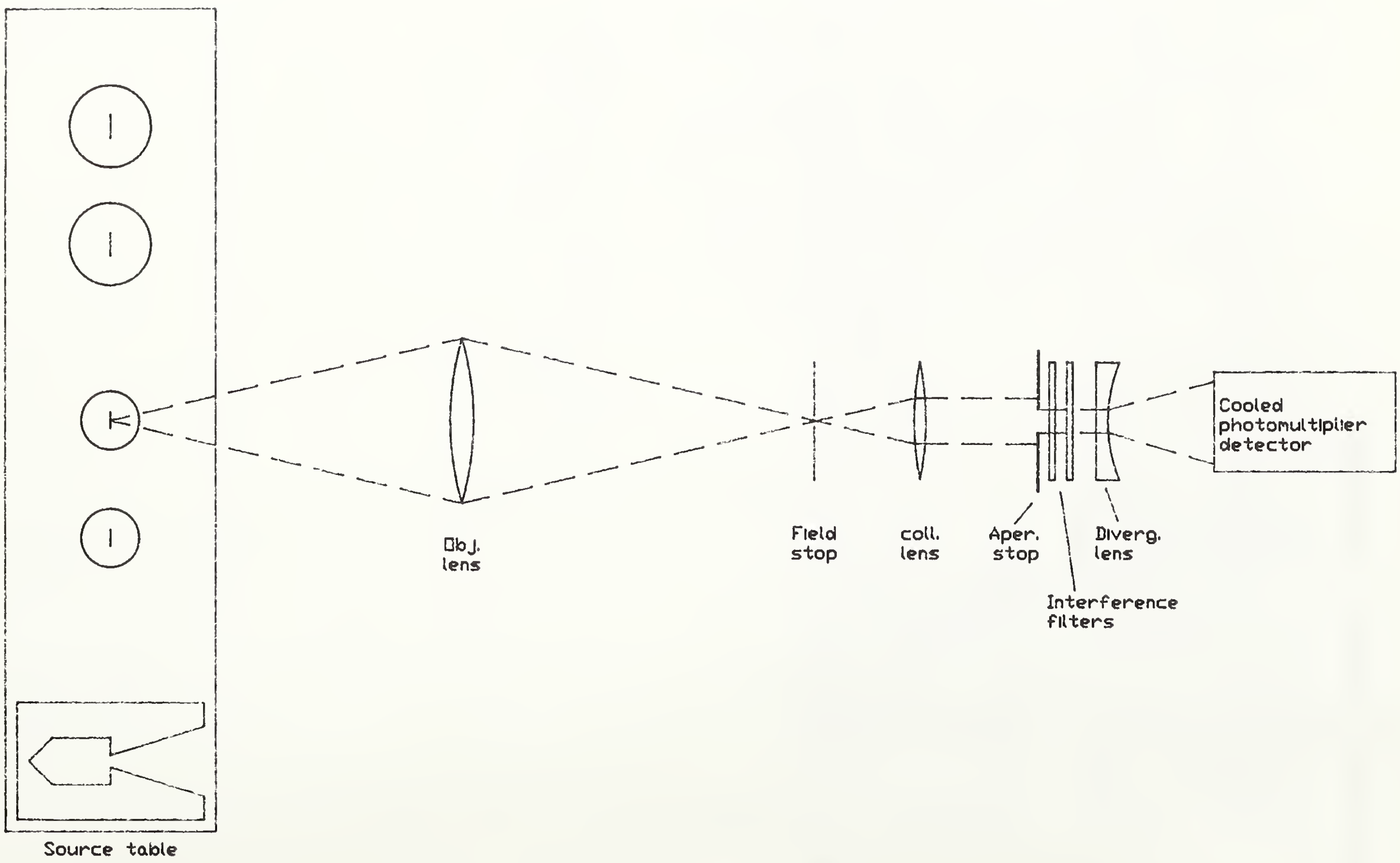

FIGURE 2. Schematic of Photoelectric Pyrometer

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

Appendix A.

