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July 15, 1965

Taks II, Item 5, First Technical Report

Lamps For Rear Projection Viewers

Work Statement

Review literature and make an economic and performance per watt profile of the types of lamps applicable to rear projection viewers, such as: 1000 watt xenon, mercury xenon, quartz iodine, and tungsten. Performance analysis to include estimates of heat rejection, visible light level and spectral distribution obtainable from band pass filters. The analysis and report preparation will be accomplished jointly be [redacted]

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1. Summary

1.1 Introduction

In this report an attempt has been made to

(a) gather basic data and representative information on several 1000 watt lamps;

(b) define terms and calculate representative performance;

(c) establish a format for presentation of the data.

There are many gaps. For example there is no good information on the conversion efficiency of Tungsten and it was estimated. Some of the arc brightness data appears to be inconsistent and needs further checking. We are not satisfied with the presentation of screen illumination data (especially the projection lens aperture) in Table I and will give it added consideration. With the further cautionary note that all of the data is preliminary and subject to revision we submit this first report.

1.2 Discussion Summary

Photometry deals with the response of the eye to light. Thus radiant power from a source or a surface must always be multiplied by the relative spectral sensitivity function of the eye to obtain values in photometric units.

All tungsten lamps of whatever size and power when operated at the same color temperature have the same spectral distribution. The spectral distribution depends only upon the filament color temperature. Two filament shapes C-13 and C-13D are of greatest interest in projection work. The radiation lobes of these filaments are quite different but all lamps which use C-13 filaments will have approximately the same radiation lobe and all lamps which use the C-13D filaments will have approximately the same radiation lobes.

The xenon high pressure arc lamps have the same spectral distribution regardless of wattage and the spectral distribution of other high pressure arc lamps depends on the gas used.

The conversion efficiency (radiated watts per input watt) of the compact high pressure arc lamps is approximately 50%. No good data is available for tungsten but the conversion efficiency is believed to be about 80%.

1.3 Data Summary

Lamp data are summarized in Table I for ready reference.

The color temperature, lamp life and lamp cost are manufacturer's published data. Note that the color temperature of the compact high pressure arc lamps are only approximate correlations to black body radiation, disregarding spectral lines. The luminance in lumens is from manufacturer's published data. The luminance in visible watts is lumens divided by 621* and is the area under the visibility curve expressed in watts. Note that this is quite different from the watts radiated in the visible region of the spectrum.

The radiation conversion efficiency is an estimate for tungsten and for the arc lamps is taken from manufacturer's data. The heat dissipated at the lamps and the

* The quoted conversion value of lumens per watt varies from 621 to 692 depending on the source of information.

Summary Tabulation of Lamp Data for Rear Projection Viewers, Table I

Lamp Type	Color Temp.	Life-Cost			Luminance			Power Required
		Lamp Life	Lamp Cost	Cost Per Hr.	Total Visible Radiation		Cost	
	°K	Hours	$	¢/Hr	Lumens	Visible Watts	¢ Per 1000 lm. Per Hr.	
1000 Watt								
Tungsten C-13								
ASA #DPW	3200	50	9.80	19.6	28,000	45.1	0.7	115-120 VAC Line Power
ASA #DRC	3250	50	7.50	15.0	30,000	40.3	0.5	115-120 VAC Line Power
ASA #DRB	3350	25	6.90	27.6	32,000	51.5	0.86	115-120 VAC Line Power
Tungsten C-13D								
ASA #DRS	3325	25	6.75	27.0	28,500	45.9	0.95	115-120 VAC Line Power
ASA #DFD	3375	10	5.75	57.5	30,500	49.1	1.89	115-120 VAC Line Power
ASA #DGS	3375	10	7.25	72.5	33,000	53.2	2.20	115-120 VAC Line Power
Quartz Iodine								
ASA #DXW	3200	150	16.95	11.3	26,000	41.9	0.43	115-120 VAC Line Power
ASA #DXN	3400	30	14.95	50.0	33,000	53.1	1.52	115-120 VAC Line Power
Xenon-Mercury								
D.C Hanovia 528B9	5500	1000	200.00	20.0	40,000	63.4	0.5	58-72 Volts 16 amps. D.C.
A.C Hanovia 537B9	5500	1000	200.00	20.0	50,000	80.5	0.4	60-70 Volts 18 amps. A.C.
900 Watt								
Xenon								
D.C Hanovia 538C9	5500	1000	200.00	20.0	35,000	56.4	0.57	29-35 Volts 28 amps.
D.C OSRAM XBO900								D.C. Power Supply.
870 W. Rated Values	6000	1500	245.00	16.3	30,500	49.1	0.53	70-110 Volts 30-50 amps. D.C. Power Supply.
1105 W. Maximum Values	6000	2000	245.00	12.3	41,500	66.9	0.30	70-110 Volts 30-50 amps. D.C. Power Supply.

Summary Tabulation of Lamp Data for Rear Projection Viewers, Table I (cont'd)

Lamp Type	Color Temp.	Luminance	Heat					Screen Illumination			
			Conversion Effic.	Total Radiation	Non-Visible	Collect Filter Factor	Power at Gate	Projection Factor	Screen Brightness	Cost	Projection lens
	°K	Lumens	%	Watts	Watts	%	Watts	%	Ft-L	¢ per 100 ft-L per hour	Aperture
1000 Watt											
Tungsten C-13											
ASA #DPW	3200	28,000	80	800	672	.044	25.6	8.4	376	5.2	
ASA #DRC	3250	30,000	80	800				8.4	403	3.7	
ASA #DRB	3350	32,000	80	800				8.4	430	6.4	
Tungsten C-13D											
ASA #DRS	3325	28,500	80	800				8.4	383	7.1	
ASA #DFD	3375	30,500	80	800				8.4	410	14.0	
ASA #DGS	3375	33,000	80	800				8.4	444	16.4	
Quartz Iodine											
ASA #DXW	3200	26,000	80	800				7.1	296	3.8	
ASA #DXN	3400	33,000	80	800				7.1	375	13.4	
Xenon-Mercury											
D.C Hanovia 528B9	5500	40,000	50	500	295	.027	27.3	7.1	455	4.4	
A.C Hanovia 537B9	5500	50,000	50	500	295	.027	27.3	7.1	568	3.5	
900 Watt											
Xenon											
D.C Hanovia 538C9	5500	35,000	50	450	344	.027	14.1	7.1	400	5.0	
D.C OSRAM XB0900											
870 W. Rated Values	6000	30,500	53	460	338	.027	16.2	7.1	346	4.7	
1105 W. Maximum Values	6000	41,500	53	585	431	.027	20.6	7.1	471	2.6	

radiation are derived from the conversion efficiency. The radiation power in the non-visible and the radiated power in the visible were measured on the black body spectral distribution curves for tungsten and were taken from the manufacturer's data for xenon and xenon-mercury lamps. The power at the gate depends upon the collection efficiency and filter efficiency and is dervied from both the visible and non-visible radiation.

