Spectral irradiance standard for the ultraviolet: the deuterium lamp

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A set of deuterium lamps is calibrated as spectral irradiance standards in the 200–350-nm spectral region utilizing both a high accuracy tungsten spectral irradiance standard and a newly developed argon mini-arc spectral radiance standard. The method which enables a transfer from a spectral radiance to a spectral irradiance standard is described. The following characteristics of the deuterium lamp irradiance standard are determined: sensitivity to alignment; dependence on input power and solid angle; reproducibility; and stability. The absolute spectral radiance is also measured in the 167–330-nm region. Based upon these measurements, values of the spectral irradiance below 200 nm are obtained through extrapolation.

I. Introduction

High accuracy, stable radiometric standard sources based upon Planck's law and a high accuracy temperature measurement of a blackbody cavity are available throughout the region from 225 nm in the uv to 2400 nm in the ir. At NBS, for example, a small area of a tungsten strip lamp can be calibrated for spectral radiance[1] (W cm^{-2} nm^{-1} sr^{-1}) with uncertainties ranging from 4½% at 225 nm to 1% at 250 nm. With such a source as a base, tungsten quartz–halogen lamps are then calibrated for spectral irradiance (W cm^{-2} nm^{-1}) at a specified distance from the lamp with uncertainties of about 2% between 250 nm and 350 nm. The lower wavelength limit for these lamps is determined basically by the rapid decrease in radiant power as the wavelength becomes shorter.

In order to obtain more radiant power in the uv, one often turns to the carbon arc or the high power xenon arc. Although these lamps emit a continuum equivalent to about 3800-K and 4000-K blackbodies, respectively, their spectra are complicated by line structure, and the lamps are not as stable or convenient to use as the tungsten lamps. Also, they have an unfavorable low ratio of uv to visible radiant power, a characteristic which can be responsible for systematic errors due to scattered light effects when making measurements in the uv. There is a lamp, however, which emits considerable uv radiant power, is compact and convenient to use, and has a very favorable ratio of uv to visible radiant power. In fact, the maximum radiant power occurs at 190 nm. This is the molecular deuterium lamp.

It is well known that uv continuum radiation[2] can be produced in a low pressure hydrogen plasma by the transition from the stable ${}^3\Sigma_g^+$ first excited electronic state of the molecule to the lower repulsive state ${}^3\Sigma_u^+$. A variety of hydrogen or deuterium lamps based upon this principle has been used over the years, and several types are available commercially. Such lamps have been especially useful, for example, in uv spectrophotometers where it is desirable to have a strong line-free source of continuum radiation. This type of source is preferred in such an application since, after dispersion by a prism or grating, the radiative output can be continuously tuned to any particular wavelength and adjusted for any desired bandpass.

One particular variety of deuterium lamp[3] has been investigated by several groups as a transfer standard of spectral radiance and has been calibrated between 167 nm and 350 nm by comparison with the following primary standards: synchrotron radiation[4]; a plasma blackbody[5]; and a high temperature hydrogen wall-stabilized arc.[6] Intercomparison of the bases determined by these independent primary standards has on several occasions[5,7,8] been facilitated through use of a deuterium lamp transfer standard since it is more portable and convenient than any of the various primary standards. The deterium lamp also has been investigated for its suitability as a transfer standard of spectral irradiance and has been calibrated above 250 nm by comparison with a standard tungsten quartz–halogen lamp.[9,10] In one case,[10] deuterium lamp spectral irradiance calibrations have been extended to 200 nm by

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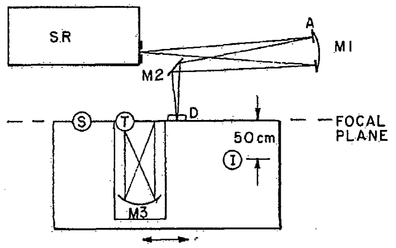


Fig. 1. Schematic of the optical system used to effect a transfer from a spectral radiance standard to a spectral irradiance standard.

comparison with the known spectral distribution of synchrotron radiation.

