SPECTRAL DISTRIBUTION OF ENERGY RADIATED FROM A NEW TYPE OF TUNGSTEN MERCURY ARC

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Abstract

This paper describes measurements with a quartz monochromator and thermopile of the energy flux from the tungsten mercury arc which is the source of radiation in the General Electric Sunlamp. Data are given on the energy flux radiated in each of the principal mercury lines below 6000A and a curve is given for the distribution of energy in the continuous spectrum between 2500 and 17000A. The maximum in the continuous spectrum curve comes at about 10600A where the energy flux in a 50A band is 6.5_9 microwatts per cm^2 at one meter distance from the center of the arc in a direction normal to the plane of the leads when the arc is operated with 115 volts on the primary of the transformer. The energy maximum corresponds to that of tungsten at about 2500°K but the shape of the curve below 5000A corresponds more closely to that of tungsten at 3250°K which is approximately the maximum temperature of the electrodes. For the radiation in a direction normal to the plane of the leads 1% of the total energy flux was found to lie between 2500 and 3200A, 1% between 3200 and 4000A, 10% between 4000 and 7600A, 46% between 7600 and 17000A, $29._5$% between 17000A and the cutoff (roughly 40,000A) of a fused quartz plate 2.4 mm thick and the remaining $12._5$% at longer wave-lengths.

In recent years many new applications have been found for sources of radiation in the ultraviolet and infrared as well as the visible portion of the spectrum. With each new source put into use there has arisen the need for measurements of the spectral distribution of its radiant energy. This paper presents data of this sort for the tungsten mercury arc which is the source of radiation in the General Electric Sunlamp. An analysis of the spectrum of this source over the wave-length region from 2800 to 7400A has been published by Benford.[1] An article by Coblentz[2] gives some data on the spectral distribution of the energy radiated from the complete Sunlamp unit. In the present article the average of energy flux values for a number of lamps are given for the principal mercury lines between 2500 and 6000A and for the continuous spectrum up to 17000A.

For making these measurements the quartz prism monochromator described in a recent paper[3] was used. The lamp to be measured was mounted in front of the collimator slit without any intervening lens. It was turned so that the axis of the arc was perpendicular to the line from the center of

[1] F. Benford, J. Motion Picture Eng. **14**, 414 (Apr. 1930), N. T. Gordon, F. Benford, G. E. Rev. **33**, 290 (May 1930).

[2] W. W. Coblentz, J.A.M.A. **95**, 411–Aug. 9, 1930.

[3] W. E. Forsythe and B. T. Barnes, R.S.I. (Oct. 1930).

the arc to the center of the slit. With this arrangement energy radiated from all parts of the arc and from the electrodes entered the monochromator. The slit height was 6.6 mm, the focal length of the collimator lens 12 cm, and the distance from the slit to the center of the lamp 15 cm. Thus, light from the region approximately 1 cm in diameter containing the electrodes and the arc would illuminate an area 20 mm high and 8 mm wide at the collimator lens. Since the latter is 30 mm in diameter there was practically no loss of light in the monochromator except by reflection. Correction was made for the latter by use of the transmission curve for this instrument shown in the article mentioned previously.[3] For use in the red and infrared this curve was extended parallel to the calculated curve up to 17000A. Such a long extrapolation, of course, introduces some uncertainty into the infrared values computed by use of the curve.

The energy passing through the rear slit of the monochromator fell on a thermopile. The sensitivity of the latter as determined by means of incandescent lamps calibrated by the Bureau of Standards is $2.3_1 \times 10^{-7}$ volts per microwatt when it is used behind a 0.70 mm slit. This thermopile could be connected to either a D'Arsonval high sensitivity or a Coblentz type moving magnet galvanometer. The latter was adjusted to a sensitivity about five times that of the D'Arsonval and used in the ultraviolet portion of the spectrum where the amount of energy to be measured was relatively small.

