X-322-70-23

PREPRINT

NASA TM X-63837

# SPECTRAL IRRADIANCE OF TOTAL AND SPECTRAL ENERGY STANDARDS


M. P. THEKAEKARA

A. R. WINKER

T. A. RILEY



JANUARY 1970





GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-322-70-23
PREPRINT

# SPECTRAL IRRADIANCE OF TOTAL AND SPECTRAL ENERGY STANDARDS

by

M. P. Thekaekara
A. R. Winker
T. A. Riley

Thermodynamics Branch, Test and Evaluation Division

January 1970

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

## PROJECT STATUS

This report discusses the results of spectral irradiance measurements made on different types of total and spectral irradiance standards and calibration units. The spectral range has been extended in the UV and IR over the whole wavelength band where there is measurable energy.

## AUTHORIZATION

Test and Evaluation Division Number 322-124-09-27-01

SPECTRAL IRRADIANCE OF

TOTAL AND SPECTRAL ENERGY STANDARDS

M. P. Thekaekara
A. R. Winker
T. A. Riley

ABSTRACT

A program of measurements of the spectral irradiance of different types of tungsten filament lamps and a carbon filament lamp was undertaken. A total of sixteen sources of spectral and total irradiance were scanned in the wavelength range 0.235 to 4.85 $\mu$. The techniques of extending the range in the UV and IR beyond that usually covered in calibration tables are discussed. The results are presented in a series of graphs and tables. The limits of accuracy of these measurements and of the accepted standards of spectral irradiance are discussed.

# CONTENTS

## ILLUSTRATIONS



## TABLES

## SPECTRAL IRRADIANCE OF TOTAL AND SPECTRAL ENERGY STANDARDS

### I. INTRODUCTION

The spectral irradiance of sources of radiant energy is of great importance in space simulation research. The test object in a simulator is subjected to electromagnetic radiation which approximates as closely as possible in both total energy and its spectral distribution the radiation encountered in space. The measurement of irradiance requires total energy detectors and monochromators. The total energy detectors tend to change their calibration with long use and require a suitable standard source of total irradiance for periodic recalibration. The monochromators require a reliable standard of spectral irradiance with which to compare the simulator source in signal output.

Standards of total and spectral irradiance have been developed over a period of many years by the National Bureau of Standards, Washington, D. C. The earliest of these is the carbon filament standard of total irradiance (Reference 1) which was developed in 1914 by W. W. Coblentz and still serves as a convenient source of calibration for low levels of irradiance. Operating at about 40 watts, it has an irradiance of about 40 $\mu W\ cm^{-2}$ at a distance of 2 meters. A detailed account of the different types of standards which were since developed and issued by the NBS was published by Stair, Schneider and Jackson (Reference 2) in 1963 when the new 200 watt tungsten filament quartz iodine lamp for spectral irradiance was introduced. The 200 watt lamp has since been replaced by a 1000 watt lamp. Calibrated sources of spectral irradiance are now being issued by two other laboratories, the Eppley Laboratory, Newport, R.I. and Optronic Laboratories, Waltham, Mass. These standards are also 1000 W quartz idoine lamps, and are calibrated with reference to a group of "primary" standards maintained at the respective laboratories; the primary standards are presumed to represent a radiation scale in exact agreement with that of the NBS lamps to which they have been compared.

A parallel development is that of sources of total irradiance. Calibrated originally at the NBS, they are now being issued by Eppley. These standards are of three types, 100 W, 500 W and 1000 W. There are also high intensity calibration source units, which are tungsten filament projection lamps of 1000 W, 2000 W and 5000 W. The 5000 W lamp has an irradiance of about 8.6 $mW\ cm^{-2}$ at a distance of 2 meters. This is over 200 times the irradiance of the carbon filament lamp at the same distance. The 1000 W quartz iodine spectral irradiance standard of Optronics is also calibrated as a standard of total irradiance.

## II. OBJECTIVES OF THE MEASUREMENT PROGRAM

A program of intercomparison of the spectral irradiance of a large number of these sources was recently undertaken in our laboratory. Such a study serves several purposes.

The calibrated sources are relatively expensive and should be kept as shelf items to be used only sparingly. Lamps essentially similar to them can be set up as working standards for routine measurements. A calibration table for the working standards should be obtained by comparing their output with that of the shelf items.

Our calibrated sources of spectral irradiance have been obtained at different times and have a history of varying amounts of burning time. Lamps tend to increase in irradiance with number of burning hours. It is important to compare periodically the output of lamps with longer burning time with one which has little been used.

The standards and calibration source units of total irradiance have a spectral distribution of energy which is characteristic of the lamp and differs considerably from that of spectral irradiance standards. The tungsten filament operates at a slightly lower temperature than the 1000 W quartz iodine lamp, and the envelope being larger is also cooler. The calibration table supplied along with the lamps gives the total irradiance in mW $cm^{-2}$ at different distances from the lamp. But the total irradiance is not the only parameter which determines the output of a total energy detector. Most detectors have a window of quartz, sapphire or other optical material covering the sensitive element in order to protect it from air currents. The energy transmitted by the window is a function of the incident spectral irradiance and the spectral transmittance of the window. Even for windowless detectors it would be inaccurate to assume that the absorbance of the detector surface is independent of wavelength. In the wavelength range longer than 2 $\mu$, the changes in the source spectrum, absorbance of the detector surface and transmittance of the intervening air are all important parameters which affect the response of the detector. Thus the calibration of a total irradiance detector is dependent not only on the characteristics of the detector and total incident energy but also on the spectral distribution of the energy.

For certain applications the 1000 W quartz idoine lamp is highly useful as a calibration source for total irradiance. Its primary use is for spectral irradiance measurements. But since the tungsten filament and the lamp envelope are both considerably smaller than in the projection type lamps used for total irradiance calibration, it is more nearly a point source and hence permits the application of the inverse square law to shorter distances. Calibration tables of these lamps extend to 2.5 $\mu$ only. If the irradiance of these lamps can be determined in the longer wavelength range, the total irradiance of the lamp can be computed by integrating the area under the curve of spectral irradiance vs wavelength. This value can be compared with that obtained by a detector which has been calibrated with reference to a total irradiance standard. This method has been discussed in detail in a report of the Goddard Summer Workshop (Reference 3).

## III. DESCRIPTION OF THE LAMPS MEASURED

Figure 1 shows a photograph of representative lamps from each of the different groups which were measured. Shown in the figure are, from left to right, 1) HTS lamp with ceramic holder, 2) E2K, 2000 W, 3) ETK, 1000 W, 4) carbon filament lamp, E 6511, 5) E5K, 5000 W, and 6) 1000 W quartz iodine lamps, types EPI and SS.

A total of 16 lamps were measured. They are referred to by their type and serial number, and are listed below, with a brief description of each. EPI-1095, EPI-1096 and EPI-1111 are quartz iodine lamps of rated power 1000 watts,