The objective of the research to be described here is to extend the NBS spectral irradiance scale down to 200 nm by calibrating a set of commercially available deuterium lamps. This is done by utilizing a recently developed uv source, the argon mini-arc, as a radiance standard and by slightly modifying the calibration techniques[11] which have been applied at longer wavelengths. The characteristics of the deuterium lamp as a transfer standard are also determined. In particular, its sensitivity to alignment, its dependence on input power, and its stability, reproducibility, and lamp-to-lamp variation are measured. Finally, a comparison is made of the spectral radiance and spectral irradiance of the deuterium lamp. If the wavelength dependence of the two quantities is the same, it would suggest that an extrapolation of spectral irradiance from 200 nm down to 167 nm could be carried out based upon the calibrated spectral radiance of the lamp under investigation.

II. Calibration Method

Since the only difference in the units of spectral radiance and irradiance is the quantity steradian, it may seem at first glance that one might determine the spectral irradiance of a lamp simply by measuring its spectral radiance and then measuring the solid projected angle of the radiation incident on the measuring system. However, this is not so trivial since the spectral radiance of a standard source is usually calibrated only for a rather limited portion of the source, the portion which is nearly homogeneous. Therefore, to apply a radiance standard properly it is necessary to limit the field of view in order to measure only that portion which is calibrated and then only for a specific solid angle. This can be done either with a set of collimating apertures, or as in our case, with a simple optical system. Of course, once an auxiliary optical system has been placed between a radiance standard and the measuring system, the transmission of the optics would have to be determined in order to complete the irradiance calibration. This additional step is effectively bypassed in our procedure by directly calibrating the spectral radiance of the image formed by an uncalibrated stable radiance lamp and its associated auxiliary optical system. This is done through direct substitution of a calibrated radiance lamp in place of the image source.

The optical layout used to effect the transfer from a spectral radiance standard to a spectral irradiance standard illustrated in Fig. 1. Prism-grating spectroradiometer (*SR*) and mirrors $M1$ and $M2$ comprise the basic measurement system. Three light sources are mounted and precisely aligned on a movable table so that they can be conveniently measured by the measurement system. I is the deuterium lamp whose spectral irradiance is to be determined. It is positioned 50 cm from the focal plane of the measurement system. T is an uncalibrated deuterium lamp whose radiation can be focused by $M3$ onto the focal point of the measurement system. A diffuser D, located at this point, serves as part of the measurement system for radiation from I and T. It compensates for the different geometry of sources I and T; without the diffuser, both sources would illuminate the measuring system in different ways, and one would have to account for nonuniformities across the optical reflecting surface or the detector photocathode.[12] Finally, S is the standard source of spectral radiance which can be moved to the focal point of the measurement system in the place of the diffusing element.

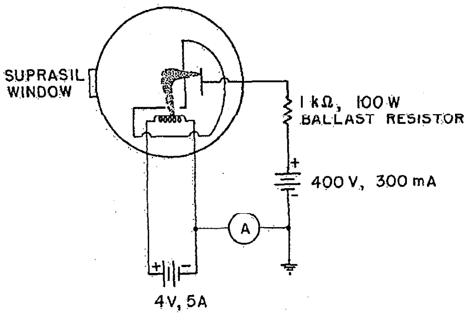
The two focusing systems (measurement system, T-$M3$ system) have a 1:1 image to object ratio. The aperture A is interchangeable on mirrors $M1$ and $M3$. A 0.3-mm circular field stop is attached to the front surface of the diffusing element D. The diffuser-field stop combination is also interchangeable: it is used either as a spectrometer entrance slit or as a field stop placed in the focal plane as shown in the figure.

The calibration procedure is as follows. The table is positioned initially so that irradiance source I irradiates D; the radiation passing through the circular field stop is diffused and then focused y mirror $M1$ (aperture A removed) onto the spectroradiometer. The image formed by source T and $M3$, stopped down by aperture A, is then moved into position and irradiates the same measuring system as I. the aperture A in front of $M3$ and the distance between $M3$ and D define the solid angle of radiation incident on D. The circular field stop at D defines the portion of the light source being observed and the area of irradiation. The spectral irradiance of the system T-$M3$ at D is then given simply by the product of the spectral radiance at D and the projected solid angle. The spectral radiance of the image is determined by moving D over to the spectroradiometer where it performs the function of the entrance slit and by moving aperture A to mirror $M1$. The radiation from the source system, T and $M3$, is then compared directly with the radiation from the standard radiance source S by moving the table in order to observe either S or the image formed by T and $M3$.