Below 6000A readings were taken on the principal mercury lines and at suitable intervals between them. To get the radiation due to the lines alone it was necessary to subtract the deflection due to the continuous spectrum from the actual readings which included both line and continuous radiation. To accomplish this the readings at settings where line radiation was negligible were plotted and the deflection due to the continuous spectrum at each setting for a mercury line was obtained from the curves through these points. Below 4500A the less important mercury lines which were necessarily included with the continuous radiation may have raised the curve appreciably since the continuous spectrum is relatively weak in the ultraviolet. On the other hand, in the red and infrared the mercury lines are too weak, compared with the continuous radiation from the tungsten electrodes, to be detected.

Having separated the line radiation from the continuous spectrum each may be reduced to absolute intensity. The energy flux in microwatts per cm^2 at one meter distance in the radiation comprising one of the lines of the mercury spectrum is:

$$E_L = Sd_L x^2/tA$$

where S is the sensitivity of the galvanometer-thermopile combination in microwatts per cm deflection; d_L is the galvanometer deflection due to the line itself—that due to the continuous radiation having been deducted from the actual reading—x is the distance in meters from the center of the arc to the slit—t is the transmission of the spectrometer at the wave-length of the line in question, and A the area of the front slit. It is assumed that the rear slit is at least as wide as the front slit. Actually the rear slit was set at 0.70 mm and the front slit at 0.50 mm so that for groups of neighboring lines such as at 3650 and 3130A all the radiation entering the front slit could pass through the rear slit and the above formula would still apply. In the case of the continuous spectrum it is desirable to introduce a dispersion factor to reduce the results to terms of a wave-length band of constant width. For the data given here this band was chosen as 50A. The energy flux in microwatts per cm² at one meter distance radiated in a band of continuous spectrum of this width is:

$$E_c = \frac{Sd_c x^2}{tA} \cdot \frac{50}{w}$$

where d_c is the deflection produced by the continuous radiation and w is the width in Angstroms of the band passing through the rear slit (0.70 mm wide). For obtaining w the dispersion curve was computed from the formula for the refractive index of quartz given by Coode-Adams[4] and the relation for minimum deviation—

$$\frac{ds}{d\lambda} \equiv f \cdot \frac{dD}{d\lambda} \equiv f \cdot \frac{dD}{dn} \cdot \frac{dn}{d\lambda} = \frac{4f}{(4 - n^2)^{1/2}} \cdot \frac{dn}{d\lambda}$$

where s represents distance along the spectrum, f is the focal length of the telescope lens (120.7 mm), D is the total deviation produced by both quartz prisms and n the refractive index.

No correction was made for impurity of the continuous spectrum due to finite slit-widths as it was found from computations on one set of data that the correction was not over 1% in any case. However, a correction for stray light in the ultraviolet portion of the spectrum was found necessary. Readings taken on a lamp with a purple Corex filter in front of the slit were divided by the transmission of the filter at each wave-length and the results subtracted from the corresponding readings without any filter. The difference—presumably due chiefly to light scattered from the more intense portions of the continuous spectrum—was subtracted from corresponding readings on all other lamps.

Spectral Distribution of Energy Flux Below 17000A

The averages of energy flux measurements made on twenty-six lamps. each operated with 115 volts on the primary of the transformer, are given by Figure 1. The curve shows the energy flux in microwatts per cm² at one meter distance in a direction perpendicular to the plane of the leads radiated in a band of the continuous spectrum 50A wide at any given wave-length. The energy radiated in the mercury lines is given by the length of the heavy lines drawn above the curve. These are plotted as if 50A wide so that the ratio of the area representing the line to the area under the curve for the continuous spectrum will be the ratio of the corresponding amounts of energy radiated from the lamp.

[4] Coode-Adams Proc. Roy. Soc. **A117**, 209 (1927–8).