The screen illumination data is based on total lamp lumens, the projection efficiency and a 30" square screen. In turn the projection efficiency is based on the product of a number of factors standardized for this report:

a.) Collection efficiency (90^{o} Collection angle)
b.) Condenser transmission efficiency
c.) Filter efficiency
d.) Film gate blocking factor
e.) Projection lens aperture blocking factor
f.) Screen transmission 75%, screen gain 1.0.

It was assumed that screen brightness would not change with magnification. This of course is an approximation which is good only over a reasonable range of magnification such as up to 48x. The approximation results from the requirement to add condenser elements at higher magnifications. In addition for large filaments and large projection lens magnifications, the projection lens f/number may be unavailable.

2. Definition of Terms

2.1 Units and Equations

There has been much unnecessary confusion with regard to photometry largely owing to the existence of an unnecessary number of terms that have found their way into the vocabulary. Actually there are four quantities that suffice to handle any problem that may arise in either radiometry or photometry. These disciplines together with the basic quantities are defined herein. (See also Table II)

a.) Radiometry is the science of measurement of radiant energy.

b.) Photometry is the science of measurement of visible radiant energy.

c.) Radiant Flux is radiant energy transferred per unit of time. It is measured in units of power.

d.) Luminous Flux is radiant flux evaluated with respect to the luminous efficiency of the radiation.

e.) Radiant Intensity is the radiant flux emitted from a point per unit solid angle in a specified direction.

f.) Luminous Intensity is the luminous flux emitted from a point per unit solid angle in a specified direction.

g.) Radiance is the radiant intensity per unit area of an extended source.

h.) Luminance is the luminous intensity per unit area of an extended source. Synonymous with brightness the term has been adopted to maintain analogous terminology between photometry and radiometry.

i.) Irradiance is the radiant flux received per unit

TABLE II TABLE OF UNITS

Radiometry (Total Radiation)			Photometry (Visible Radiation)			
TERM	SYMBOL	UNITS	TERM	SYMBOL	UNITS	COMMENTS
Radiant Energy	U	Joule	Luminous Energy	Q	Talbot	
Radiant Flux	P	Watt	Luminous Flux	F	Lumen	a.) Also talbots/sec. b.) 1 watt = 621 lumens at 0.555 microns c.) Also called luminosity
Radiant Intensity	J	Watt per Steradian	Luminous Instensity	I	Lumen per Steradian	a.) Also candles
Radiance	N	Watta/steradian m^2	Luminance	B	Lumen/steradian cm^2	a.) Also candle/cm^2, also lambert
					Lumen/steradian ft^2	a.) Also candle/ft^2, also foot lambert b.) Also called Brightness c.) Density of Intnesity emitted from a surface
Irradiance	H	Watts/m^2	Illuminance	E	Lumen/m^2	a.) Also meter candle
					Lumen/ft^2	a.) Also foot candle b.) Density of luminous flux falling on a surface
Radiant Emittance	W	Watts/m^2 Watts/ft^2	Luminous emittance	L	Lumen/m^2 Lumen/ft^2	Density of luminous flux emitted <u>from</u> a surface

area of a surface. It is also sometimes known as flux density.

j.) Illuminance is the luminous flux received per unit area of a surface. Also referred to as illumination, or flux density, it has been adopted to maintain analogous terminology between photometry and radiometry.

The above are the quantities essential for solving problems. Other quantities of interest are:

a.) Radiant Emittance is the radiant flux emitted per unit area of an extended source.

b.) Luminous Emittance is the luminous flux emitted per unit area of an extended source.

c.) Luminosity. Total luminous flux expressed in lumens. Mathematically expressed as

$$L = 621\int_{0}^{\infty} V(\lambda)\, E(\lambda)\, d\lambda$$

where $V(\lambda)$ is the relative visibility function standard which has been adopted as most representative of the human eye, and $E(\lambda)$ is the spectral emittance function of the source.

d.) Luminous Efficiency : The ratio of luminosity to total radiant flux. Expressed in lumens per radiated watt.

e.) Luminous Coefficient : Ratio of luminous power (i.e. luminous flux) in watts to radiant power (i.e. radiant flux) in watts.

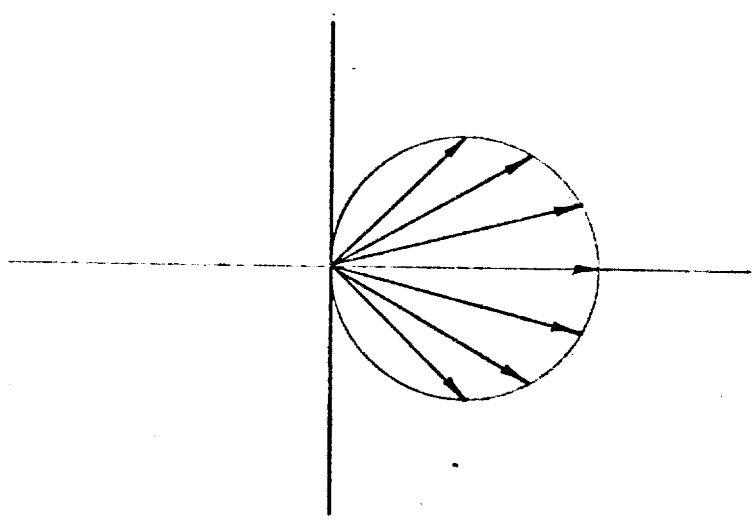
f.) Radiant Efficiency : Ratio of radiated power in watts to input power in watts. Also called conversion efficiency.

g.) Lumen - Unit of luminous flux. That amount of light that produces the visual response provided by .00161 watt of monochromatic light at 555 millimicron.

h.) Foot-Lambert - A unit of luminance (applied to screens) that is numerically equal to the illuminance in lumens per square foot incident on the screen, if the screen is perfectly diffuse and perfectly transmitting or reflecting.

The terms Lambert and Foot-Lambert used in reference to brightness of screens deserve some explanation. The difference between the Lambert and Foot-Lambert is the unit area of screen referred to. Lambert refers to cm^{-2} as unit area and foot-lambert refers to ft^{-2} as unit area.

The lambert is a convenient term for expressing the transmission or reflection of the visible light falling on a screen. The assumption is that the visible light falling on a screen is transmitted (or reflected) over a full hemisphere (i.e. 2π steradians). The intensity lobe of a Lambertian screen is therefore shown as:



Thus a lambertian screen is considered to be perfectly transmitting (or reflecting) and perfectly diffuse. If a screen is not Lambertian, then the transmission (or reflection) and the screen gain must be taken into account.