III. Apparatus

A. Deuterium Lamp

A schematic illustrating the operation of the deute-



ig. 2. Schematic illustrating the operation of a deuterium lamp. he radiation is measured through the Suprasil window sealed to the quartz lamp envelope.

rium lamp is shown in Fig. 2. In order to start the lamp, the cathode coil is first heated for 5 sec by a dc power supply (4 V at 5 A) in order to provide some free electrons which facilitate initiating a discharge. When a voltage of about 400 V is applied to the lamp, an arc forms between cathode and anode in the general form of an L. Most of the uv light is generated at the constricting aperture (1-mm diam in our case) located in front of the anode. The main dc power supply is a 400-V, 300-mA constant current supply, with 0.1% current regulation. A ballast resistor (1 kΩ, 100 W) is used in the anode circuit because most power supplies cannot react fast enough to maintain a constant arc. After the arc is started, the voltage across the arc drops to about 100 V. At this point the heater current is switched off, and the lamp output stabilizes in 20 min or less. If the lamp is switched off, it should be allowed to cool back to room temperature before restarting.

Because of variations in fabrication from one deuterium lamp to another, optical alignment of the deuterium lamp with respect to one of its physical characteristics does not necessarily result in a lamp whose radiation output is least sensitive to alignment uncertainties. Therefore, optical alignment of lamps calibrated at NBS is with respect to a precision bipost base n which each lamp has been individually positioned to ield maximum irradiance and then potted. Through his technique any number of deuterium lamps can be ut into the system in a reproducible way such that ncertainties in the spectral irradiance due to small variations in alignment are minimized. Also, since the bipost base is identical with the one used to mount NBS calibrated tungsten quartz–halogen lamp standards, these potted deuterium lamps are compatible with calibration systems designed to accommodate the quartz–halogen lamp. The orientation procedure is as follows. First, the bipost base, mounted in a kinematic support,[13] is positioned so that the optical axis of the spectroradiometer optics forms a perpendicular with the plane defined by the front surfaces of the post and passes midway between the posts and 9.5 cm above the bottom of the posts. This adjustment was made precisely and quickly with the use of an auxiliary alignment jig made by sealing a piece of glass plate onto the posts of an identical base mounted into the kinematic support; an etched cross on the glass serves as a target for the laser beam, and the mount is adjusted so that the laser beam reflects back on itself. With the position of the base so determined, the deuterium lamp is placed in the base so that the laser beam passes through the center of the 1-mm diam discharge-constricting aperture inside the lamp. The pitch and yaw of the lamp are then adjusted about the center of the 1-mm lamp aperture for the condition giving maximum spectral irradiance at 250 nm as measured using a 0.3-mm diam field stop and diffusing window as the spectroradiometer entrance slit optics. The lamp is then potted in the base. It can now be positioned in a precise, reproducible way anywhere in the optical system by properly adjusting the orientation of the kinematic support through use of laser retroreflection from the alignment jig and then substituting the potted deuterium lamp in place of the alignment jig.

B. Spectral Radiance Standard

The standard source *S* in Fig. 1 was an argon mini-arc[14] which was calibrated in the 114–330-nm region by comparison with a primary standard of spectral radiance, the wall-stabilized hydrogen arc.[15] The mini-arc was operated with 30-V at 30-A dc power with 0.1% current regulation. The uncertainty in the spectral radiance in the region between 200 nm and 330 nm was estimated to be ±5.3% due mostly to a 5% uncertainty in the hydrogen arc primary standard. Although the mini-arc has a larger spectral radiance uncertainty than a tungsten strip lamp, it was chosen as the more appropriate standard for this application for the following reasons. First, it is calibrated below 225 nm, the short wavelength limit of NBS-calibrated tungsten strip lamps. Second, the spectral radiance of the mini-arc is larger than that of the tungsten strip lamp at the shorter wavelengths. For example, the ratio of mini-arc to strip lamp spectral radiance is about 200 at 300 nm, 2000 at 250 nm, and 10,000 at 225 nm. This characteristic is especially useful in this experiment since the radiance source needed in the transfer procedure can then be stopped down to a solid angle comparable to that determined by the deuterium lamp irradiance source and its field stop. In this way, uncertainties associated with the quality of the diffuser are minimized without sacrificing a good SNR.