Several features of the curve for the continuous spectrum given in Fig. 1 are of interest. The peak of this curve comes at about 10600A which is quite close to the maximum in the curve for the energy radiated by tungsten at 2500°K. However, the shape of the energy flux curve below 5000A is approximately the same as that for tungsten at 3250°K which is the temperature of the hottest parts of the electrodes. Also the output of visible and ultraviolet radiation is much too high in comparison with the infrared energy for tungsten at 2500°K. These facts are easily explained if one takes into consideration the composite nature of the continuous radiation. The electrodes having temperatures above 3000°K radiate a relatively high proportion of energy in the visible and ultraviolet. The filament and the in-

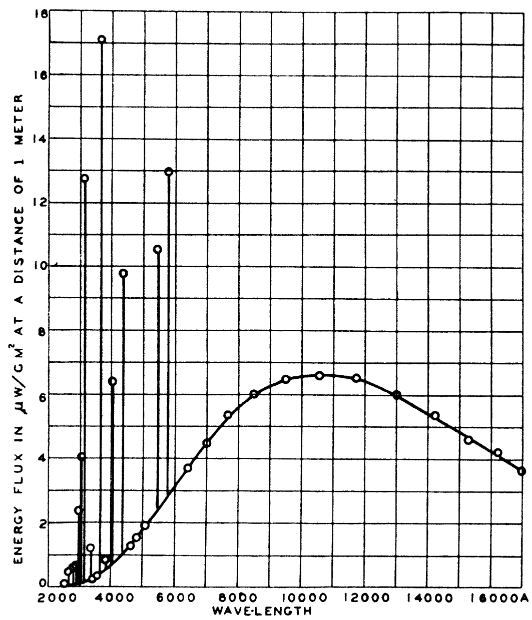

Fig. 1. Energy flux ($\mu w/cm^2$) 1 meter from center of arc in a direction normal to the plane of the leads. Lamp burning in the open (without reflector) with 115 volts on primary of transformer. Average lamp current and voltage 30.9_5 amps. and 10.6 volts. Curve represents energy in 50A band of continuous spectrum. Heavy lines above curve give energy flux in lines or groups of lines in arc spectrum.

candescent portions of the leads which are at much lower temperatures, but which, taken together, have a larger area than that of the electrodes, contribute a considerable portion of the infrared radiation and shift the maximum in the continuous spectrum curve toward longer wave-lengths.

Distribution of Total Energy Flux From Lamp

Although the range of the monochromator limited the energy distribution measurements to the region below 17,000A the amount of radiation of longer wave-lengths was obtained by measuring the total energy flux and subtracting from it the total flux of wave-lengths shorter than 17,000A. Six of the lamps were mounted two meters in front of a calibrated thermopile and readings made on the total energy flux and that transmitted by a fused quartz plate 2.4 mm thick and by 2.5 cm of water in a Pyrex cell. Measurements with the water cell served as a check on the agreement between the energy flux measured after passing through the monochromator and that measured directly. The total energy flux transmitted by the cell was computed by multiplying the measured energy flux at each wave-length by the transmission of the cell and integrating. The value obtained by this method was 553 microwatts per cm^2 at one meter as compared with 560 measured directly. On a set of four lamps each located at one meter distance from the thermopile computations by the above method indicated that the average energy flux through the cell should be 588 microwatts per cm^2 at one meter distance. The measured value was 604. The agreement in both cases is within the limits of experimental error indicating that the extrapolation of the transmission curve of the monochromator was not seriously in error in the wave-length region between 5780 and 11,000A.

The measured transmission of the water cell for the total energy flux from the lamp averaged $24._7$ percent for the group of six lamps with the distance to the thermopile two meters and $23._5$ percent for the group of four lamps located one meter from the thermopile. The difference may be due to increased absorption of the longer infrared rays by the water vapor in the air-making the proportion of the rays not transmissible by the water cell less at two meters than at one meter distance. The vapor pressure computed by psychrometric readings was $12._2$ mm when the group of six lamps was measured and $11._3$ mm when the group of four lamps was measured. The corresponding room temperatures were $25._3$ and $24._0$°C.