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

REPORT OF CALIBRATION

LAMP STANDARD OF RADIANCE TEMPERATURE

Requested by

(See your Purchase Order No. dated

Material

One gas-filled tungsten ribbon filament lamp has been calibrated by NBS for this test and bears the designation

2. Calibration

The lamp was calibrated using the equipment and procedures described in the enclosed document, "Lamp Standards of Radiance Temperature-1984". The preparation of test lamps is described in paragraph II of this document. Note particularly paragraph III.B which describes the orientation and operation of the test lamp. The calibration was performed with the lamp operating on direct current and the center contact of the lamp base at positive potential. The lamp was aligned while operating at a radiance temperature of 1700°C. The calibration was performed at a room temperature of 23°C. For radiance temperatures below 1500°C for gas-filled lamps, the radiance temperature will change as the room or ambient temperature changes (see page 14 of reference [5] in the enclosed document).

3. Results

Table I gives the radiance temperature of the test lamp at 654.6 nm. The values in this table apply at the conclusion of the lamp calibration. Table II gives the uncertainties of the calibration.

NBS Test No. 534/
October , 1985

REPORT OF CALIBRATION LAMP

The polarization measurements at 654.6 nm, described in paragraph II of the enclosed document, showed that the degree of polarization was 0.0042. The direction of polarization of the larger component was approximately 15 degrees clockwise from the horizontal when viewed from the spectroradiometer.

Prepared by:	Approved by:
James H. Walker Radiometric Physics Division Center for Radiation Research	Donald A. McSparron Radiometric Physics Division Center for Radiation Research

NBS Test No. 534/
October , 1985

TABLE I

RADIANCE TEMPERATURE AT 654.6 nm

LAMP

Degrees C (IPTS-68)	Direct Current (amperes)
800	10.909
900	11.764
1000	12.806
1100	14.054
1200	15.508
1300	17.153
1400	18.965
1500	20.922
1600	23.008
1700	25.211
1800	27.510
1900	29.913
2000	32.403
2100	34.988
2200	37.660
2300	40.437

NBS Test No. 534/
October , 1985

TABLE II

Summary of Estimated Uncertainties in Degrees C

	TEMPERATURE (Degrees C)				
SOURCE OF UNCERTAINTY	800	1100	1400	1800	2300
1) Calibration of Pyrometer Lamp relative to the International Practical Temperature Scale (IPTS-68)	0.14	0.23	0.34	0.53	0.82
2) Temperature determination of Test Lamp (3 x Standard Deviation of Mean)	0.27	0.27	0.28	0.37	0.67
3) Polarization effects	0.04	0.06	0.09	0.14	0.21
4) Current measurement	0.29	0.18	0.12	0.09	0.07
5) Wavelength measurement	0.03	0.03	0.01	0.06	0.15
6) Lamp alignment	0.13	0.21	0.32	0.49	0.76
7) Temperature scale	0.26	0.42	0.62	0.96	1.48
Total estimated uncertainty relative to S.I. units (3σ) (square root of the sum of the squares of the individual uncertainties)	0.5	0.6	0.8	1.3	2.0

CAUTION: Lamp current cycling has been observed to cause changes in lamp temperature of up to 1 degree in gas lamps (see paragraph IV of the enclosed document).

NBS Test No. 534/
October , 1985

LAMP STANDARDS OF RADIANCE TEMPERATURE

1984

I. Introduction and Lamp Description

Lamp standards of radiance temperature are calibrated by the National Bureau of Standards for the temperature range 800 to 2300 °C. Tungsten ribbon filament lamps are calibrated in terms of the International Practical Temperature Scale of 1968 (IPTS-68) [1] by direct comparison with a standard pyrometer lamp calibrated at 654.6 nm.

II. Preparation

Gas lamps are annealed at a radiance temperature of 2350 °C at 654.6 nm for two hours on direct current. Vacuum lamps are annealed at 1450 °C for about 16 hours.