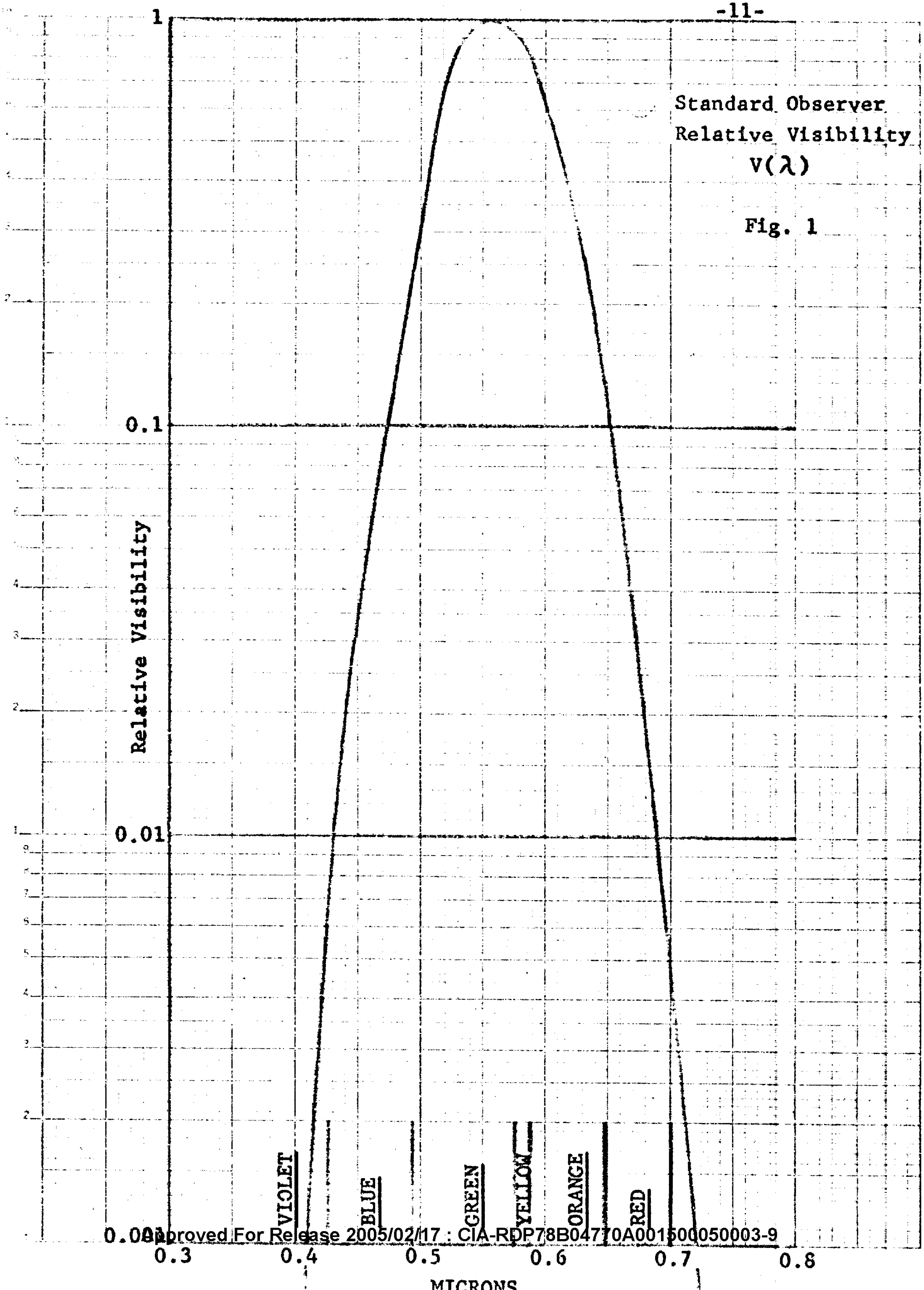
i.) Diffuse - Descriptive of an emitting, reflecting or transmitting surface. A surface whose intensity varies as the cosine of the angle of emission of transmitted (or reflected) light. In consequence of this property, the brightness of a diffuse surface is independent of the viewing angle.

j.) Screen Gain - The ratio of the length of the intensity lobe of an actual screen to that of a perfectly diffusing screen. The "length" is the radius vector of the polar plot in the direction of the light for transmitting screens.

2.2 Visibility

The relative visibility function, $V(\lambda)$ of the standard observer is given in Fig. 1.

The eye is well adapted to the peak of the spectral distribution of sunlight as shown in Fig. 2. Sunlight is approximately equivalent to Black Body radiation at about 6000^{o}K. At lower color temperatures, a much lower fraction of radiant power is visible, as illustrated in Fig. 3 for Black Body Radiation at 3250^{o}K. Note in Fig. 3 that the cross hatched area, which is the multiplication of ordinates of the visiblity function and the radiated power, is the visible power in watts/cm^2. Multiplying by 621 gives the visible power in lumens/cm^2. The visible power is quite



Standard Observer
Relative Visibility
V(λ)
Relative Visibility
1
0.1
0.01
0.001
0.3
0.4
0.5
0.6
0.7
0.8
MICRONS
VIOLET
BLUE
GREEN
YELLOW
ORANGE
RED