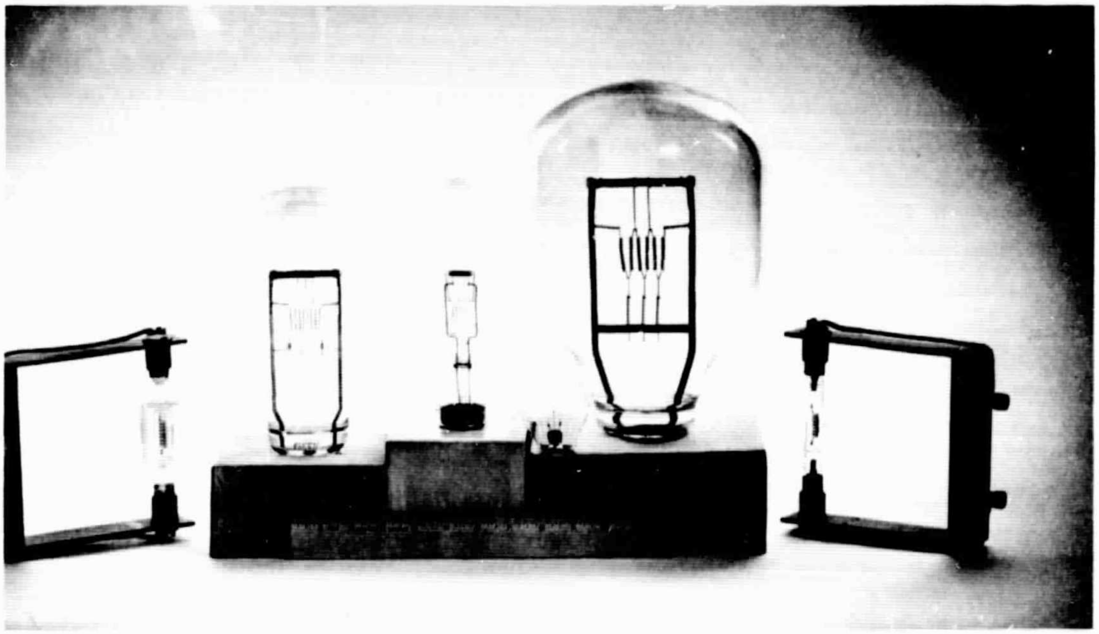

Figure 1. Showing six of the calibration sources of which the spectral irradiance was measured. From left to right: an HTS lamp in its ceramic holder; 2000 watt E2K lamp; 1000 watt ETK lamp; carbon filament lamp; 5000 watt E5K lamp; an EPI lamp.

manufactured by the General Electric Company, GE type DXW. These lamps have each a calibration table supplied by the Eppley Laboratory, which gives their spectral irradiance at a distance of 50 cm in the wavelength range 0.25 to 2.5 $\mu$. The lamps are operated at 8.3 amps. Four lamps similar to the above are SS-116, SS-117, SS-118 and EPI-1112. The letters SS stand for Space Simulation; these lamps are intended for use in the Space Simulation Research Section as working standards, while the first three EPI lamps are shelf items to be used only occasionally. EPI-1112 though it is labelled EPI has no Eppley calibration table and hence for practical purposes is of the same group as the SS lamps.

Another calibrated lamp is HTS-25, supplied by Optronic Laboratories. It is also a GE 1000 watt type DXW lamp mounted in a concave ceramic holder. The inner surface of the holder is a diffuse reflector with a coating of flame sprayed $Al_2O_3$. The calibration table supplied along with the lamp gives the irradiance at a distance of 40 cm. The wavelength range of the calibration for the HTS lamp is 0.3 $\mu$ to 2.5 $\mu$. Two other lamps similar to HTS-25 are HTS-A and HTS-B, both 1000 W quartz iodine lamps, mounted in the ceramic reflector but with no calibration table supplied by Optronic Laboratories. Like the SS lamps these are secondary working standards while HTS-25 is to be kept as a shelf item.

Five other lamps which were measured were ETK-6704, ETK-6705, E2K-671, E2K-672 and E5K-674. These are also tungsten filament coiled coil lamps, with the radiating surface covering a larger area than in the quartz iodine lamps. The bulb is larger and is of pyrex; it has no halogen gas filling and operates at a slightly lower temperature. The ETK lamps are standards of total irradiance, and the E2K and E5K lamps are high intensity calibration source units. They were obtained from the Eppley Laboratories. The wattage of the lamps is 1000 W for ETK, 2000 W for E2K and 5000 W for E5K. The ETK lamps are operated with a specified shutter and baffle system and the E2K and E5K lamps are mounted in a lamp house unit which is water cooled, forced air ventilated and fitted with a quartz window.

The last lamp included in the present series of measurements was a carbon filament standard of total irradiance E-6511, also obtained from the Eppley Laboratories. It was operated at about 40 watts. It is of the same type as was originally developed by Coblentz.

## IV. EXPERIMENTAL ARRANGEMENT

The experimental arrangement was essentially the same for all lamps. The lamp was mounted at a known distance from a diffuse screen. The diffuse screen was made of aluminum evaporated on a ground glass surface. The illuminated surface of the diffuse screen was viewed by a Perkin-Elmer monochromator Model 112. The normal to the diffuse screen was at 45° to both the incident beam from the lamp to the screen and the reflected beam from the screen to the entrance slit of the monochromator. In front of the monochromator slit was mounted a diaphragm of area 1.1 × 0.7 inch at a distance of 4.0 inches from the slit. Thus the monochromator could receive light from only a limited area at the center of the diffuse screen. This area subtended an angle of 14° in the vertical plane and 10° in the horizontal plane at the center of the entrance slit. The distance of the diffuse screen from the slit was 9 inches for all 16 scans. The distance of the lamp from the diffuse screen was 40 cm for the HTS lamps, 50 cm for the lamps of the series EPI, SS, and ETK and for the carbon filament lamp, 100 cm for the E2K and E5K lamps. The reference point in the lamp from which the distances were measured varied slightly with the type of the lamp. It was the front of the ceramic holder for the HTS lamps, the axis of the tungsten coil for the EPI and SS lamps, the central plane of the filament for ETK, E2K and E5K lamps and for E 6511. These points were chosen in accordance with the operating instructions for the respective lamps.

The lamps were operated at voltage and current as specified in the instructions. For the EPI, SS and HTS lamps a constant DC current was provided by a Hyperion power supply model HY-T1-130-10; the current was monitored by a Weston digital voltmeter model 1420 reading the voltage across a Leeds Northrup 0.1 ohm precision shunt. A current of 8.3 amps was maintained with a stability of ±0.001 amp. For the total irradiance standards a constant voltage supply was provided by an Allis-Chalmers A.C. motor generator, type GBB; the 110 volt input to the lamps was maintained with a stability of ±0.1 volt.

The Perkin-Elmer monochromator was used to scan the spectrum continuously in the wavelength range 0.235 to 4.86 $\mu$. Each scan took 23 minutes. The dispersing element of the monochromator is a lithium fluoride prism. A littrow mirror is mounted behind the prism and rotated at a pre-selected speed to direct different parts of the spectrum to the detector. The detector is a photomultiplier tube 1P28 for the UV, visible and near IR from 0.235 to 0.630 $\mu$ and a thermocouple for the IR from 0.528 to 4.86 $\mu$. The entrance and exit slits were in the PMT range, 0.5 mm for the range 0.235 to 0.362 $\mu$, 0.1 mm from 0.362 to 0.63 $\mu$, and 2.0 mm for the TC range. The signals were recorded on a Leeds Northrup chart. A drum count marker was superposed on the chart to indicate the wavelenth. Gain settings in the detector amplifier circuit were adjusted to keep the pen deflection within about 30 to 90 percent of the maximum range of the chart paper. Further details about the Perkin-Elmer monochromator and its use may be found elsewhere (Reference 4).

## V. DATA REDUCTION

All data were reduced manually from the Leeds Northrup charts, without the aid of magnetic tape record and computer analysis. This method proved to be time consuming, but permitted a continuous check on the accuracy of the data and was believed to yield more reliable results. Signals were read along with the gain settings at intervals of 20 drum counts on each of the sixteen charts. The corresponding wavelength intervals increase gradually from about 0.0025 $\mu$ at 0.235 $\mu$ to 0.1 $\mu$ at 1.1 $\mu$ and thereafter decrease gradually to 0.034 $\mu$ at 4.8 $\mu$. The total number of readings on each chart was 112. After a preliminary comparison of these data with the calibration table of the three EPI lamps and HTS 25, it was decided to use EPI 1096 as a working standard to which each of the other lamps, calibrated and uncalibrated, could be compared.