Radiance temperature calibrations are performed for a rectangular target area 0.6 mm wide by 0.8 mm high, centered on the filament at the notch. The lamp orientation chosen for calibration minimizes the variation in lamp output while maintaining the optical axis of the measuring instrument approximately normal to the lamp filament. This orientation is determined with the lamp operating at approximately 1700 °C for a gas lamp, or 1200 °C for a vacuum lamp. An arrow is etched onto the rear surface of the lamp envelope to allow reproducible alignment of this orientation (see section III.B below).

For the lamp types used in this calibration, the radiation from the target area has been found to be slightly polarized. At 654.6 nm, the degree of polarization, P, defined as

$$P = \frac{L(\max)-L(\min)}{L(\max)+L(\min)}$$

and the direction of polarization of the larger component, L(max), are determined. The measured value of P and the direction of polarization of L(max) are given in the report of calibration.

III. Calibration

A. Method

The measured radiance temperature is determined by a spectral comparison of the test lamp to a standard vacuum pyrometer lamp calibrated at 654.6 nm in terms of the

International Practical Temperature Scale of 1968 (IPTS-68) [1]. Measurements are made with a spectroradiometer [2] incorporated into the NBS Facility for Automated Spectral Calibrations (FASCAL) [3]. The photomultiplier-amplifier combination used was determined to be linear to better than 0.1% over a photomultiplier current range from one nanoampere to 500 nanoamperes.

B. Conditions

The values of radiance temperature measured for the test lamp are associated with a specific target area on the filament surface and with a specific solid angle of the radiation emitted from the target area. These values of radiance temperature apply when the lamp has been aligned to a specified orientation while operating at a designated radiance temperature and after the lamp has reached thermal stability at each specified operating current. The test lamp is operated on direct current with its center contact at positive potential.

The alignment is performed with the lamp operating base-down, the filament vertical, and the optical axis of the spectroradiometer passing through the lamp envelope and intersecting the center of the filament at the height of the notch. The alignment is done with the lamp operating at 1700 °C for a gas lamp or at 1200 °C for a vacuum lamp.

The exact location of the target area and the rotational alignment of the lamp are as follows.

The calibration is performed for a rectangular target area 0.6 mm wide by 0.8 mm high. The sides of the target area are approximately parallel to the sides of the lamp filament. The center of the target area is located at the intersection of two orthogonal lines on the viewed filament surface. One line bisects the filament lengthwise, and the other passes through the point centered at the mouth of the notch.

The center of the target area is viewed along the horizontal optical axis of the spectroradiometer. The lamp is positioned so that the etched arrow on the lamp envelope is to the rear, as viewed from the spectroradiometer. A plumb line is used to make the notch side of the filament vertical. The lamp is then successively rotated about the horizontal and vertical centerlines through the target area until the tip of the arrowhead appears centered at the mouth of the notch.

The above described alignment is performed only at one temperature. At all other temperatures small vertical and/or horizontal translational adjustments are made so that the target area viewed is always centered on the lamp filament at the height of the notch. No additional rotational alignments are performed.

The solid angle used is a rectangular pyramid whose longer dimension is vertical. The size of the solid angle is defined by the vertex angles at the apex of the pyramid. The vertex angles are 0.125 radian (7.16 degrees) in the vertical plane and 0.0625 radian (3.58 degrees) in the horizontal plane.

The bandpass of the spectroradiometer is 2.2 nm at 654.6 nm.

IV. Discussion

A more detailed description of tungsten ribbon filament lamps and their operating parameters is given in NBS Monograph 41 [5].

When lamp current settings are approached from one direction one time and from the opposite direction the next time, changes in radiance temperature can occur. In gas lamps changes of up to 1 °C have been observed. In vacuum lamps changes of up to 0.5 °C have been observed. This calibration is performed starting at the highest current setting and then lowering the current for each additional setting.

When a gas lamp is operated at its highest temperatures (2200 and 2300 °C), the radiance temperature of the lamp will change at a more rapid rate than if operated only at low temperatures. If operated at its highest temperatures a typical change is a decrease of about 1 °C at all temperatures per 10 hours burning time on a lamp.