C. Diffuser

The spectral radiance of the mini-arc is calibrated only for the central 0.3-mm diam portion of the 4-mm diam arc discharge and for a solid angle of *f*/200. Because of this property of the uv radiance standard, the beam from the image source *T*-*M*3 that can be calibrated is also quite limited. Aperture *A* in Fig. 1 was selected to specify a solid angle of *f*/200, and the circular field stop on the diffuser *D* was 0.3 mm in diameter. With such restrictions the use of an integrating sphere for the diffusing element becomes impractical because

Table I. Typical Spectral Irradiance at 50 cm of a Deuterium Lamp Operated at 300 mA

Wavelength (nm)	Spectral irradiance (W/cm^3)	Normalized spectral irradiance
200	0.48	208
210	0.43	186
220	0.36	156
230	0.32	137
240	0.27	116
250	0.23	100
260	0.19	84
270	0.17	73
280	0.146	63
290	0.126	54
300	0.108	47
310	0.093	40
320	0.083	36
330	0.073	32
340	0.065	28
350	0.057	25

of signal-to-noise considerations at the shorter wavelengths. Therefore, a transmitting front surface ground Suprasil window, whose transmission efficiency was nearly independent of wavelength between 200 nm and 350 nm, was used as a diffusing element.

IV. Results

The deuterium lamps were operated in an open region of the laboratory with normal room air circulation. Operation in a confined region, such as a lamp housing, can be expected to affect the flux output and the source calibration since the gas pressure in the lamp is affected by changes in cooling patterns about the lamp. Likewise, directing an air flow onto the lamp envelope will affect the calibration. Although the temperature coefficient for the lamps was not investigated in detail, it was observed that changes in the ambient temperature (25°C) of a few degrees introduced less than 1% change in the flux output. Operation of the lamp in a confined region was avoided also because of the possibility of radiation absorption by short wavelength uv-produced ozone. In an open region, the ozone that is produced along the air optical path is dispersed by normal room convection currents. Because the interior of the spectroradiometer had little natural air circulation, it was routinely purged with a small flow of argon during all measurements.

A. Spectral Irradiance Calibration

Table I lists the values of spectral irradiance determined for a typical 30-W deuterium lamp. Figure 3 illustrates the spectrum of this lamp as compared with the calibrated 1000-W tungsten quartz–halogen lamp.

The spectral irradiance of the two types of lamps is equal at about 260 nm. At 350 nm the quartz–halogen lamp is stronger by a factor of 100. At 200 nm, the converse is true, the deuterium lamp being a factor of 100 stronger than the quartz–halogen lamp. The spectrum of the deuterium lamp above 350 nm is not illustrated, but is a continually decreasing continuum, about a factor of 10 lower at 550 nm than at 350 nm. Superimposed on the continuum there is an atomic hydrogen line at 486 nm and a combination of emission and absorption line structure in the region between 550 and 700 nm. However, the dominant feature in the spectrum is the intense uv continuum.

Since the shapes of the spectra of the two lamps illustrated in Fig. 3 are so different, a critical test of a spectroradiometer's performance at some specific wavelength can be applied by irradiating the instrument with each lamp. If the ratio of signals from the two lamps is not equal to the ratio of their calibrated spectral irradiances, it would follow that a systematic source of error is present in the measuring system, for example, scattered light, second order radiation, poor out-of-band rejection characteristics, or detector nonlinearity. We ourselves have experienced such an inconsistency which was eventually traced to fluorescence of a particular integrating sphere coating formerly used in our system.[16]

B. Spectral Radiance Calibration

Table II lists the values of spectral radiance obtained for the deuterium lamp described in Table I. The lamp was operated at 300 mA and positioned so that the region calibrated was the 0.3-mm diam area which provided maximum radiance at 250 nm for a solid angle $f/200$ (0.00002 sr). The instrumentation used for this calibration has been described previously.[6] The absolute values were determined through direct comparison with the argon mini-arc spectral radiance standard

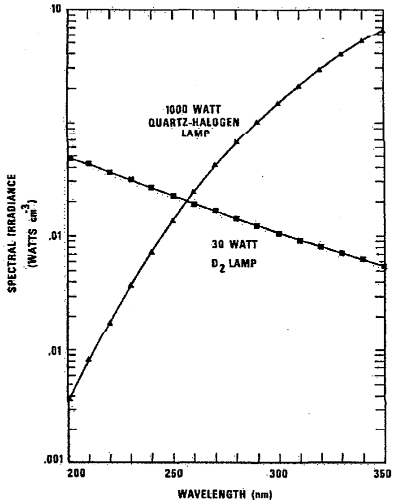


Fig. 3. Typical spectral irradiance of a 1000-W quartz–halogen lamp and a 30-W deuterium lamp.