Fig. 1

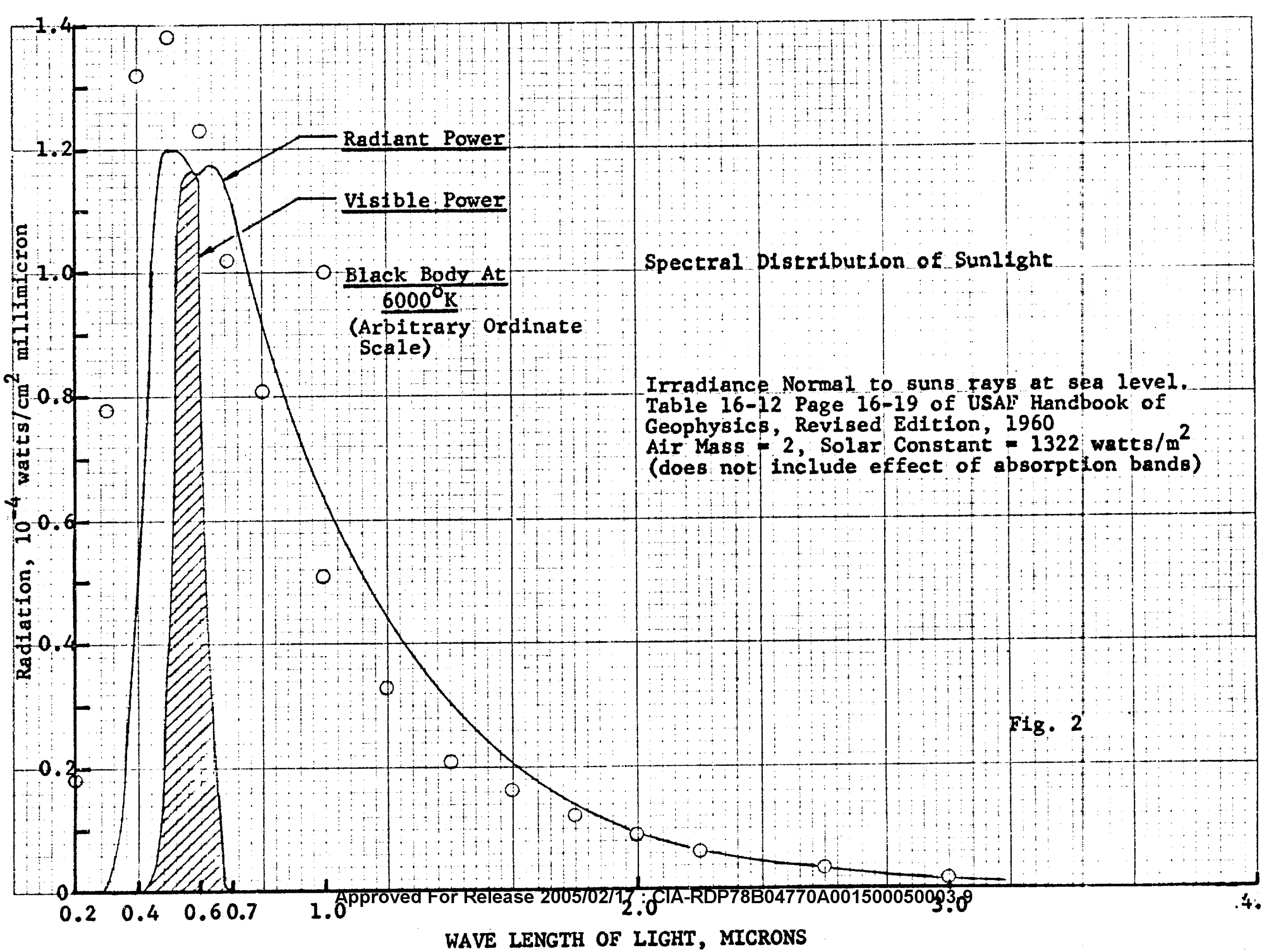

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Radiation, 10^{-4} watts/cm^2 millimicron
Radiant Power
Visible Power
Black Body At 6000^oK
(Arbitrary Ordinate Scale)
Spectral Distribution of Sunlight
Irradiance Normal to suns rays at sea level.
Table 16-12 Page 16-19 of USAF Handbook of Geophysics, Revised Edition, 1960
Air Mass = 2, Solar Constant = 1322 watts/m^2
(does not include effect of absorption bands)
0.2 0.4 0.6 0.7 1.0 2.0 3.0 4.0
WAVE LENGTH OF LIGHT, MICRONS

Fig. 2

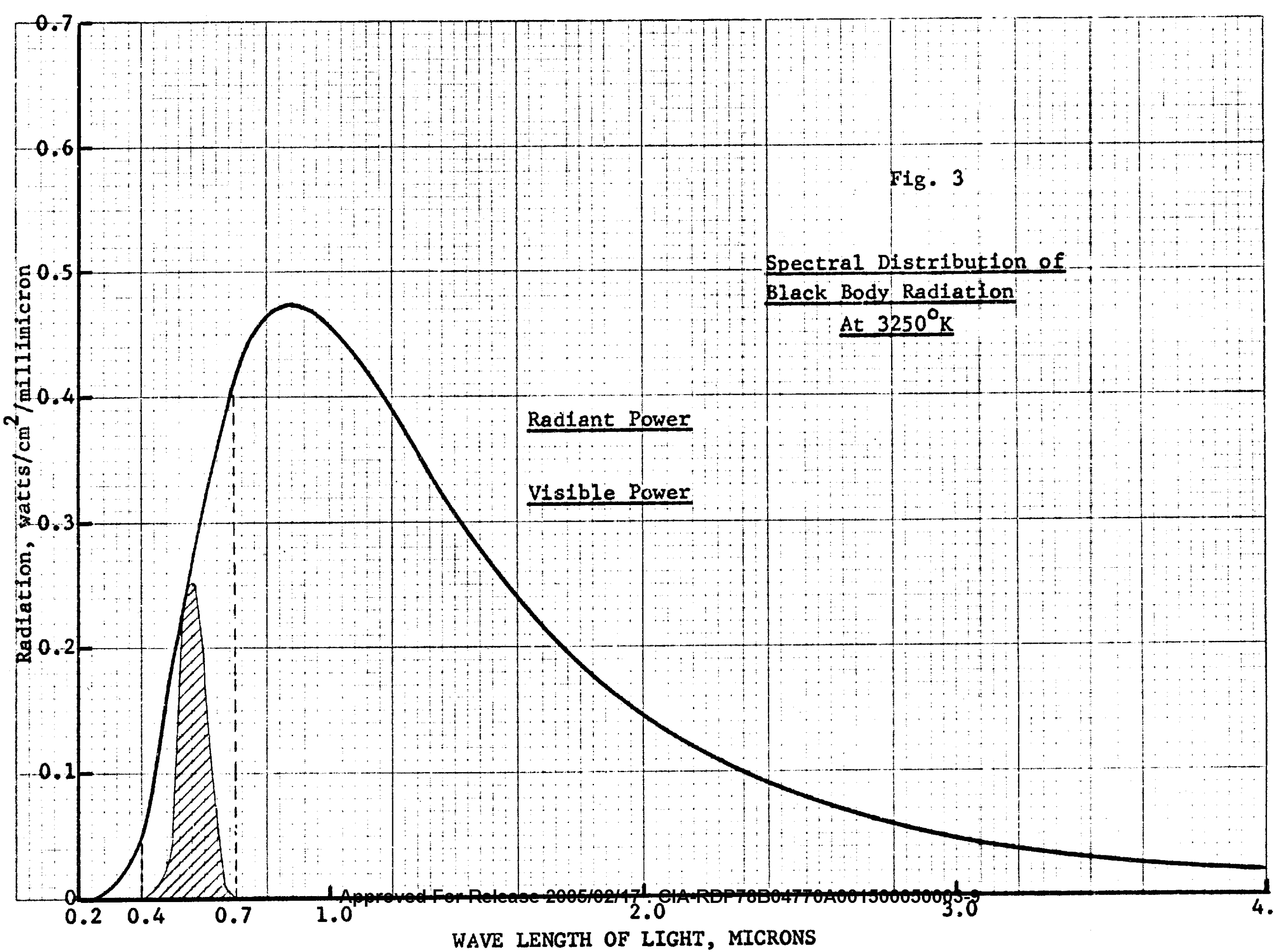


Fig. 3
Spectral Distribution of Black Body Radiation At 3250°K
Radiant Power
Visible Power
Radiation, watts/cm²/millimicron
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.7
1.0
2.0
3.0
4.0
WAVE LENGTH OF LIGHT, MICRONS

different from the radiant power in the visible region of the spectrum which is the area under the radiant power curve between 0.4 to 0.7 microns.