Additional information on tungsten ribbon filament lamps can be found in references [6] and [7].

V. References

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Appendix B.

Measurement of Instrument and Source Polarization

The measurement of source polarization and the determination of its effect on the measurement of spectral radiance is carried out with a sheet polarizer mounted in a motorized rotating mount. This mount fits a slot milled into a bracket attached to the front of the spectroradiometer. By this means the polarizer can be reproducibly positioned in the same location between the source and the spectroradiometer whenever required.

Before the polarizer can be used for source polarization measurements its polarization and that of the spectroradiometer must be measured. This is accomplished with the help of an integrating sphere and a second polarizer similar to the first. The integrating sphere is mounted in the radiometer source plane so that its exit port serves as a source of unpolarized radiance. Its entrance port, located at about 90° from the exit port, is irradiated with a suitable light source, such as a quartz-halogen lamp. Then a series of spectral radiance measurements of this source is recorded: a) with no polarizer, b) with the first polarizer in its slot, c) with the second polarizer added in a second milled slot in the mounting bracket between the first polarizer and the source, and, d) with the first polarizer removed leaving only the second polarizer. At each wavelength of interest measurements are taken as a function of polarizer orientation as the polarizers are rotated about the optic axis. The first polarizer is typically sampled every 15° and the second every 30°. The second polarizer is tilted in its mount by about 10° to avoid polarizer-polarizer interreflections. All of these measurements are automated and require typically about an hour at each wavelength.

In the analysis of this data we write the first row Mueller matrix elements of the spectroradiometer responsivity as

$$R = R_0 \begin{vmatrix} 1 & B & 0 & 0 \end{vmatrix} \tag{1a}$$

where R_0 is the ordinary responsivity neglecting polarization and we take the reference direction for polarization to be in whatever direction the radiometer polarizance lies, thus forcing the 45° component to vanish. The reference direction was determined to be horizontal by simply observing the effect of a hand-held polarizer of known polarization axis upon a lamp measurement. The polarization axis of the polarizer, in turn, was confirmed by viewing sunlight reflected at glancing incidence through the polarizer. Circular polarization is assumed to be negligible for the type of instrument and sources employed here. The quantity B represents the degree of linear polarization of the spectroradiometer. The Mueller matrix of a polarizer is taken to be of the form

$$P = \begin{vmatrix} s & dC & dS & 0 \\ dC & eC^2+\phi & gSC & 0 \\ dS & X & X & X \\ 0 & X & X & X \end{vmatrix} \qquad (2a)$$

where $C = \cos 2(\phi - \phi_0)$, $S = \sin 2(\phi - \phi_0)$ and the parameters s, d, e, ϕ, g, and ϕ_0 are obtained by least-squares fitting of the measurements. The angle ϕ is the orientation angle of the polarizer read from a scale on the polarizer mount. The matrix elements marked X are not involved in these measurements. This form of the Mueller matrix was found, by trial and error, to fit our data well. The simpler model of an ideal dichroic polarizer in which $e = s$ and $g = s-\phi$ (where, in terms of the principle transmittances k_1 and k_2, we have $s=[k_1+k_2]/2$ and $d=[k_1-k_2]/2$) is adequate for our visible and infrared polarizers but fails to fit the ultraviolet polarizer data. Finally, the Stokes vector of the unpolarized source is given by

$$L = L_0 \begin{vmatrix} 1 \\ 0 \\ 0 \\ 0 \end{vmatrix} \qquad (3a)$$

The various measurements then lead to equations of the following forms.