Table II. Spectral Radiance of a Deuterium Lamp Operated at 300 mA [a]

Wavelength (nm)	Spectral radiance (W cm^{-3} sr^{-1})	Normalized spectral radiance
166	6.2×10^4	248
167	4.91×10^4	196
168	4.04×10^4	161
170	3.82×10^4	152
175	4.47×10^4	178
180	5.02×10^4	200
185	5.5×10^4	217
190	5.6×10^4	222
195	5.6×10^4	222
200	5.09×10^4	203
210	4.57×10^4	182
220	3.88×10^4	155
230	3.40×10^4	135
240	2.92×10^4	116
250	2.51×10^4	100
260	2.12×10^4	84
270	1.81×10^4	72
280	1.53×10^4	61
290	1.33×10^4	53
300	1.17×10^4	47
310	1.02×10^4	41
320	0.88×10^4	35
330	0.76×10^4	30

[a] The calibrated area is 0.07 mm^2; the values listed are for the same lamp whose spectral irradiance is given in Table I.

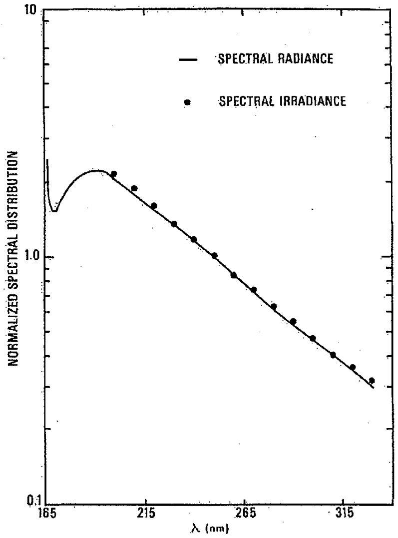


Fig. 4. Comparison of the spectral radiance and spectral irradiance of a deuterium lamp. The data are nomalized at 250 nm.

Table III. VUV Spectral Irradiance at 50 cm of the Deuterium Lamp Used in Tables I and II. [a]

Wavelength (nm)	Spectral irradiance (W/cm^3)
195	0.51
190	0.51
185	0.50
180	0.46
175	0.41
170	0.35
168	0.37
167	0.45
166	0.57

[a] The values are obtained through an extrapolation based on the measured spectral distribution of the spectral radiance of the deuterium lamp.

between 167 nm and 330 nm using a VUV monochromator. Second order radiation in the measurements above 220 nm was eliminated by the use of an atmospheric pressure air cell in the optical path.

In Fig. 4 we compare the spectral radiance and irradiance of the lamp. Since the two quantities have different units, the curves are arbitrarily normalized at 250 nm. Both the spectral radiance and irradiance have a similar relative dependence on wavelength throughout the 200–330-nm region. The rms difference of the data points (see also Tables I and II) is 2.5%, with a maximum difference of 6.5% at 330 nm. The data comparison would look even better if a best fit normalization procedure were used. Based upon these results, it seems to be a reasonable approximation to extrapolate the spectral irradiance down to 167 nm using the relative spectral radiance of the lamp as a guide. Table III lists the extrapolated values for the spectral irradiance so obtained.