3. Technical Discussion

3.1 Source Characteristics

All present lamps use a hot gas or a hot solid as their radiation source (with the exception of lasers). All incandescent lamps using tungsten filaments (regardless of wattage or filament geometry) will have a spectral distribution and brightness determined by the color temperature at which the filament is operated. Tungsten radiates much like a black body as shown in Fig. 4. The brightness of tungsten rises rapidly with color temperature as shown in Fig. 5. The luminous coefficient also increases with color temperature, however, filament life goes down.

Black body radiation for a number of color temperatures is shown in Fig. 6 and can be taken as a close approximation of the radiation distribution of tungsten filament lamps at the given color temperatures. As the color temperature increases the peak moves up and to the left (towards the blue end of the spectrum). The curve becomes more peaked with less radiation in the infra-red. The area, P, under the radiated curve increases markedly with color temperature.

$$P = \quad T^4$$

where:

P = Radiant flux, watts per unit radiating area

σ = Stefan-Boltzmann radiation constant*, 5.709×10^{-12} watts/cm^2 deg^4

T = Absolute temperature, degrees Kelvin

Thus for higher color temperatures, less radiating area is required to radiate a given amount of power. The above equation neglects ambient temperature.

* The quoted figures for the Stefan-Boltzmann constant vary from 5.67 to 5.735 depending on the source of information.

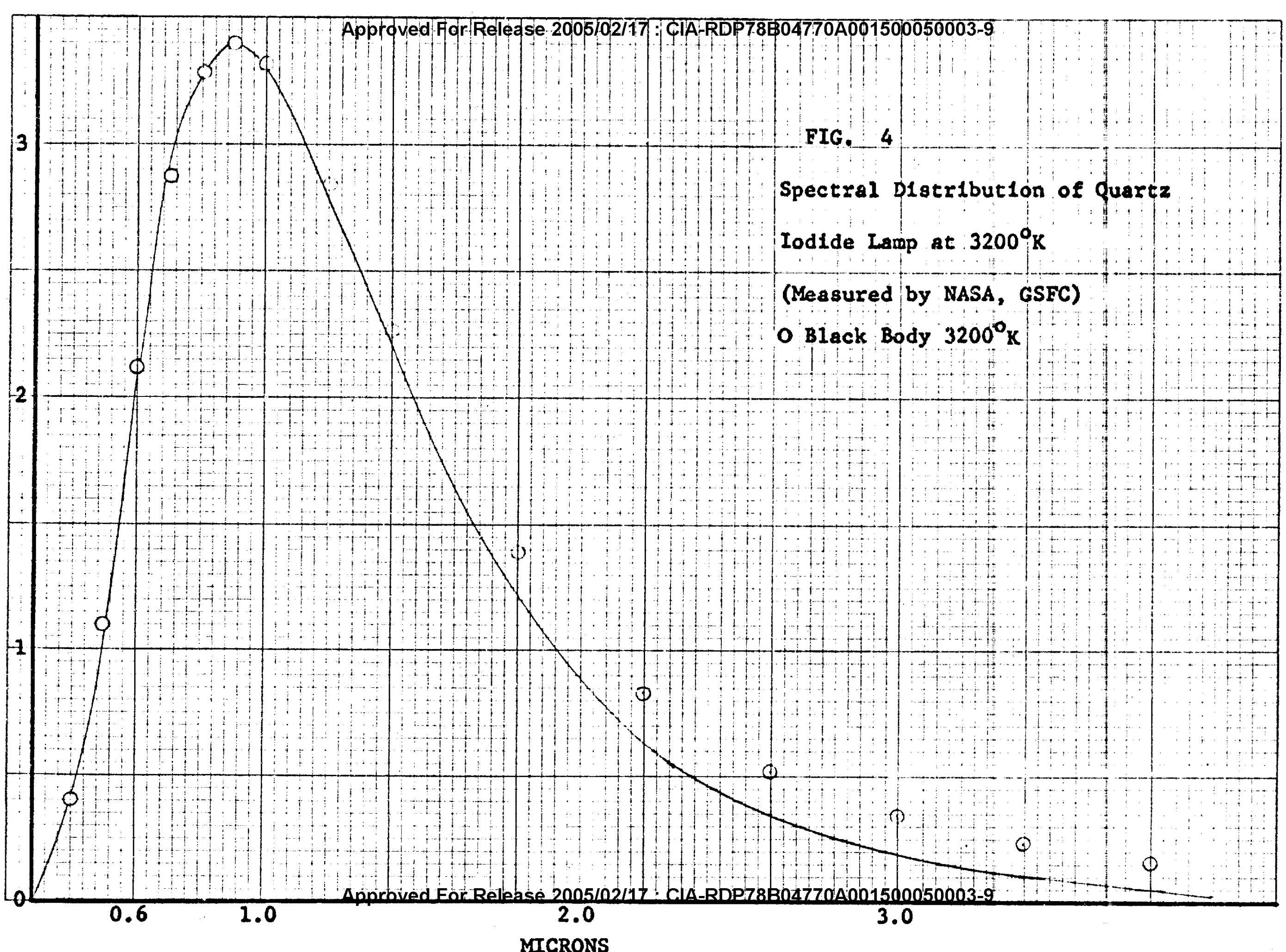


FIG. 4

Spectral Distribution of Quartz Iodide Lamp at 3200°K

(Measured by NASA, GSFC)