Let $A_s$ be the signal or amplitude of the pen deflection due to the standard lamp EPI 1096 at a given drum count and let $A_x$ be the signal at the same drum count due to any of the other lamps. If the other lamp is measured at a different gain setting from the standard, the signal is reduced to the same gain setting as for EPI 1096. The ratio $A_x/A_s$ is plotted as a function of drum count. The points showed very little scatter. A smooth curve is drawn through the points, thus to give an average value of the ratio $R_\lambda$ of the signals as a function of the wavelength. Nearly 90% of the observed points were seen to lie within plus or minus 1/2% of the curve. This amount of variation about the mean can be readily explained as due to the uncertainties in reading the spectrum charts. The pen deflection is between 3 and 9 inches and the smallest division on the chart paper is 1/10 inch. In the wavelength range longer than 3 $\mu$ where signals are weak and noisy a wider scatter of 5 to 10 percent was observed.

Let $P_{\lambda\ell}$ denote the spectral irradiance of a calibrated lamp as given in the table, and $P_{\lambda m}$ the irradiance of a lamp as determined from our measurements. By multiplying $P_{\lambda\ell}$ of EPI-1096 by $R_\lambda$ of any other lamp, say EPI 1095, $P_{\lambda m}$ of EPI-1095 can be obtained. Thus measured values of $P_{\lambda m}$ for three lamps EPI-1095, EPI-1111 and HTS-25 are obtained. These values were compared with $P_{\lambda\ell}$ of the same lamps as given in the respective calibration tables. A detailed comparison at each wavelength between $P_{\lambda m}$ and $P_{\lambda\ell}$ for the two EPI lamps 1095 and 1011 showed that the differences were well within the margin of error that could be expected from their longer hours of burning and the estimated accuracy of the calibration tables. For HTS-25, however, the differences were greater. The ratio $P_{\lambda m}/P_{\lambda\ell}$ decreased from a maximum of 1.14 at 0.32 $\mu$ to 1.01 at 0.7 $\mu$. For longer wavelengths the ratio was between 1.00 and 0.98. The relatively high values of the ratio in the UV and visible may be due to errors in the present set of measurements. In the UV and visible the irradiance of the HTS lamps is between 3 to 4 times that of the EPI lamps, whereas the other types of lamps SS, ETK, etc. have practically the same irradiance as the EPI lamps at the respective distances at which they were measured. Hence our measured values of $P_{\lambda_m}$ for the HTS lamps are less reliable. The difference may also be partly due to experimental errors in the calibration tables of the two lamps HTS 25 and EPI 1096 or a difference between the two scales of radiometry maintained at the two laboratories. Both scales of radiometry are traceable to NBS lamps of the QM series, and comparison between two individual lamps is quite inadequate to establish any difference between the two scales.

Because of the relatively large differences between $P_{\lambda_m}$ and $P_{\lambda \ell}$ of HTS-25, it was decided to ignore the values of $P_{\lambda_m}$ of HTS-25 in the wavelength range 0.30 to 2.5 $\mu$, and retain instead $P_{\lambda \ell}$ given in its calibration table. In the wavelength range below 0.30 $\mu$ our measured values were scaled up by 14.8% as indicated by the difference between the two sets of values for $\lambda > 0.30\ \mu$.

A similar correction was applied to the measured values $P_{\lambda_m}$ of HTS-A and HTS-B by multiplying them with the ratio $(P_{\lambda \ell}/P_{\lambda_m})$ of HTS-25. This in effect changes the reference of the two HTS working standards from EPI-1096 to HTS-25 which has nearly the same irradiance.

The calibration table of EPI lamps, following the pattern set by the National Bureau of Standards, is over the wavelength range 0.25 to 2.5 $\mu$. For HTS lamps the range is 0.30 to 2.5 $\mu$. These wavelengths are at intervals of 0.1 $\mu$ for wavelengths greater than 0.9 $\mu$ and at closer intervals in the shorter wavelength range.

For the purposes of this study it was highly desirable to obtain values of $P_{\lambda}$ in the IR beyond 2.5 $\mu$. Two independent methods were tried to determine the spectral irradiance of EPI 1096 in the range 2.6 to 5 $\mu$. One was to compare the signals of the tungsten lamp with those from two black body sources, one operating in the range 800° to 1400°K, manufactured by Infrared Industries, and the other operating in the range 1700° to 3000°K manufactured by Astro-Industries. The major sources of error in these measurements are that the diffuse screen receives a certain amount of radiation from portions of the black body cavity which are at a lower temperature and that the temperature determination of the cavity is open to some uncertainty. Another method is to estimate the temperature of the tungsten filament and the quartz envelope and to determine the energy emitted. This method has been discussed in detail elsewhere (Reference 3). In the wavelength range beyond 3 $\mu$ where quartz begins to be highly opaque the energy from the quartz bulb is more significant. Air currents in the room seem to affect the temperature of the bulb, so that measurements made at different times do not always yield the same value. We have adopted a table of values for the spectral irradiance of EPI 1096 in the range 2.6 to 5.0 $\mu$ which is based on several sets of measurements. These values are valid for normal operating conditions, and in view of the uncertainties in the measuring technique, should be considered provisional.

An attempt has also been made to extend the spectral irradiance table of the EPI and SS lamps to the UV range below 0.25 $\mu$. A plot of the log of the irradiance vs wavelength in the range 0.25 $\mu$ to 0.30 $\mu$ is nearly a straight line so that an extrapolation to lower wavelengths can be made. Another method is to assume a temperature of 2900°K for the tungsten filament and to multiply the radiance of a black body at that temperature by the emissivity of tungsten and the transmittance of quartz. Both methods yield practically the same values. They are provisional. The uncertainty is ±10%. The irradiance of EPI 1096 at 50 cm in units of $\mu$W cm$^{-2}$ nm$^{-1}$ is 0.00913 at 0.24 $\mu$, 0.00425 at 0.23 $\mu$, 0.00181 at 0.22 $\mu$, 0.000702 at 0.21 $\mu$ and 0.000245 at 0.20 $\mu$. For the other EPI and SS lamps the ratio of irradiance to that of EPI 1096 in the shorter wavelength range may be assumed to be nearly the same as in the range 0.25 to 0.30 $\mu$. This permits an extrapolation to the shorter wavelength range for these other lamps as well. This method cannot however be applied for the HTS lamps. The ratio of the irradiance of HTS 25 to that of EPI 1096 decreases rapidly from 3.2 at 0.4 $\mu$ to 2.6 at 0.35 $\mu$ and 1.8 at 0.25 $\mu$; this is due to a corresponding decrease in the reflectance of the ceramic holder. Hence extrapolation to lower wavelengths is less reliable for the HTS lamps. No attempt has been made to extend the calibration table of the HTS lamps below 0.24 $\mu$.

## VI. RESULTS

The results of the measurements are presented in Table 1. The values of spectral irradiance are in units of microwatts cm$^{-2}$ nm$^{-1}$. The spectral range covered is from 0.24 to 4.8 $\mu$. The wavelength intervals up to 2.6 $\mu$ are the same as in the NBS tables.

Data are presented on sixteen lamps. As stated earlier, the values for EPI-1096 and HTS-25 are $P_{\lambda\ell}$ from their respective calibration tables. For the other lamps the values are $P_{\lambda_m}$ as determined from the present series of measurements. The reference standards are HTS-25 for HTS-A and HTS-B, and EPI-1096 for all the other lamps.

For six of the sources the results are also presented graphically in Figures 2 to 7. Note the scale change in the x-axis for $\lambda > 1.0\ \mu$.