No polarizer: $V = R \cdot L = R_0L_0$ (4a)

Polarizer #1: $V(\phi) = R \cdot P \cdot L = R_0L_0(s+BdC)$ (5a)

Both polarizers: $V(\phi,\phi') = R \cdot P \cdot P' \cdot L$ (6a)

$$= R_0L_0(ss'+Bs'dC+dd'CC'+Bd'\phi C'+dd'SS'+Bd'gSCS'+Bd'eC^2C')$$

Polarizer #2: $V(\phi') = R \cdot P' \cdot L = R_0L_0(s'+Bd'C')$ (7a)

where $C'= \cos 2(\phi' - \phi_0')$, $S' = \sin 2(\phi' - \phi_0')$, and V represents the recorded radiometer signal output as a function, in general, of polarizer orientation angles. Altogether our measurements produce about 200 equations. The values of the ten unknowns s, s', d, d', e, ϕ, g, B, ϕ_0 and ϕ_0' are then obtained by a non-linear least squares solution. As far as polarization is concerned the parameters s, d, e, ϕ, g, and ϕ_0 completely characterize the first polarizer, at least within the accuracy of the model represented by the Mueller matrix of eq. (1a), and the parameter B characterizes the spectroradiometer. Since the factor R_0L_0 is common to all equations these measurements yield no information about it.

Using the characterized polarizer and radiometer we are now able to measure the polarization of an unknown source by recording spectroradiometer measurements obtained from the source: a) without a polarizer, and b) with the first polarizer again mounted on the bracket as when it was characterized. As before, the measurements are made at 15^o intervals of the polarizer. We take the Stokes vector of the unknown source to be

$$L = L_0 \begin{vmatrix} 1 \\ p_1 \\ p_2 \\ 0 \end{vmatrix} \tag{8a}$$

where, as always, we have neglected circular polarization. p_1 and p_2 are given by $p_1 = p\cdot\cos2\gamma$ and $p_2 = p\cdot\sin2\gamma$, where γ is the direction of polarization measured from the reference direction of the radiometer and p is the degree of polarization,

$$p = (Lmax - Lmin)/(Lmax + Lmin) \ . \tag{9a}$$

In Eqn.(9a) Lmax and Lmin are the maximum and minimum readings of a polarization-indifferent radiometer when an ideal linear polarizer is rotated in the source beam. Then our measurements lead to a no-polarizer equation:

$$V = R_0L_0(1+Bp_1) \tag{10a}$$

and to 24 equations:

$$V(\gamma) = R_0L_0[(s+BdC) + (dC+BeC^2+Bf)p_1 + (dS+BgSC)p_2]. \tag{11a}$$

Aside from the factor R_0L_0 which is common to all equations and cancels out, the only unknowns in these 25 equations are p_1 and p_2 which we can then obtain by a least-squares solution. These two parameters completely characterize the state of (linear) polarization of the source. Normally, only the second described experiment of 25 measurements need be performed to measure the polarization of a source since the polarizers and radiometer are relatively stable and, once characterized, will only infrequently need to be remeasured.

Equation (10a) gives the relationship between the spectral radiance of a source, L_0, and the radiometer output signal, V, assuming linearity of response and only linear polarization. If we apply this equation both to the measurement of an unknown source and to the measurement of a spectral radiance standard used to calibrate the radiometer we obtain:

$$L_0 = L_0^s[V/V^s][(1+Bp_1^s)/(1+Bp_1)] \qquad (12a)$$

where L_0^s is the known spectral radiance of the standard, V/V^s is the measured signal ratio, B is the radiometer polarizance, and p_1^s and p_1 are the relative Stokes components measured as described above for the standard and for the unknown source. (For a blackbody standard, presumably, $p_1^s = 0$.) This shows that the presence of polarization introduces the extra factor

$$(1+Bp_1^s)/(1+Bp_1)$$

into the simple measurement relationship which is valid in the absence of source polarization or if the radiometer is indifferent to polarization.

The polarization measurement uncertainty by this process can be judged by the statistics of the least-squares fitting and by the measurement reproducibility when different polarizers are used. Both indications suggest typical uncertainties (one standard deviation) in the visible where the polarizers are very good and the noise level very low of ± 0.0003 in the radiometer polarizance B and uncertainties of ± 0.001 in the source relative Stokes components p_1 and p_2.