O Black Body 3200°K

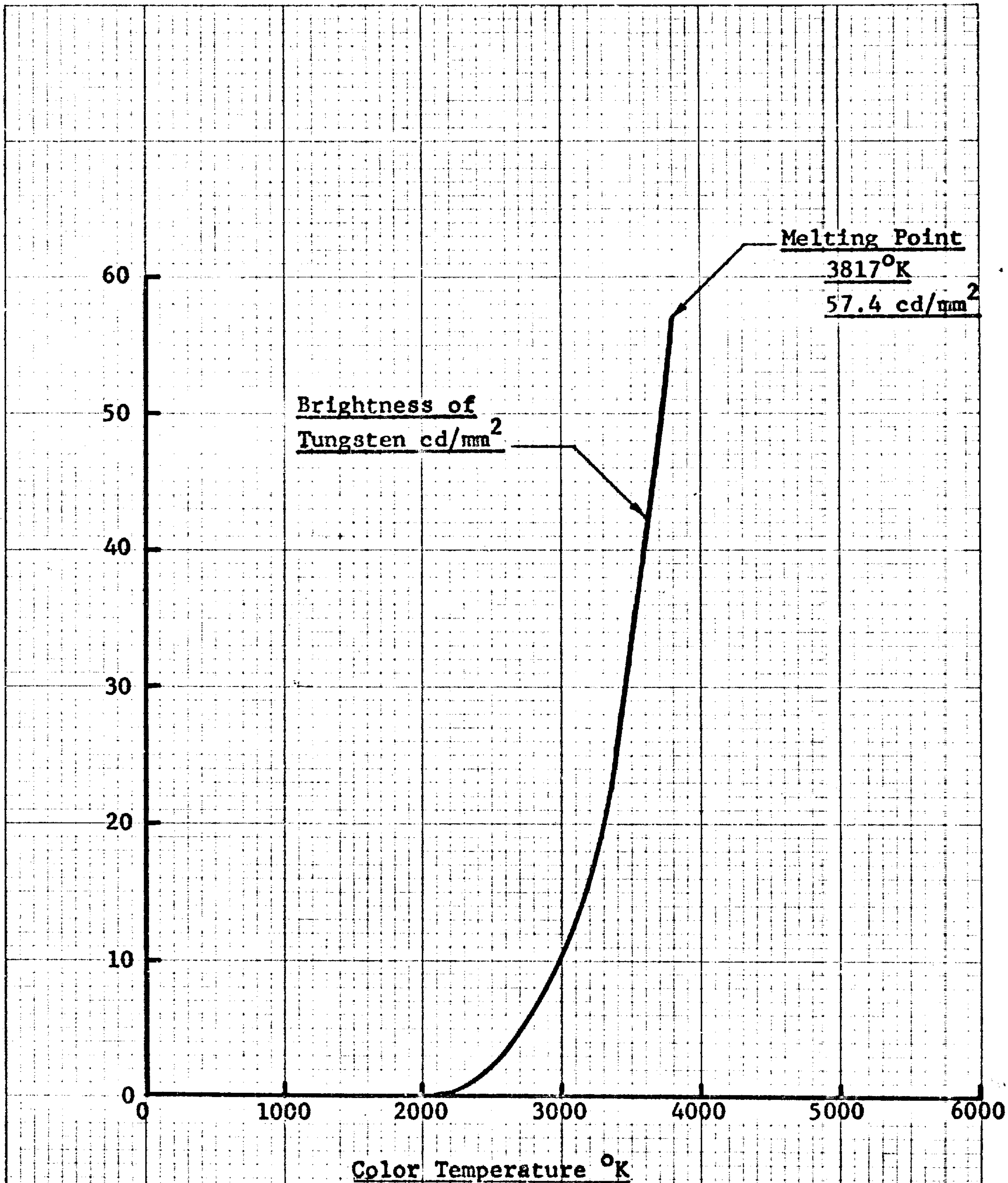

Melting Point
3817°K
57.4 cd/mm²
Brightness of
Tungsten cd/mm²
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
Color Temperature °K

Fig. 5

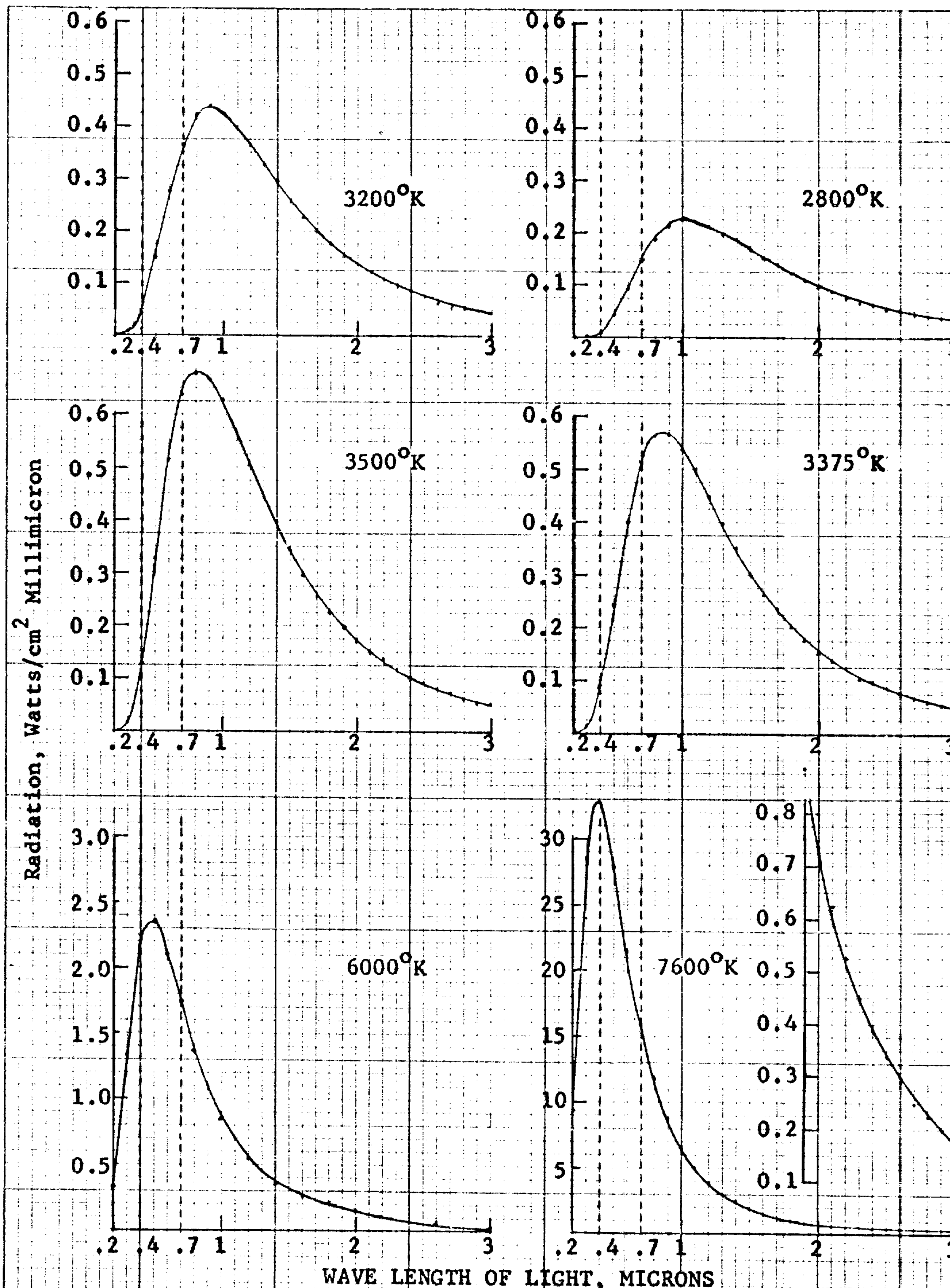


Fig. 6 Black Body Radiation for Various Color Temperatures

All the common high pressure arc lamps, regardless of wattage, have the same spectral distribution of radiation which is determined by the gas used. Spectral radiation lines are superimposed on the black body radiation of the hot gas.