In Table 1 the last row gives the area under the spectral irradiance curve for each of the sources. The area is computed from the expression

$$A = \sum P_{\lambda_i} \Delta\lambda_i$$

Table 1

Spectral Irradiance of Calibration Sources Wavelength λ in Microns.
Irradiance in Microwatts $cm^{-2}$ $nm^{-1}$ at Distances as Indicated for Each Lamp.

| $\lambda_\mu$ | EPI-1096 50 cm | EPI-1095 50 cm | EPI-1111 50 cm | SS-116 50 cm | SS-117 50 cm | SS-118 50 cm | EPI-1112 50 cm | HTS-25 50 cm | HTS-A 40 cm | HTS-B 40 cm | ETK-6704 50 cm | ETK-6705 50 cm | E2K-671 100 cm | E2K-672 100 cm | E5K-674 100 cm | E-6511 50 cm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.240 | .00913 | .0103 | .0092 | .0101 | .0102 | .0132 | .0106 | .0188 | .0262 | .0241 | | | | | | |
| 0.250 | .0185 | .0207 | .0187 | .0203 | .0194 | .0253 | .0211 | .0338 | .0510 | .0478 | | | | | | |
| 0.260 | .0332 | .0365 | .0339 | .0355 | .0322 | .0438 | .0392 | .0724 | .0877 | .0820 | | | | | | |
| 0.270 | .0565 | .0609 | .0576 | .0593 | .0537 | .0729 | .0627 | .123 | .143 | .136 | | | | .0011 | | |
| 0.280 | .0901 | .0955 | .0919 | .0933 | .0865 | .1135 | .0987 | .197 | .233 | .217 | .0009 | .0003 | | .0181 | .0072 | |
| 0.290 | .138 | .1449 | .141 | .142 | .1311 | .1711 | .150 | .309 | .364 | .333 | .0017 | .001 | .0138 | .0290 | .0097 | |
| 0.300 | .199 | .208 | .203 | .204 | .187 | .2428 | .215 | .431 | .506 | .470 | .0036 | .0026 | .0428 | .0627 | .0398 | |
| 0.320 | .376 | .391 | .384 | .384 | .357 | .4437 | .403 | .869 | 1.06 | .997 | .0940 | .065 | .141 | .196 | .248 | |
| 0.350 | .862 | .900 | .879 | .883 | .819 | 1.01 | .922 | 2.21 | 2.59 | 2.45 | .414 | .397 | .397 | .513 | .828 | |
| 0.370 | 1.32 | 1.38 | 1.35 | 1.36 | 1.25 | 1.53 | 1.41 | 3.68 | 3.91 | 4.13 | .779 | .752 | .640 | .792 | 1.37 | .000132 |
| 0.400 | 2.30 | 2.39 | 2.34 | 2.37 | 2.21 | 2.65 | 2.45 | 7.25 | 8.34 | 8.17 | 1.52 | 1.47 | 1.13 | 1.38 | 2.46 | .00069 |
| 0.450 | 4.57 | 4.72 | 4.63 | 4.70 | 4.43 | 5.21 | 4.84 | 16.4 | 18.2 | 17.7 | 3.20 | 3.15 | 2.22 | 2.65 | 4.94 | .00274 |
| 0.500 | 7.68 | 7.88 | 7.76 | 7.93 | 7.45 | 8.68 | 8.08 | 29.6 | 32.6 | 30.9 | 5.61 | 5.61 | 3.84 | 4.38 | 8.29 | .00845 |
| 0.550 | 11.1 | 11.4 | 11.2 | 11.5 | 10.9 | 12.4 | 11.7 | 44.1 | 47.2 | 45.3 | 8.21 | 8.49 | 5.66 | 6.44 | 12.0 | .0189 |
| 0.600 | 14.6 | 14.9 | 14.7 | 15.1 | 14.5 | 16.2 | 15.3 | 59.1 | 61.4 | 61.4 | 11.3 | 11.5 | 7.59 | 8.18 | 16.1 | .0365 |
| 0.650 | 17.9 | 18.3 | 18.0 | 18.5 | 17.9 | 19.9 | 18.8 | 73.3 | 79.0 | 79.9 | 14.3 | 14.5 | 9.40 | 9.58 | 20.1 | .0555 |
| 0.700 | 20.5 | 21.0 | 20.6 | 21.3 | 20.5 | 22.6 | 21.5 | 85.1 | 88.2 | 89.3 | 16.8 | 16.8 | 10.9 | 11.7 | 23.0 | .0738 |
| 0.750 | 22.4 | 22.9 | 22.5 | 23.3 | 22.6 | 24.5 | 23.5 | 93.8 | 96.0 | 97.1 | 18.7 | 18.6 | 11.9 | 12.8 | 25.5 | .092 |
| 0.800 | 23.8 | 24.3 | 23.9 | 24.7 | 24.0 | 25.9 | 24.9 | 99.0 | 103.0 | 103.0 | 20.2 | 20.0 | 12.7 | 13.6 | 27.1 | .112 |
| 0.900 | 24.7 | 25.2 | 24.8 | 25.6 | 25.1 | 26.7 | 25.9 | 104.0 | 106.0 | 106.0 | 21.7 | 21.2 | 13.2 | 14.1 | 28.2 | .148 |
| 1.000 | 23.9 | 24.4 | 24.0 | 24.7 | 24.5 | 25.6 | 25.1 | 101.0 | 103.0 | 103.0 | 21.5 | 21.0 | 12.8 | 13.6 | 27.7 | .430 |
| 1.100 | 22.4 | 22.9 | 22.5 | 23.1 | 23.1 | 24.0 | 23.4 | 94.6 | 96.8 | 94.6 | 20.6 | 20.1 | 12.1 | 12.5 | 26.2 | .582 |
| 1.200 | 20.6 | 21.0 | 20.7 | 21.2 | 21.4 | 21.9 | 21.5 | 87.2 | 89.2 | 87.2 | 19.4 | 19.0 | 11.1 | 11.5 | 24.3 | .659 |
| 1.300 | 18.7 | 19.0 | 18.8 | 19.2 | 18.8 | 18.8 | 19.5 | 79.0 | 80.8 | 79.0 | 17.9 | 17.4 | 10.1 | 10.5 | 22.1 | .711 |
| 1.400 | 16.6 | 16.9 | 16.7 | 17.0 | 17.4 | 17.6 | 17.3 | 71.0 | 71.8 | 71.0 | 16.1 | 15.8 | 8.96 | 9.30 | 19.8 | .764 |
| 1.500 | 14.7 | 14.9 | 14.8 | 15.0 | 15.4 | 15.6 | 15.3 | 62.9 | 63.6 | 62.9 | 14.5 | 14.1 | 8.01 | 8.31 | 17.6 | .764 |

Table 1 (Continued)