C. Alignment

The sensitivity of the spectral irradiance to lamp position is illustrated in Fig. 5 for two different lamps. The measurements were made for a wavelength of 250 nm. The contours were obtained by changing the pitch and yaw of the lamps in 0.5° increments over a ±2° grid. A $BaSO_4$ coated integrating sphere with a 1-cm^2 diam aperture 50 cm from the lamp provided the field stop located at the entrance slit of the monochromator. Over such a small range of angular changes, the contours may also be considered a measure of the sensitivity of the spectral irradiance to vertical and horizontal positioning over a grid range of ±1.75 cm. The two contours are shown to illustrate the typical variation from lamp to lamp. Lamp A4199 appears to be more uniform since it exhibits a falloff of 2% or less through most of the grid. This is due mostly to the fact that the lamp was positioned very well for maximum irradiance when it was being potted. It can be seen that the center of maximum irradiance for the A1347 lamp is not at the 0,0 grid position but rather in the fourth quadrant. The potting procedure in this case was not as precise as for the A4199 lamp. Nevertheless, the results for both lamps indicate that if the lamp can be mounted so that the 0,0 position can be reproduced within ±0.9 cm, the alignment error will be no more than ±1%.

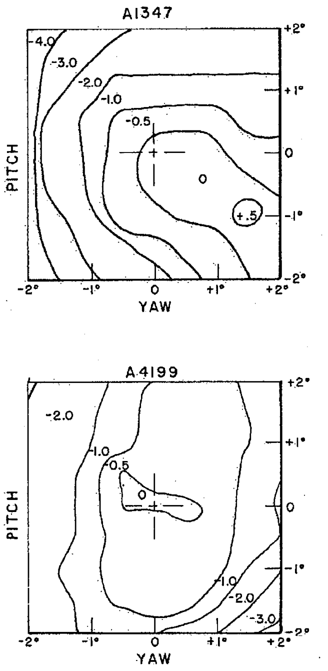


Fig. 5. The dependence of the spectral irradiance upon pitch and yaw of a deuterium lamp located 50 cm from a 1-cm^2 aperture. A 2° angular change is equivalent to a 1.75-cm translational change.

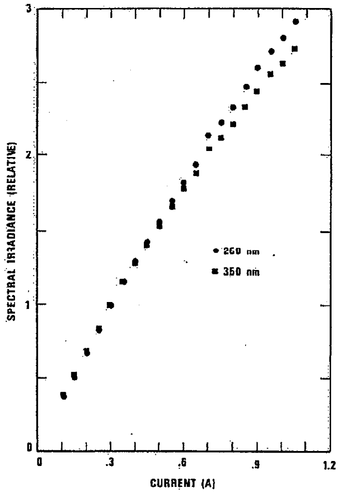


Fig. 6. Spectral irradiance as a function of lamp current for two representative wavelengths. The values are normalized to the spectral irradiance at a current of 0.3 A.

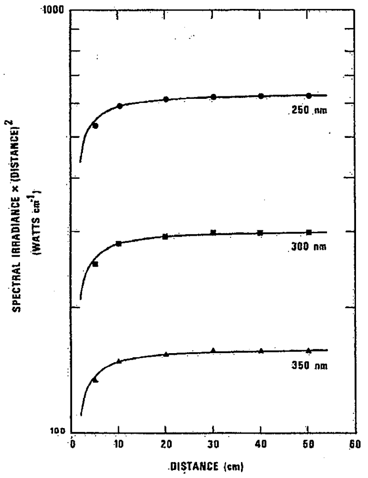


Fig. 7. Spectal irradiance measurements as a function of distance between the deuterium lamp envelope and a 1-cm^2 field stop. Results expected by assuming the inverse square law and taking into account the finite size of the field stop and the position of the radiation center (determined by least squares fitting) are illustrated by the solid line. The data are taken at three representative wavelengths.

D. Lamp Current

The dependence of the spectral irradiance on lamp current is illustrated in Fig. 6. Below 100 mA, the lamp is not stable. Above 1 A the lamp overheats and is in danger of failure. Between these limits, the spectral irradiance can be varied about a factor of 10 and is nearly linear with current, with a slope weakly dependent on wavelength. It can be seen that high precision current measurements are not required in order to maintain lamp accuracy. For example, a precision of 1 mA at a lamp current of 300 mA causes an uncertainty of only 0.3% in the spectral irradiance.