3.2 Lamp Efficiency

There are two kinds of efficiency that must be considered in the evaluation of a lamp, conversion efficiency and luminous efficiency. That fraction of the electrical input power that is converted into radiant power is termed the conversion efficiency. The remainder of the power is converted into heat in the base, connecting leads, envelope, etc. Thus conversion efficiency is an indication of the cooling that must take place at the source. Comparing the data of several manufacturers, the conversion efficiency of the compact arc is approximately 50%, although General Electric claims 60% for their 5 KW Xenon lamp.

Good information regarding conversion efficiency of tungsten filament lamps has not been found to date. According to Hardy and Perrin, "Principles of Optics," the losses may amount to "20 percent or more of the power input."

In the course of preparing the present report, an effort was made to find a more exact number, but with questionable results. According to the Stefan-Boltzmann law, a black body at 3250°K radiates a total of 640 watts/cm^2. The distribution curve was calculated from Planck's equation for a black body at that temperature, and the ordinates multiplied by those of the relative spectral sensitivity curve of the eye. The resulting data were plotted, and the area under the curve was measured with a planimeter. It showed the luminous power to be 3.1×10^8 ergs/sec/cm^2, or 31 watts/cm^2. Over several measurements the average deviation from the value was 7%, but the maximum deviation was 14.5% and in the positive direction. The greatest negative deviation was 8%. Based on 31 watts/cm^2, the luminous efficiency is 30 lumens/radiated watt.

Information in the G. E. projection lamp catalogue indicates that lamps burning at approximately 3250°K provide 28 lumens/input watt. Similar information from Sylvania varies from 23.8 to 29 lumens/input-watt.

Using 30 lumens/watt calculated above as the luminous efficiency, the resulting conversion efficiency varies from 97% to 79.5% depending on the manufacturers data used. Taking the uncertainty of the planimeter measurements into account, the value can be in excess of 100% or as low as 68%.

While the value was not established with accuracy, it can be reasonably concluded that the conversion efficiency of the incandescent lamp is higher than that of the arc and has been tentatively assumed to be 80%.

No information is available on other lamp types.

3.3 Requirements for Cooling at Film

Despite the fact that infra-red radiation is commonly referred to as "heat waves," radiant power of any wavelength, including the visual region, is converted to heat upon being absorbed. The problem of determining the amount of heat to be dissipated at the film is one of the finding the power in watts, rather than lumens, that reaches the film.

The most reliable approach is to start with the electrical input and calculate the ultilization as follows:

1. Radiant power = Conversion Efficiency x input power
2. Collection efficiency = $\frac{\text{Solid angle collected}}{\text{Total solid angle}}$

the solid angle collected is established by the numerical aperture of the condenser, and can be taken as $\pi(NA)^2$. The total solid angle depends on the type of lamp. The gas arc lamps characteristically radiate through a meridional plane angle of 120^o, which amounts to about 11 steradians. The obscuration is generally less in incandescent lamps and 12 steradians is a reasonable approximation.

3. Collected power = Collection efficiency x radiant power

The transmission is the product of the transmission factors of all the elements in the illuminating system. Filtering is used to reduce the non-visible radiation and the filter factors are different for the visible and non-visible power, and the appropriate filter factor applied to each.

4. Luminous power = Luminous coefficient x radiant power
5. Non-Luminous power = Radiant power - luminous power

Infra-red rejecting interference filters begin to lose their effectiveness at slightly over 1 micron, and the heat absorbing glass is used to absorb the longer wavelengths. Transmission curves are presented in section 3.6. From these curves we estimate that approximately 75% of the luminous power and 3% of the non-luminous power will be transmitted.

Roughly one percent will be absorbed by every one centimeter of glass in the condenser. (The refinement of the increased IR absorption of the condenser lenses has not been included.) Each air-glass surface will reflect 4% at normal incidence and more at larger angles if they are not coated. With coatings this is reduced to 1% -2%. Aluminum mirrors reflect approximately 88% of the visible spectrum.

In the event that the film has large areas of density 2 or thereabouts, it is necessary to provide cooling at the film for 99% of radiant watts reaching it. We therefore assume that cooling required at the film equals the full number of watts reaching the film.

6. Power at film = Transmission x collected power

3.4 Cooling at Lamp

In most cases manufacturers state the cooling requirements at the lamp, "for ordinary circumstances." If the information is not given, or if the circumstances are not ordinary and if the conversion efficiency is known, the watts to be dissipated are

$$P_D = (1-E)\ P_1$$

where:

P_D = Power to be dissipated, watts

E = Conversion efficiency of the lamp

P_1 = Power input, watts

For example, a 1KW Xenon lamp is report to have an efficiency of 0.5. Thus provision must be made for dissipating ½KW by convection or conduction.

When considering cooling of both the lamp and the lamp house (including condensers and filters), only the power reaching the film gate can be excluded. Since about 90% of the input power does not reach the film gate, it is a safe approximation to provide cooling capacity for the entire input power.

3.5 Form Factor

The geometrical form of the light source is an important consideration in the design of projection illuminating systems. For the projection of large formats it is mandatory that the illuminating system be of the type that forms the source image at or near the entrance pupil of the projection lens rather than at the film, as in the case of commercial cinema projection.

The projection lens is utilized to the extent that its aperture is uniformly filled with the image of the source. Thus, for optimum utilization, the source should be a round disc, uniformly luminous, and sufficiently large for the condenser to magnify it to the diameter of the projection lens aperture.

It is shown in section 3.9 that the merit function of a light source is the product of its average brightness and its useful projected area. If a source has a long narrow aspect ratio, and the designer is successful in filling the projection lens aperture with the narrow dimension of the source, that portion of the length that falls outside the projection lens aperture is not useful. The following is a discussion of various lamp types in terms of the above considerations.

3.5.1 Flat Disc Sources

The flat disc source is typical of two series of lamps manufactured by Sylvania. The Zirconium arc and the RF lamp both satisfy the conditions of being round and uniformly bright, and some of them are sufficiently large to satisfy the requirement of filling the projection lens aperture. Since the sources are flat, the polar intensity distribution varies as the cosine of the angle of emittance, and the illuminance at the entrance pupil of the condenser drops off according to the $\cos^4$ law. For large aperture condensers the problem of obtaining uniform illuminance at the film is difficult.