| $\lambda_{\mu}$ | EPI-1096 50 cm | EPI-1095 50 cm | EPI-1111 50 cm | SS-116 50 cm | SS-117 50 cm | SS-118 50 cm | EPI-1112 50 cm | HTS-25 40 cm | HTS-A 40 cm | HTS-B 40 cm | ETK-6704 50 cm | ETK-6705 50 cm | E2K-671 100 cm | E2K-672 100 cm | E5K-674 100 cm | E-6511 50 cm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.600 | 13.0 | 13.2 | 13.1 | 13.3 | 13.7 | 13.7 | 13.6 | 55.3 | 55.9 | 55.3 | 13.0 | 12.6 | 7.09 | 7.35 | 15.7 | .767 |
| 1.700 | 11.3 | 11.4 | 11.4 | 11.6 | 11.9 | 11.9 | 11.8 | 48.4 | 48.7 | 47.9 | 11.5 | 11.1 | 6.22 | 6.44 | 13.8 | .746 |
| 1.800 | 9.78 | 9.91 | 9.83 | 9.99 | 10.4 | 10.3 | 9.82 | 42.0 | 42.5 | 41.0 | 10.1 | 9.78 | 5.43 | 5.67 | 12.1 | .694 |
| 1.900 | 8.45 | 8.57 | 8.50 | 8.64 | 9.0 | 9.76 | 8.79 | 36.4 | 36.8 | 35.6 | 8.92 | 8.58 | 4.77 | 4.99 | 10.5 | .659 |
| 2.000 | 7.32 | 7.42 | 7.36 | 7.49 | 7.83 | 7.72 | 7.61 | 31.7 | 32.1 | 31.3 | 7.83 | 7.50 | 4.17 | 4.32 | 9.22 | .615 |
| 2.100 | 6.37 | 6.46 | 6.41 | 6.54 | 6.82 | 6.69 | 6.61 | 27.9 | 28.0 | 27.5 | 6.88 | 6.63 | 3.66 | 3.82 | 8.15 | .573 |
| 2.200 | 5.63 | 5.72 | 5.66 | 5.78 | 6.02 | 5.94 | 5.84 | 24.8 | 24.8 | 24.6 | 6.19 | 5.88 | 3.27 | 3.38 | 7.26 | .541 |
| 2.300 | 5.02 | 5.11 | 5.05 | 5.15 | 5.35 | 5.32 | 5.21 | 22.2 | 22.2 | 21.8 | 5.57 | 5.26 | 2.96 | 3.01 | 6.53 | .497 |
| 2.400 | 4.53 | 4.62 | 4.57 | 4.65 | 4.80 | 4.80 | 4.69 | 20.3 | 20.3 | 20.1 | 5.07 | 4.76 | 2.70 | 2.76 | 5.93 | .462 |
| 2.500 | 4.17 | 4.25 | 4.21 | 4.27 | 4.42 | 4.44 | 4.31 | 18.6 | 18.6 | 18.3 | 4.65 | 4.42 | 2.46 | 2.52 | 5.17 | .430 |
| 2.600 | 3.51 | 3.59 | 3.55 | 3.59 | 3.69 | 3.77 | 3.63 | 15.6 | 15.6 | 15.3 | 3.58 | 3.55 | 1.86 | 1.90 | 3.51 | .365 |
| 2.700 | 3.08 | 3.16 | 3.11 | 3.16 | 3.23 | 3.33 | 3.18 | 14.1 | 13.7 | 13.2 | 2.34 | 2.19 | .616 | .739 | 1.26 | .339 |
| 2.800 | 2.78 | 2.87 | 2.81 | 2.86 | 2.92 | 3.02 | 2.87 | 13.0 | 12.6 | 12.0 | 1.00 | .876 | .445 | .111 | .139 | .275 |
| 2.900 | 2.44 | 2.52 | 2.47 | 2.52 | 2.57 | 2.64 | 2.52 | 11.7 | 11.2 | 10.8 | 1.46 | 1.17 | .780 | .732 | .537 | .234 |
| 3.000 | 2.15 | 2.23 | 2.18 | 2.23 | 2.27 | 2.30 | 2.23 | 10.6 | 10.2 | 9.87 | 1.61 | 1.40 | .882 | .882 | 1.08 | .200 |
| 3.200 | 1.76 | 1.83 | 1.79 | 1.84 | 1.85 | 1.84 | 1.81 | 9.14 | 8.84 | 8.75 | 1.65 | 1.46 | .968 | .880 | 1.38 | .155 |
| 3.400 | 1.38 | 1.44 | 1.40 | 1.46 | 1.44 | 1.41 | 1.42 | 7.82 | 7.20 | 7.14 | .856 | .814 | .469 | .524 | .607 | .099 |
| 3.600 | 1.30 | 1.34 | 1.30 | 1.37 | 1.37 | 1.29 | 1.32 | 7.68 | 6.85 | 6.79 | .364 | .338 | .163 | .390 | .130 | .0182 |
| 3.800 | 1.15 | 1.17 | 1.16 | 1.20 | 1.21 | 1.12 | 1.15 | 6.68 | 6.00 | 5.89 | .311 | .253 | .115 | .023 | .0058 | |
| 4.000 | 1.04 | 1.05 | 1.05 | 1.07 | 1.06 | .962 | 1.02 | 5.63 | 5.17 | 5.12 | .260 | .218 | .026 | | | |
| 4.200 | .990 | .986 | .992 | .993 | .916 | .842 | .958 | 4.78 | 4.29 | 4.31 | .238 | .099 | | | | |
| 4.400 | .930 | .913 | .925 | .919 | .763 | .716 | .886 | 4.08 | 3.66 | 3.68 | .186 | | | | | |
| 4.600 | .890 | .867 | .878 | .869 | .632 | .641 | .835 | 3.68 | 3.55 | 3.32 | .187 | | | | | |
| 4.800 | .870 | .828 | .846 | .842 | .505 | .609 | .809 | 3.64 | 3.50 | 3.28 | .174 | | | | | |
| 0.235 to 4.9 mW $cm^{-2}$ | 32.16 | 32.78 | 32.36 | 33.12 | 32.99 | 34.65 | 33.45 | 138.35 | 140.16 | 138.31 | 28.58 | 27.66 | 16.35 | 16.79 | 34.85 | 1.233 |

where $P_{\lambda_i}$ is the spectral irradiance $\lambda_i$ and $\Delta\lambda_i$ is the wavelength interval. For $\lambda_i = 0.24\,\mu$, $\Delta\lambda_i$ is $0.01\,\mu$ and for $\lambda_i = 4.8\,\mu$, $\Delta\lambda_i = 0.2\,\mu$. Thus the total irradiance or area is for the wavelength range 0.235 to 4.9 $\mu$. The units are milliwatts per $cm^2$.

The accuracy of these measurements depends primarily on the reference standards EPI-1096 and HTS-25 and secondarily on the methods used to extend the wavelength range in the UV and IR beyond that of the calibration table of the reference standards.

The two reference standards are traceable to the NBS standards of the QM type. The QM type lamps like the earlier 200 W QL type lamps were established as calibration standards by reference to the tungsten strip lamps and the radiance of the tungsten strip lamps was determined by comparison with a black body. Thus the primary standard is a black body. Hence arises the question, what was the melting point of gold assumed for computing the Planck functions of the black body. The International Committee of Weights and Measures approved in October 1968 the International Practical Temperature Scale of 1968, (IPTS-68) according to which the melting point of gold is 1337.58°K (Reference 5). The NBS standards of reference were established several years earlier at a time when the accepted value for the melting point of gold was, as defined by the International Temperature Scale of 1948 (ITS-48), 1063°C or 1336.15°K. However, the NBS text of the International Temperature Scale of 1948 recognized that significant differences existed between ITS-48 and the Thermodynamic Kelvin Temperature Scale (TKTS). Various corrections were applied to make temperatures measured on ITS-48 to agree as closely as experimentally possible to TKTS. Thus, the primary standard for the irradiance standards is a black body of which the temperatures are defined on the Thermodynamic Kelvin Temperature Scale.

More recently attempts have been made by H. J. Kostkowski at the NBS to compare the 1000 W quartz iodine irradiance standard directly with a black body (Reference 6). The black body temperature is defined on the IPTS-68 which agrees with the TKTS. Significant differences have been observed between the irradiance values as determined from these measurements and those given in the earlier NBS tables. The earlier values have to be decreased by 6.5% at 2500 Å, by 4.5% at 3000 Å, 0% at 4500 Å, 2% at 6500 Å and 4% at 8000 Å. These findings are claimed to be preliminary; no measurements have been made in the wavelength range $\lambda > 8000$ Å.

Two other questions to be considered are the accuracy claimed for the calibration tables of the NBS lamps and the agreement between the NBS standards and those issued by Eppley and Optronics. It is generally assumed that the accuracy of the commercially available standard lamps is essentially the same as that of the primary standard lamps maintained at the NBS. The values of accuracy quoted by Eppley Laboratory are: between ±4% and ±8% for the range 2500 to 2900 Å, ±3% for the range 3000 to 4500 Å, ±2% for the range 4500 to 7500 Å and between ±2% and ±4% for the range 7500 to 25000 Å (Reference 7). Stair, Schneider and Jackson (Reference 2) had estimated for the 200 W QL lamps a maximum uncertainty ranging from about 8% at the shortest wavelength, 2500 Å, to about 3% in the visible and IR.

An estimate of possible differences between the lamp standards maintained at the NBS and other calibrating labs can be obtained from the results of a Round Robin of spectral irradiance measurements recently sponsored by H. J. Kostkowski of NBS (Reference 8). Three lamps calibrated at NBS were sent to three laboratories, Redstone Arsenal, Eppley and Optronics. Measurements were made at five wavelengths. The maximum values of the differences in percentage are given in Table 2. They are of the order 1 to 3 percent. It would seem that differences of this order of magnitude are to be expected also in individual standard lamps issued by the labs.