E. Solid Angle

Figure 7 illustrates the dependence of the spectral irradiance of a deuterium lamp on solid angle. The field stop was a circular 1-cm^2 aperture on the entrance port of a BaSO$_4$ coated integrating sphere. If the source and this aperture were infinitely small and distance measurements were made between the aperture and the precise radiation center (rather than the lamp pins), the data points on this plot would be expected to fall on a straight horizontal line. As can be seen, when the distance between the deuterium lamp and the field stop is reduced from 50 cm to 5 cm, the irradiance gradually departs from the ideal inverse square dependence. For distances greater than 20 cm, the deviation is less than 2%. The curve in Fig. 7 represents the results one expects strictly from geometric considerations when the finite aperture size and radiation center are taken into account. Because the radiation center is inside the sealed lamp and cannot be precisely measured, a least squares fitting of the curve to the data was carried out. Although the 50–10-cm data fit the curve to within 1%, the 5-cm datum does not. This is expected in view of the variation with position illustrated in Fig. 5. Thus, when the detector aperture size and radiation center are properly accounted for, the calibrated deuterium lamp may be operated at distances as close as 10 cm, i.e., at solid angles up to $f/10$ (0.008 sr), to within an uncertainty in spectral irradiance of 1%.

F. Variability

Because there was a fairly large variation in the stability, reproducibility, and aging characteristics from one lamp to another, much of the discussion in this section is in the form of observations rather than generalizations.

Warmup time varied from lamp to lamp. Some required none at all; others required up to 20 min. For the latter, typically the signal would rise to a maximum during the first minute and then slowly decrease, reaching an equilibrium value about 20% lower than the maximum after about 20 min. Because of this variation, it was decided that the lamps should be switched on routinely for 30 min prior to application. With this precaution, the radiative output of lamps, already aged for 100 h, was measured to be stable at all wavelengths to within 1% over a 24-h period of continuous operation.

Aging over the first 100 h was more significant, amounting in general to a decrease of about 15% from the initial values. However, a slight wavelength dependence observed in some lamps, and the ability of several lamps to recover from their diminished values during the first 100 h, implied that the aging process was not simple. Consequently, this study does not attempt to generalize on the lamp behavior during the first 100 h of its lifetime.

There was also a variation associated with striking the lamps. Some lamps would produce more signal if, after the normal warmup time, they were switched off and on again. Because the magnitude of this effect was not reproducible and certainly not characteristic of all lamps, it was decided always to start the lamp when it was at room temperature. The reproducibility of twelve lamps was tested by igniting the lamps every 2 h for a total of 100 h. After 30 min of warmup time, the spectral irradiance of the lamp was measured between 200 nm and 350 nm. The lamp was then turned off and allowed to cool down in time for the next ignition. Six lamps were reproducible with a standard deviation from their respective mean values of 1%. The worst of the twelve lamps had a standard deviation of 5%. For this particular lamp, the values of spectral irradiance seemed to cluster into two distinct groups indicating that the lamp may have been bistable. Significantly, the relative spectral distribution of all the lamps tested was constant to within a standard deviation of 1%, i.e., the absolute values may have changed by about 5%, but the shape of the spectral irradiance vs wavelength curve did not vary by more than 1% on the average. From these tests, it is concluded that the standard deviation of a single measurement of a typical deuterium lamp may be as large as 5%, although one may preselect for greater dependability.

G. Calibration Checks and Accuracy

As a check on the accuracy of the method, it was standard procedure to check the calibration of a deuterium lamp, immediately after it was calibrated between 200 nm and 330 nm using the argon mini-arc, by comparison with a high accuracy calibrated quartz–halogen lamp between 250 nm and 350 nm. The uncertainty in the absolute values (*SI*) based on the argon mini-arc is 5.3%; based on the quartz–halogen lamp, it ranges from 3% at 250 nm to 2% at 350 nm. The variability of the deuterium lamp does not enter as a factor in this comparison since all measurements were done consecutively during the same run. On the average, the values based upon the arc calibration were 2.1% lower than those based upon the quartz–halogen lamp. The standard deviation of the differences was 2.8%. We interpret this agreement, to within the calibration uncertainties of the standards, to indicate that the radiance-to-irradiance calibration method used was free of significant systematic error and that the one scale traceable to the hydrogen wall-stabilized arc (through the mini-arc) is consistent with the other scale traceable to blackbody based methods.