Appendix C. Detailed Procedures for Routine Radiance Temperature Calibrations

A. Lamp Preparation

1. Visual Inspection

The lamp that is issued as a radiance temperature standard is a specially made lamp from General Electric designated type 30A/6V/T24. Upon unpacking, each lamp is inspected to see that
a. the lamp envelope is clear.
b. the filament is within 2mm of being centered in the envelope.
c. the area through which the filament will be viewed and the area on the opposite side of the envelope (used for alignment) are free of striations.
d. the filament has electrical continuity with the electrodes.

2. Initial Lighting

Each lamp is positioned in a lamp mount, wired to ensure that the center contact of the lamp will be at positive potential. Power is applied, and the current is set at 35 amperes. If the lamp does not fail, then the next step in the lamp preparation procedure is performed.

THE LAMP IS ALWAYS OPERATED ON DC, WITH CENTER CONTACT POSITIVE.

3. Annealing

An automatic pyrometer is used to set each lamp at approximately 2350°C where it is annealed for 2 hours.

4. Arrowing

In order to accurately reproduce the alignment of each lamp, an alignment arrow is etched on the rear of the lamp envelope.
a. Set the lamp temperature to approximately 1700°C with the automatic pyrometer.

b. Position and orient the lamp so that the Helium Neon laser beam defining the optical axis of the spectroradiometer (see A.5.b.) is normal to the envelope and passes through the notch on the lamp filament, when the filament is normal to the laser beam.

c. Make a small dot with a marking pen on the rear of the lamp envelope at the point where the laser beam strikes.

****
*   CAUTION   *
****
* Great care should be taken to avoid   *
* any direct eye contact with the laser   *
* beam. Either position a blocking   *
* finger on the 45 degree plane mirror   *
* to block the direct beam or translate   *
* the lamp horizontally so that the lamp *
* filament blocks the beam.   *
****

d. Translate the lamp so that the filament image is focussed and centered horizontally on the monochromator slit, with the notch centered vertically on the mask opening.
e. Rotational mappings about the horizontal and vertical axes are now performed on the test lamp. The lamp mounts are motorized to allow automated mappings. The computer program used to perform the mappings is "RADMAP3.CRO"
f. Plot the data and locate the rotational settings which minimize variations in spectral radiance with rotation. Set mount at this orientation.
g. Align a viewing scope behind the lamp so that the scope is normal to and views along the optical axis of the spectroradiometer defined by the laser beam (see A.5.h.).
h. Block off the laser beam.
i. Using the scope (with a small aperture on the objective lens to improve the depth of field), view the position of the dot relative to the notch in the filament and draw a picture of the relationship.
j. Draw an arrow on the picture with its tip centered on the mouth of the notch and pointing into it.
k. Turn off the lamp and remove it from the mount.
l. Paint an etching wax solution on the area of lamp envelope containing the small dot.
m. Allow the etching wax to dry for at least 20 minutes and then using a sharp needle and a transparent straightedge, scribe a small arrow in the wax at the location relative to the dot indicated by the drawing.
n. Position a small wax ring around the area to be etched to prevent acid from etching unwaxed portions of the lamp envelope.
o. Using a small paintbrush, put a droplet of concentrated hydrofluoric acid on the scribed arrow.

****
*   CAUTION   *
****
* Do not allow the hydrofluoric acid to   *
* contact the skin. Rinse thoroughly   *
* with cold water if skin contact occurs.*
****

****

p. After 3 minutes, rinse off the acid with cold water, clean off the etching wax with xylene, and wash the entire lamp envelope and nozzle with detergent and hot water. Then dry thoroughly with tissues to remove any water spots.