Table 2

Maximum Value of the Difference Between Measurements in Four Laboratories.

$$D_{max} = \frac{P_{\lambda L} - P_{\lambda B}}{P_{\lambda B}} \times 100$$

$P_{\lambda L}$ = irradiance as evaluated by the laboratory other than NBS.

$P_{\lambda B}$ = irradiance as evaluated by NBS, both values for the case where the difference was maximum.

| $\lambda_\mu$ | $D_{max}$ | | | Max Diff. Between Any Two Labs | Standard Deviation |
|---|---|---|---|---|---|
| | Redstone | Eppley | Optronics | | |
| .25 | | -2.5% | -1.9% | 4.5% | .5% |
| .45 | 2.4% | -2.5 | -0.9 | 4.9 | .8 |
| .65 | 1.5 | -2.3 | -1.5 | 3.8 | 1.5 |
| .9 | 1.3 | +1.4 | -1.1 | 3.4 | .5 |
| 2.5 | 2.9 | +1.0 | +1.1 | 2.9 | .9 |

The precision of our measurements as may be estimated by the graphs of $R_\lambda$ vs $\lambda$ is of the order of ±1/2 percent over the wavelength range 0.25 to 2.5 $\mu$ since as was stated earlier, nearly 90% of the points lie within ±1/2% of a smooth curve. In the wavelength range of $\lambda < 0.25$ and $\lambda > 2.5$, the points show a wide scatter. Both precision and accuracy are considerably less in these ranges; we estimate the errors may be as high as 10 or 15% at the two extremes.

The Figures 2 through 7 show clearly the major differences between the different types of lamps. The maximum irradiance is at 0.9 $\mu$ for the quartz iodine lamps, at 0.95 $\mu$ for the ETK lamps and at 1.5 $\mu$ for the carbon filament lamps. The effect of the water vapor absorption band at 2.8 $\mu$ in pyrex is shown by the ETK lamps and even more strongly by the E5K lamp where there is the added effect of 100 cm of pathlength in air.

REFERENCES

1. W. W. Coblentz, Bull. Nat. Bur. Standards, 11, 87, S227 (1914).

2. R. Stair, W. E. Schneider and J. K. Jackson, App. Opt. 2, 1151 (1963).

3. M. P. Thekaekara and E. I. Mohr, "The Tungsten Lamp as a Secondary Standard for Total Radiant Flux," Summer Workshop Report, pp. B-39 to B-46, X-100-65-407, GSFC, Greenbelt, Maryland, 1965.

4. M. P. Thekaekara, J. D. Rancourt and S. E. Read, "Spectral Radiant Flux in the Solar Environment Simulator," Summer Workshop Report, pp. B-57 to B-76, X-100-65-407, GSFC, Greenbelt, Maryland, 1965.

   A. McNutt, J. Slavin and M. P. Thekaekara, "Calibration of Working Standards of Spectral Irradiance for Laboratory Use," Summer Workshop Report, pp. 439-445, X-700-67-94, GSFC, Greenbelt, Maryland, 1967.

5. R. P. Benedict, "The International Practical Temperature Scale of 1968," Leeds and Northrup Technical Journal, Number 6, p. 2 (1969); "International Practical Temperature Scale of 1968," Foreword by C. R. Barber, Metrologia 5, 35 (1969).

6. H. J. Kostkowski, Oral Presentation at East Coast Group Meeting of IES Solar Simulation Committee, GSFC, 25 June 1969.

7. Anon, "Standard Lamps and Calibration Sources," Bulletin No. 6, Eppley Laboratory, Inc., Newport, Rhode Island, May 1966, p. 4.

8. H. J. Kostkowski, Oral Presentation at East Coast Group Meeting of IES Solar Simulation Committee, Langley Research Center, November 21, 1969.

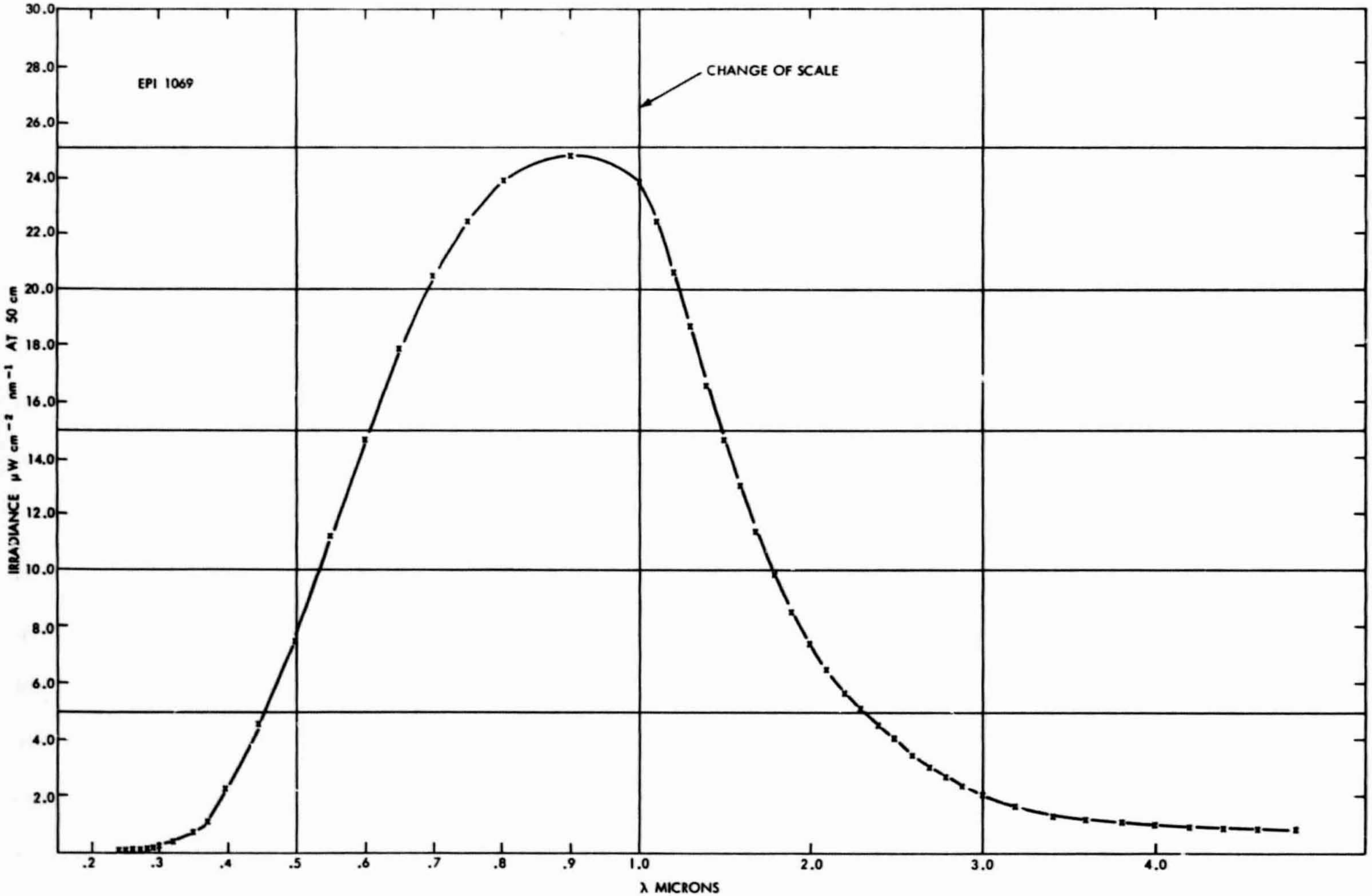


Figure 2. Spectral Irradiance of quartz iodine 1000 W lamp, EPI 1096, at 50 cm.