Confident that the scales are consistent to within 3% we can effect a reduction in the over-all deuterium lamp uncertainty by normalizing the mini-arc based values at 250 nm to the higher accuracy tungsten lamp values. Since most of the mini-arc uncertainty is traceable to a 5% uncertainty in the measurement of the hydrogen arc plasma length, essentially the normalization means that the hydrogen arc length is being determined more precisely, to within an uncertainty of 3%, based upon a radiometric measurement instead of a physical measurement. Thus, if we sum in quadrature the variability uncertainty, considered to be 5% assuming no lamp preselection, and the primary standard uncertainty, considered to be 3%, the total uncertainty in the deuterium lamp calibrations is estimated to be 6%. The uncertainty assigned to the relative spectral irradiance (ratio of the spectral irradiance at any two wavelengths in the calibrated region) is estimated to be 1% plus 0.02% times the nanometer difference between the two wavelengths under consideration. The 1% figure represents the reproducibility of the relative spectral distribution discussed previously. The $0.02\% \times \Delta\lambda$ figure represents the uncertainty in the relative spectral distribution ofthe hydrogen arc and argon mini-arc spectral radiance standards.

V. Summary

A calibration method which enables a transfer from a spectral radiance standard to a spectral irradiance standard is described. A set of commercially available deuterium lamps is calibrated as spectral irradiance standards in the 200–350-nm spectral region. At 250 nm and above, the spectral irradiance values were obtained from the existing NBS spectral irradiance scale (blackbody based). Below 250 nm the relative spectral distribution of the deuterium lamps was determined through the use of an argon mini-arc spectral radiance transfer standard whose calibration is based upon the NBS wall-stabilized hydrogen arc. The absolute values assigned to the deuterium lamp below 250 nm were then obtained by normalization to the NBS spectral irradiance scale at 250 nm. Confidence in this procedure was established by comparing the absolute spectral irradiance of the deuterium lamps as determined independently by both the argon mini-arc radiance standard and the tungsten quartz–halogen irradiance standard in the 250–330-nm region. The agreement was within 3%. The larger uv flux and high stability of the mini-arc standard are the essential features of the experiment which make possible the calibrations below 250 nm.

The deuterium lamps are aligned and potted in a bipost base identical to that used in mounting NBS calibrated quartz–halogen lamps. The two standards are thus interchangeable in a given optical system. Since the shape of the spectral distribution of these two lamps is so different, the presence of some systematic errors in one's measurement system may be detected by intercomparing the two sources. The spectral irradiance of the 30-W deuterium lamp is equal to that of the 1000-W quartz–halogen lamp at 260 nm, a factor 100 stronger at 200 nm, and a factor 100 weaker at 350 nm.

The uncertainty in the absolute values of the deuterium lamp spectral irradiance between 200 nm and 350 nm is estimated to be 6% when both the argon mini-arc and a tungsten quartz–halogen spectral irradiance lamp are used in the calibration procedure. A large part of this uncertainty is due to a variability associated with the striking characteristics of the deuterium lamps. For higher accuracy, the lamps may be preselected. Alternatively, for higher accuracy and confidence, one may take advantage of the result that the relative spectral distribution of the deuterium lamps is reproducible to within about 1%. Thus, routine normalization of the absolute scale at a convenient wavelength where a less uncertain standard, for example, the quartz–halogen lamp, is applicable makes possible a reduction of the uncertainty to about 3%.

The spectral radiance of the deuterium lamp has also been determined in the 167–330-nm region by direct comparison with the argon mini-arc standard. Since the wavelength distribution of the spectral radiance is nearly the same as that of the spectral irradiance, extrapolation of the deuterium lamp spectral irradiance down to 167 nm is possible. Future work will include construction of a VUV spectral irradiance calibration facility which would cover the 110–200-nm wavelength region and would eliminate any uncertainties involved in making such extrapolations.

The deuterium lamp is the only available portable spectral irradiance standard below 250 nm. From 250 nm to 350 nm, the tungsten quartz–halogen lamp is also available for near uv radiometry. However, if long wavelength scattering in one's measurement system is significant, and short wavelength scattering is not, the deuterium lamp irradiance standard should be seriously considered for use in the full 200–350-nm wavelength region.

Requests for deuterium lamp spectral irradiance calibrations in the 200–350-nm region should be made to D. McSparron, National Bureau of Standards. Requests for deuterium lamp spectral radiance calibrations in the 167–350-nm region should be made to W. R. Ott, National Bureau of Standards.

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