****
*   CAUTION   *
****
* **Avoid any direct breathing of the**   *
* **xylene vapors.**   *
****

5. Lamp Alignment

A precise technique for lamp alignment has been developed and must be followed each time a lamp is aligned. A highly polished stainless steel mask with an 0.8 mm square cut in it is positioned just in front of the entrance slit of the monochromator (with the cutout square centered on the slit). The image of a source is focussed onto this mask and is reflected back toward a low light level TV camera. The image from the camera is viewed on a TV monitor and is used when performing alignments. Neutral density filters can be placed in front the objective lens of the TV camera to prevent high level sources from saturating the vidicon tube.

a. Set the monochromator wavelength to 632.8 nm (the Helium Neon laser wavelength).
b. Turn on and position the alignment laser located in the detector box portion of the monochromator.
    1) Push the LASER button on the detector positioning controller circuit.
    2) Position a white card in front of and centered on the focussing mirror of the spectroradiometer.
    3) Manually rotate the detector positioning wheel about 1 and 1/3 turns clockwise until a maximum signal from the laser beam appears on the white card.
    4) The laser beam exiting from the entrance slit of the monochromator and reflecting off the mirror surfaces defines the optical axis of the spectroradiometer. The laser beam can now be used to aid in source alignment.

c. Let the alignment laser stabilize for 20 minutes.

d. With the lamp off, orient it so that the laser beam passes through the notch in the lamp filament and the tip of the arrowhead on the rear of the lamp envelope.