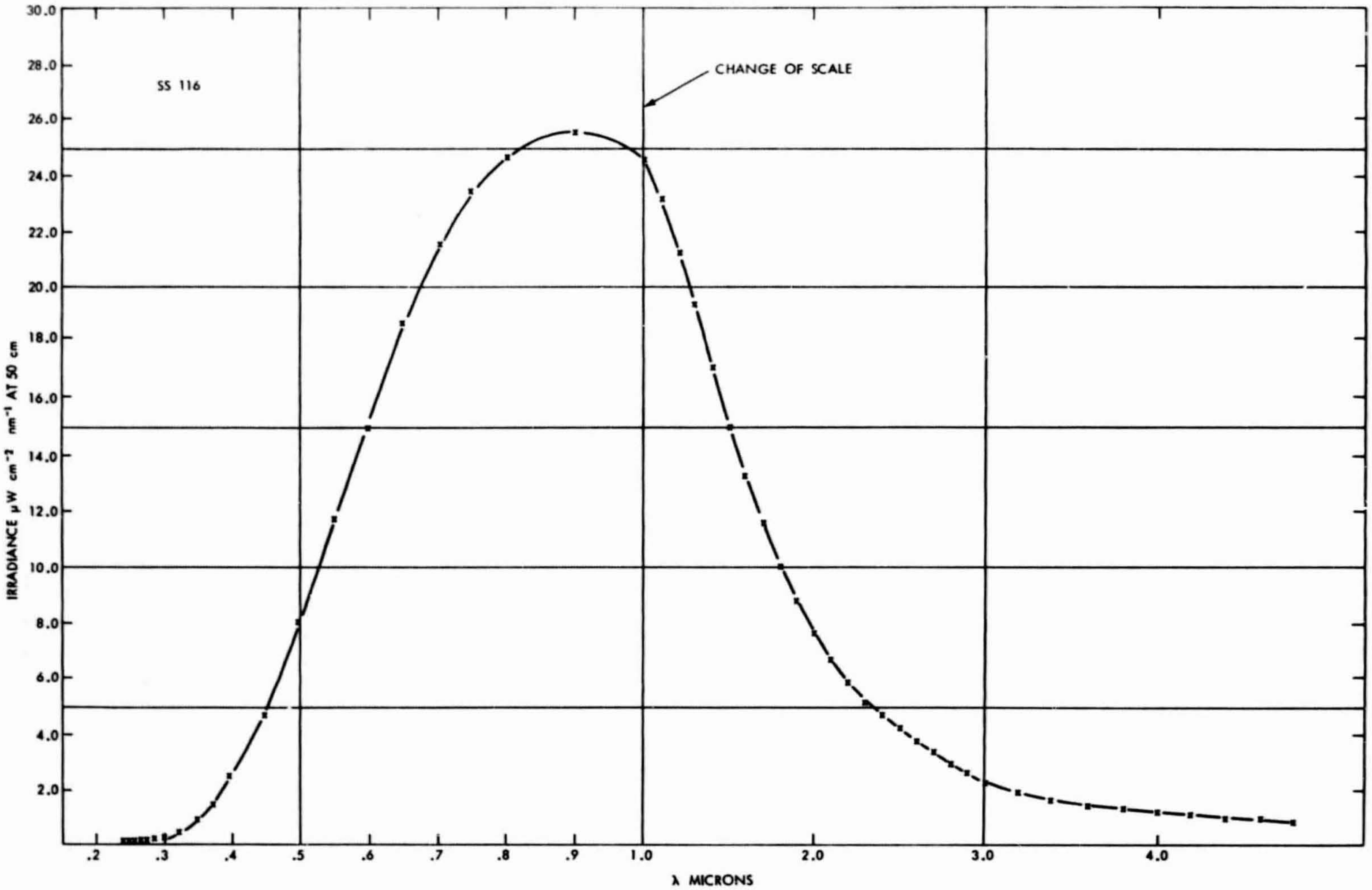


Figure 3. Spectral Irradiance of quartz iodine 1000 W lamp, working standard, SS 116, at 50 cm

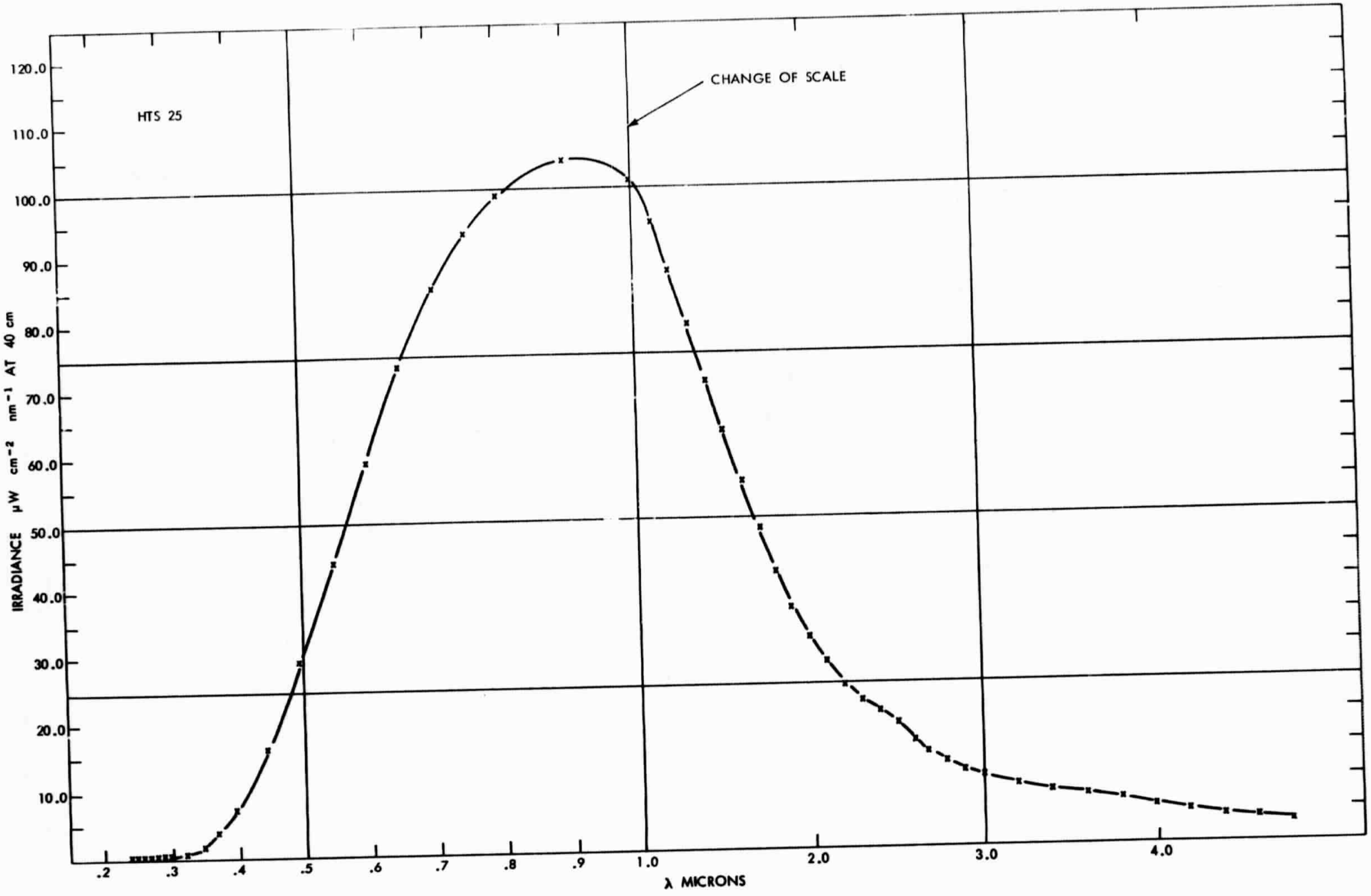


Figure 4. Spectral Irradiance of quartz iodine 1000 W lamp, Optronics standard, HTS 25, at 40 cm