For these ten lamps the average cut-off of the water layer as defined by Stockbarger and Burns,[5] *i.e.*, the wave-length for which the amount of radiation absorbed at shorter wave-lengths is equal to that transmitted for longer wave-lengths was 10500A. The maximum transmission of the cell was 0.87—a slight deposit on the interior of the cell making the actual value somewhat less than the computed one. Then we find that of the total energy flux at one meter distance along a line perpendicular to the plane of the leads the fraction which is of wave-lengths shorter than 10500A is approximately 0.24_2 divided by 0.87 or 0.27_8. This is an average of the two sets of data disregarding the increased absorption of the air path for the lamps tested at a distance of two meters.

Although the transmission curve for the fused quartz plate has not been determined, measurements with this filter give an upper limit to the amount of radiation beyond about 4μ, the effective cut-off for a piece of crystalline quartz of the same thickness. Since the transmission of the fused quartz plate for the average total radiation for the ten lamps was 0.79_8 while the maximum transmission of quartz is 0.91_2 then 0.79_8 divided by 0.91_2 or 0.87_5 is the fraction of the radiation below the effective cut-off of the filter which

[5] Stockbarger and Burns, Phys. Rev. **34**, 1263 (1929).

is probably between 3.5 and 3.9μ. The bulb of the lamp having a temperature of about 300°C doubtless furnishes a large proportion of the energy of wave-lengths longer than 4μ.

By dividing the average value for the energy flux for each individual line by the average total energy flux one finds the fraction of the total radiation comprised in each line. Table I gives the results, representing the average of ten lamps, for the strongest lines and groups of lines in the mercury spectrum. The average total energy flux at one meter distance for these lamps was 2380 microwatts per cm.[2] The average lamp current and voltage were 30.9_5 amp. and 10.6 volts.

TABLE I. *Average energy flux for each of the principal mercury lines and corresponding percentages of average total energy flux.*

115 volts on primary of transformer.								
Wave-length	5780	5461	4358	4047	3905	3650	3342	3130
Microwatts/cm² at 1 meter	$9.{}_7$	$8.{}_2$	$9.{}_0$	$5.{}_8$	$0.{}_4$	$17.{}_4$	$1.{}_1$	$13.{}_5$
Percent of total	0.4_1	0.3_4	0.3_8	0.2_6	0.01_7	0.7_3	0.04_6	0.5_7
Wave-length		3024	2967	2894	2804	2650	2537	
Microwatts/cm² at 1 meter		4.4_0	2.5_4	0.7_1	0.6_9	0.6_5	0.1_2	
Percent of total		0.1_9	0.10_7	0.03_0	0.02_9	0.02_7	0.00_6	

These data apply only to the energy flux in a direction perpendicular to the plane of the leads. For the total radiation from the lamp in all directions the spectral distribution of energy would be somewhat different. The total energy flux in the direction specified averaged for the ten lamps was 2.38 milliwatts per cm² at one meter distance as compared with the calculated value of 2.61 if the entire input of the lamp were assumed to be radiated with a uniform distribution. The difference is due to absorption in the layer of air traversed, losses by conduction and convection and non-uniform distribution of the radiated energy.

A summary of the energy flux in certain wave-length regions is given by Table II. These results are the averages for the same ten lamps for which data are given in Table I and likewise refer to the energy flux along a line passing through the center of the arc normal to the plane of the leads.

TABLE II. *Average energy flux in microwatts per cm² at one meter distance. 115 volts on primary of transformer. Average lamp current and voltage 30.9_5 amp. and 10.6 volts.*

Wave-length Region	2500–3200	3200–4000	4000–7600	7600–17000	>17000A	Total Radiation
Line spectrum	$22.{}_6$	$18.{}_9$	$(32.{}_7)$*	——	——	——
Continuous spectrum	$0.{}_6$	$5.{}_2$	209	——	——	——
Continuous and lines	$23.{}_2$	$24.{}_1$	242	1090	1000	2380

* Red lines in Hg spectrum included with continuous spectrum.