e. Set the lamp to 1700°C with the automatic pyrometer and let it stabilize for 20 minutes.

```
*******************************************
*                 CAUTION                 *
*******************************************
* When turning a lamp on or off the       *
* current should be slowly increased or   *
* decreased.  A period of 40 seconds to   *
* 1 minute should be taken to slowly      *
* increase the lamp current to its        *
* operating value or to slowly decrease   *
* the lamp current to turn it off.        *
*******************************************
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f. Use a plumb line to make the notched side of the lamp filament vertical.

g. Focus the lamp filament onto the entrance slit of the monochromator to plus or minus 2.5 mm.
   1) Replace the reflective mask in front of the monochromator slits with a white opaque mask.
   2) Remove any neutral density filters from in front of the TV camera.
   3) While viewing the image of the lamp filament on the TV monitor, translate the lamp in a direction parallel to the optical axis of the spectroradiometer. Continue to perform this translation until the filament is at its best focus on the TV monitor.
   4) Replace any neutral density filters removed in step 2).
   5) Replace the white opaque mask in front of the monochromator with the reflective mask.

h. Position a viewing scope behind the lamp looking along the optical axis of the spectroradiometer. Orient the scope so that the laser beam passes through the center of the objective lens when the lamp filament is in focus at the center of the field of view.
   1) Translate the lamp filament horizontally so that the laser beam passes alongside it (notch side) and exits through the rear of the lamp envelope.
   2) Position a viewing scope behind the lamp and looking toward the spectroradiometer.
   3) Adjust the viewing scope so that the laser beam passes through the center of the objective lens (a small aperture can be placed on the objective lens to help locate its center).
   4) Translate the lamp filament to block the laser beam.
   5) Adjust the scope so that the image of the lamp filament at the notch is centered in the field of view.
   6) Repeat steps 3) to 5) until the laser beam is centered on the objective lens while the image of the filament notch is centered in the field of view.

i. Position a "blocking finger" on the 45 degree plane mirror of the spectroradiometer. Rotate the arrow 2 degrees out from the notch and translate the lamp so that the image of the monochromator slit appears on the filament.

j. Translate the lamp vertically until the filament notch is vertically centered on the image of the slit.
k. Translate the lamp horizontally to approximately center the slit image behind the lamp filament.
l. Put a small aperture on the objective lens of the scope to improve the depth of field, adjust the focus of the scope to view both filament and arrow, and adjust the rotation and the tilt of the lamp filament until the tip of the arrow is aligned at the notch.
m. Set the dial setting to read zero for the lamp base rotation adjustment.
n. Remove the aperture, rotate the arrow out 2 degrees, and translate the lamp horizontally to view the slit image.
o. Translate the lamp vertically until the filament notch is vertically centered on the slit image.
p. Rotate back to the zero setting on the rotation adjustment.
q. Translate the lamp horizontally to get a left edge and a right edge reading of the slit image on the horizontal translation scale.
r. Calculate the reading for which the slit image will be centered on the lamp filament then translate in the horizontal and set that reading.
s. Recheck the focus.
t. Repeat steps k. and l.
u. If the rotation or tilt was changed significantly, then repeat steps m. to r.

6. Polarization Measurements

Because the spectroradiometer has significant polarization (0.26 at 654.6 nm and 0.85 at 2400 nm), it is necessary to measure the polarization of each test lamp so that a polarization correction can be made.

a. Use two polarizers to characterize the polarizers and the spectroradiometer (see Appendix B). Two motorized polarizers are used to do an automated characterization at 654.6 nm. The computer program used to perform these measurements is "TWOPOL·JW".
b. Use one polarizer to characterize the polarization of the test lamp. The computer program used to perform these measurements is "ONEPOL·JW".

B. Calibration Procedures

1. Data Taking Procedure

The computer program used to perform the routine radiance temperature calibration is "PLMPCAL1.LIN". The calibration begins with the lamp set at its highest temperature of 2300°C, and continues to successively lower temperatures down to 800°C. The automatic pyrometer is used to set each temperature, and after stabilization, the lamp image is recentered on the monochromator slit by slight translational adjustments of the lamp mount. The general data taking procedure is as follows:

a. Adjust the 1530°K standard lamp to its calibrated current.
b. With the spectroradiometer wavelength set at 654.6 nm, the spectral radiance output from the test lamp is compared to the spectral radiance output from the standard lamp.
    1) The spectroradiometer is positioned so that it is viewing the calibrated target area of the standard lamp. The photomultiplier output is amplified and converted to a voltage which is read with an integrating digital voltmeter (DVM). The DVM reading is recorded.
    2) The spectroradiometer is positioned so that it is viewing the target area of the test lamp. The DVM reading is recorded.
    3) The spectroradiometer is alternately positioned to view the standard lamp and the test lamp until a set of three readings is taken on each source.
    4) The spectroradiometer is positioned in front of a shutter position and the DVM reading is recorded for each range used in the measurements.
    5) For each source the mean of the three DVM readings is calculated and the shutter reading is subtracted from it.
    6) The resulting signal is corrected for the amplifier range on which it was taken and for the polarization of the source.
    7) The ratio of the test lamp signal to the standard lamp signal is determined.

c. Using the mean ratio of the test lamp to the standard lamp and the known radiance temperature of the standard lamp, the Planck equation is used to determine the radiance temperature of the test lamp. A small temperature correction is applied to account for the finite spectral bandpass.

C. Data Reduction Procedures

1. Analysis of Spectral Radiance Data

Several computer programs are used to perform the analysis of the spectral radiance data.

a. Run "SPLITRAD.1" to split the main data file into a separate data file for each test lamp.

b. Run "REPDIF.1" to calculate the percent differences in repeat measurements during the calibration. Measurements are made at 1700°C at the start, near the middle, and at the end of the calibration.)

c. Run "FLANAL.1" to calculate the following statistics

   1) Number of measurements at each temperature
   2) Range for repeat measurements
   3) Mean value
   4) Standard deviation of the mean and to store the lamp current, mean spectral radiance, and mean radiance temperature in a data file.

2. Analysis of Precision Data

The computer program "RAD'SD.RED" is used to calculate the overall precision of the source comparisons. This result is used in combination with the repeat measurement standard deviation of the mean in order to derive an over-all uncertainty in the radiance temperature determination of the test lamp.

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10. SUPPLEMENTARY NOTES

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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

This report describes the measurement methods and instrumentation used in the realization and transfer of the International Practical Temperature Scale (IPTS-68) above the temperature of melting gold. The determination of the ratios of spectral radiance of tungsten-strip lamps to a gold-point blackbody at a wavelength of 654.6 nm is detailed. The response linearity, spectral responsivity, scattering error, and polarization properties of the instrumentation are described. The analysis of sources of error and estimates of uncertainty are presented. The assigned uncertainties (three standard deviations) in radiance temperature range from ±2 °K at 2573° K to ±0.5° K at 1073° K.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

calibrations; gold-point blackbody; radiance temperature; response linearity; standards; tungsten-strip lamps.

13. AVAILABILITY

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