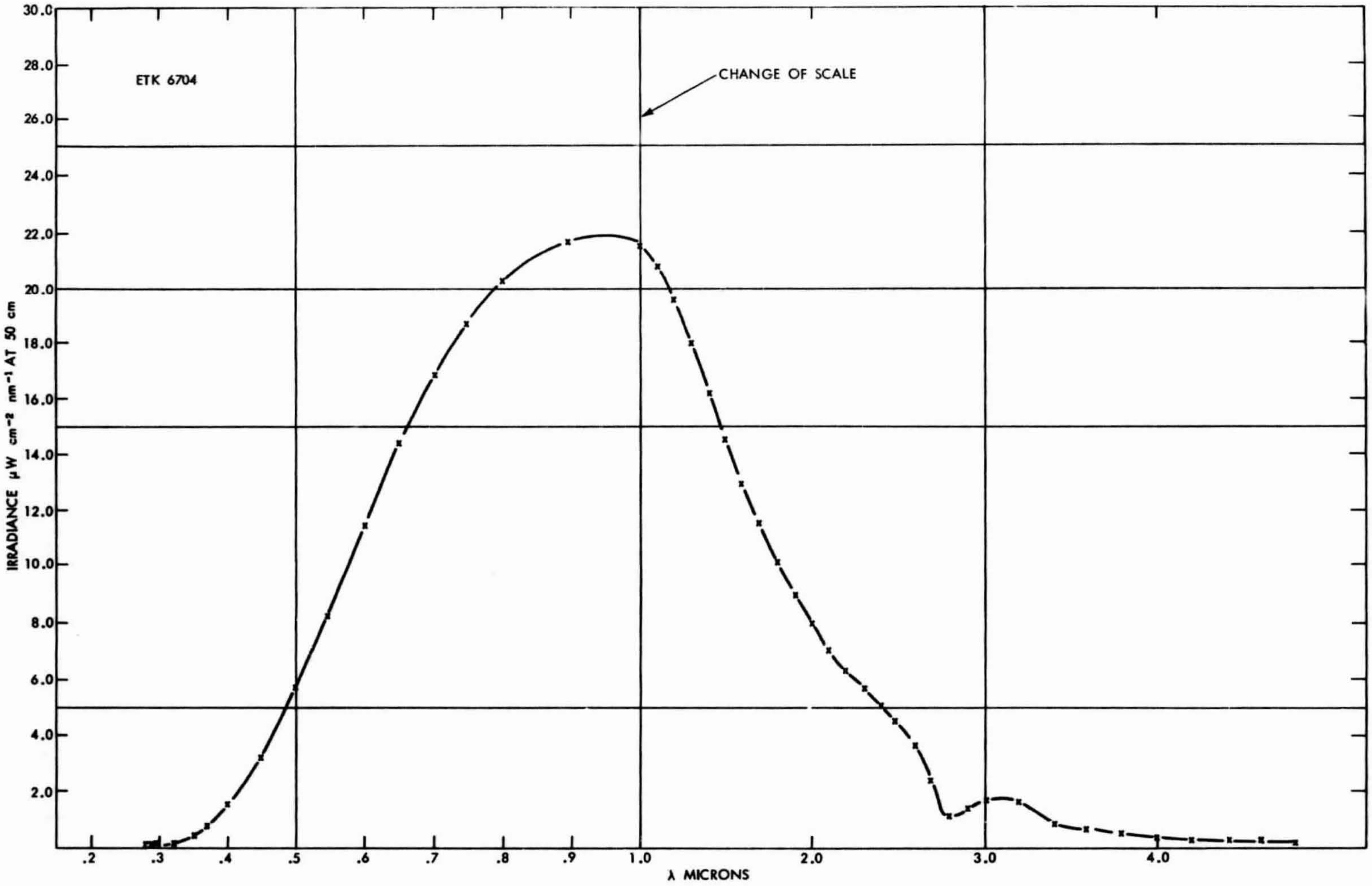


Figure 5. Spectral Irradiance of 1000 W standard of total irradiance, ETK 6704, at 50 cm

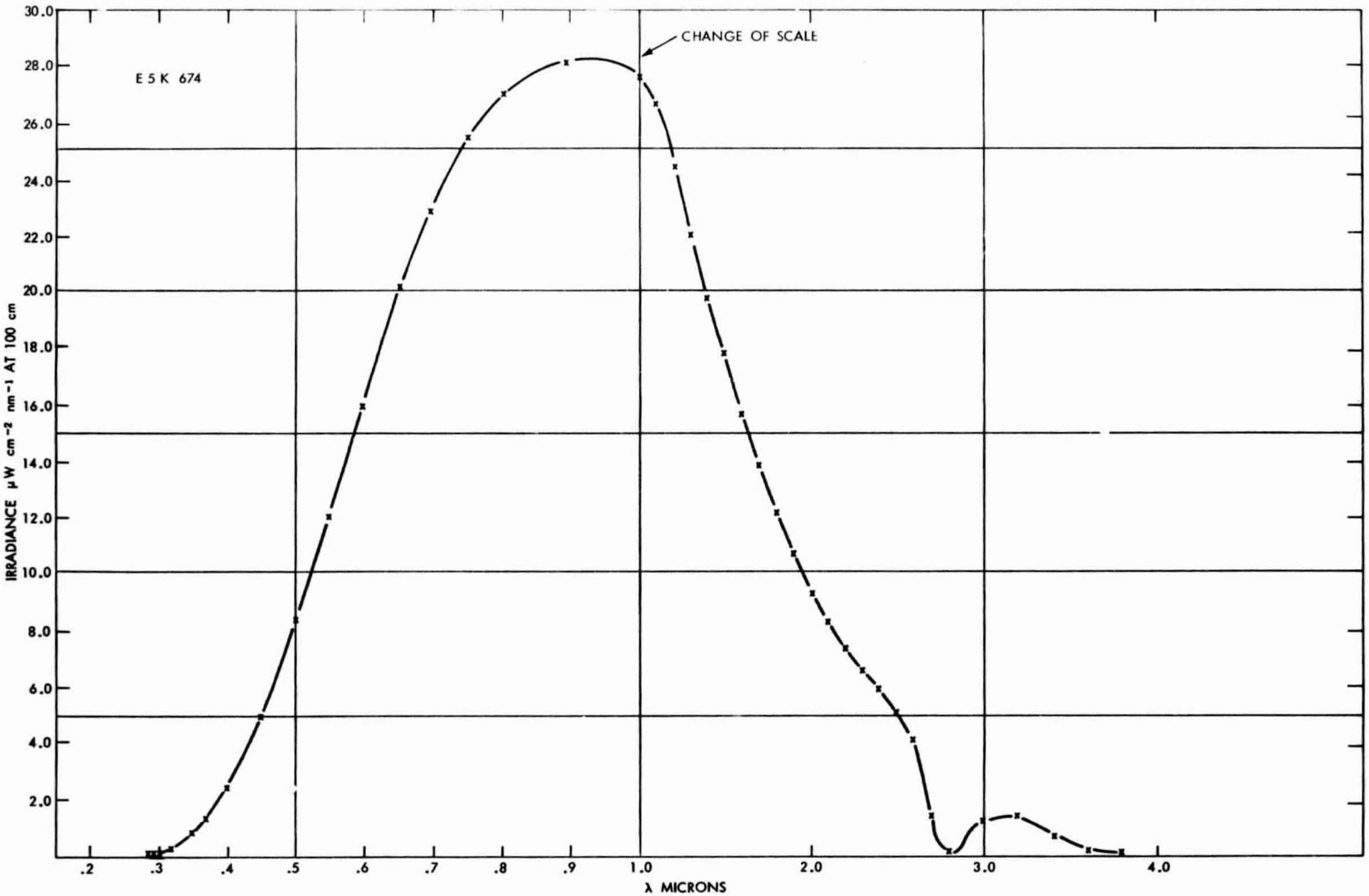


Figure 6. Spectral Irradiance of 5000 W high intensity calibration source, E5K 674, at 100 cm