The data of Table II show that the continuous spectrum furnishes less than 3% of the energy flux below 3200A but over 86% of the visible radiation. Since much of this continuous radiation is in the red end of the spectrum where the visibility is low the continuous spectrum furnishes only 76%

of the light radiated in a direction perpendicular to the plane of the leads. This result was obtained by multiplying the average data for twenty-six lamps plotted in Figure 1 by the relative visibility at each wave-length, integrating graphically for the continuous spectrum and summing for the mercury lines. Photometric measurements, on other lamps, made in this laboratory by Miss Easley indicated that for the direction perpendicular to the plane of the leads the continuous spectrum furnishes 75% of the total light. Benford[1] gives a corresponding figure of 76%, also obtained by a photometric method. There is very good agreement between the three sets of results. The energy of the weak red lines of mercury does not appreciably affect the computations of the total light radiated in all the mercury lines.

In the infrared the mercury spectrum could not be separated from the continuous radiation. Comparison with other mercury arcs indicates that between 1 and 2μ the radiation in the mercury lines is of the order of 1% of the total continuous radiation in this wavelength region.

The last line of Table II shows that for the energy flux at one meter distance in a direction perpendicular to the plane of the leads 1% of the total radiation is of wave-lengths shorter than 3200A, 1% is in the wave-length region between 3200 and 4000A, and 10% in the visible spectrum. Mercury arc radiation of wave-lengths shorter than 6000A comprises only 3% of the total energy flux in the direction specified.

Comparison of the data given in Table II and in the last two paragraphs with those published by Benford[1] indicates a fair agreement as to the amount of ultraviolet below 3200A. One would expect his values to be lower because the glass used for the bulbs which he tested had a somewhat lower transmission below 3200A than that used at the present time. Furthermore his lamps were operated at 30 amperes while ours were run with 115 volts on the primary of the transformer giving an average current of 30.9_5 amperes. One would not expect a close agreement.

The fact that Benford's data for the range from 3200 to 4000A is 41% higher than ours may be due to the circumstance that the line at 3650A which contributes the major part of this radiation varies considerably in intensity with varying mercury vapor pressure. Consequently different lamps may have a widely different output at this wave-length. Also the intensity of this line often increases over 50% during the first forty hours burning. Our data were taken on lamps which had been burned from three to five hours.

For the region from 4000 to 7000A our data gives the energy flux as 185 microwatts per cm^2 at one meter distance. Benford's value is 28% higher. This difference is hard to explain since most of the radiation in this region, being in the continuous spectrum, is little affected by mercury vapor pressure and therefore changes comparatively little in intensity during the first forty hours burning. For the group of twenty six lamps for which the distribution data is plotted in Figure 1 the average deviation of the values on individual lamps from the mean for the energy flux between 4000 to 7000A was about one-fourth the difference between Benford's and our values and the maximum deviation only about one-half of this difference. It is possible, however, that the earlier lamps were less uniform than those being manufactured now with respect to the average temperature of the electrodes. The latter of course, determines the distribution and total amount of continuous radiation from the lamp.

A satisfactory comparison of the data given in this paper with those for the complete Sunlamp unit published by Coblentz[2] is not possible. There are not sufficient data on the amount and distribution of radiation in other directions than along the normal to the plane of the leads, or on the reflecting power and the concentration of the beam by the reflector. Furthermore data obtained in this laboratory by Miss Easley showed that for six lamps the average temperature of the mercury pool was 7° greater with the lamps in the reflector unit but without the screen in place than when they were operated in open air. Data previously published[6] show that the intensity of the ultraviolet radiation below 3200A would be 10 to 15% greater at the higher temperature. The intensity of the continuous spectrum would remain practically unchanged. In consideration of the above mentioned facts it should therefore be emphasized that the data in the present paper refer to the radiation from the lamp operated in the open and not to that received from the complete Sunlamp unit.