3.5.2 Compact Arcs

The compact arc is a luminous volume, roughly in the form of a truncated cone. While there are severe brightness gradients across both its length and its width, the use of a spherical mirror to return the backward radiation to the arc has some tendency to improve the uniformity by reflecting the more intense (cathode) portion back into the less intense (anode) portion. Even though the brightness is not uniform, it is continuous, as opposed to that of a filament. While the arcs are not large enough to permit filling the aperture of a projection lens, their average brightness is so great that the highest wattage versions provide the largest amount of total luminous flux of any of the lamps found in the course of this investigation.

3.5.3 Plasma Arc

According to figures obtained from Plasmadyne Corp. early in 1963, the shape of the vortex-stabilized plasma arc closely approaches a cylinder, and has less of a gradient along the length of the arc than does the ordinary compact arc. Its polar distribution of intensity varies in much the same way, with a strong peak on the cathode side.

3.5.4 Long Narrow Cylinder

Both the quartz-iodine lamp and the mercury capillary can be classed as long narrow cylinders. With the axis of the cylinder normal to the optical axis the form factor is unfavorable in the light of the above remarks on useful area. For any practical sizes of field and projection lens aperture it is impossible for the condenser to fill the lens aperture with the narrow dimension of the source image, and to the extent that the length is magnified beyond the diameter of the lens it represents watts consumed to no other effect than the production of heat to be dissipated.

Conceivably the form might be used to better advantage if it is coaxial with the optical system. If so used at the first focus of an illipsoidal reflector, a conically shaped image volume is formed at the second focus, and this image might be used as the object for a refracting condenser. Without investigating such a system it is not possible to evaluate it fairly, but it is doubtful that it would have advantages.

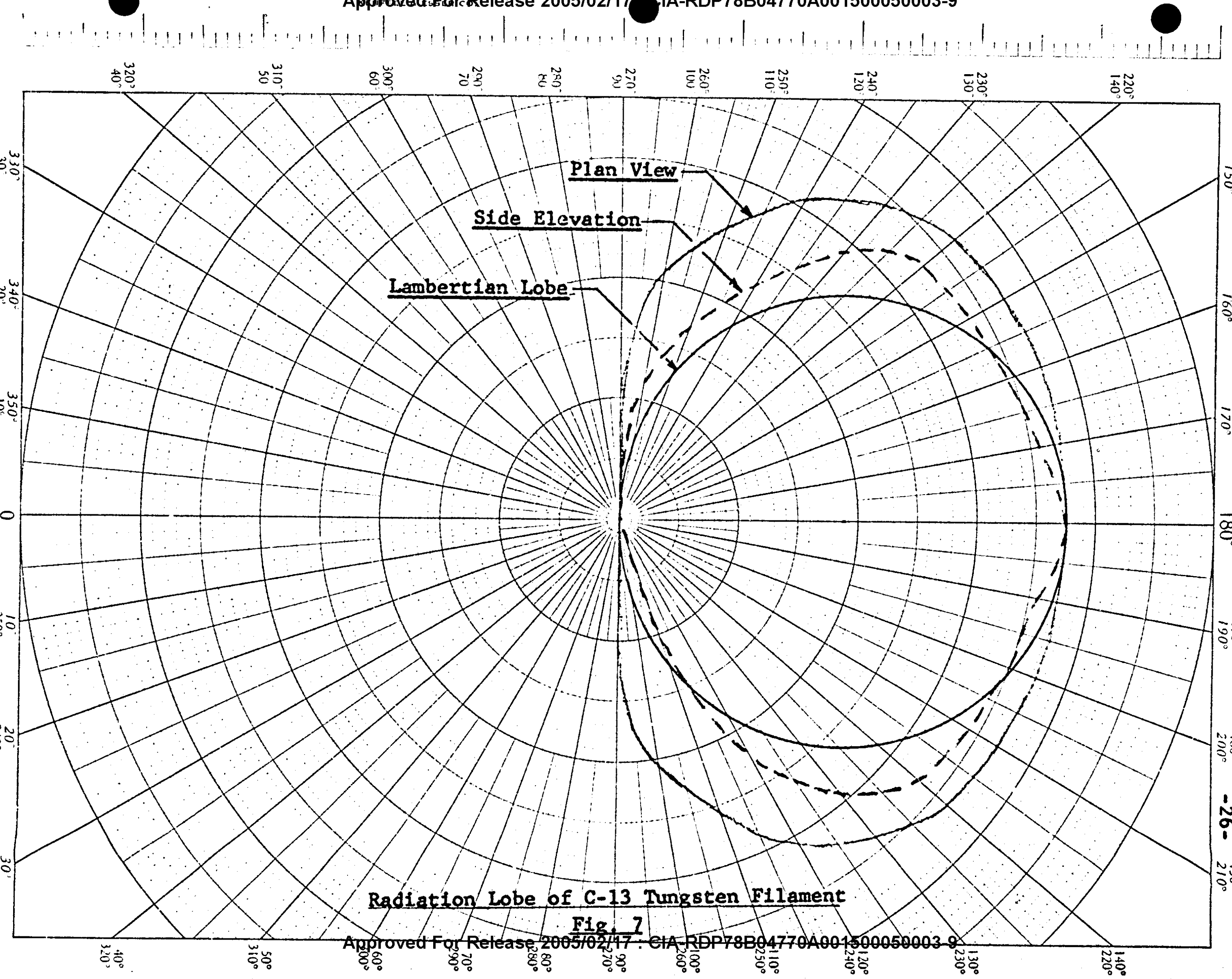
Polar plots of intensity distribution are not available for lamps of this type, but it is anticipated that there would be approximately a cosine variation in the plane containing the axis, and it may safely be assumed that it is uniform in the plane normal to the axis.

3.5.5 Tungsten Filament C-13 Type

The C-13 type of filament is a single row of Tungsten coils with a format that is almost square. Used with a spherical back-up mirror to form a filament image placed between the actual coils, a typical C-13 filament can be expected to have an average brightness over its area of almost 90% of the actual coil brightness. On such a filament measured in this laboratory, the average coil diameter was 89% of the width of the spaces between coils, and allowing a reflectivity of 88% for the reflector, the coil images will be 78% as effective as if the filament were solidly filled. Fig. 7 shows the radiation lobe of the C-13 filament as measured by Wallin Optical Systems.

3.5.6 Tungsten Filament C-13D Type

The C-13D filament is constructed with two rows of coils, staggered so that the rear row fills the gaps between those of the front row. Thus, viewed axially, or through a narrow angle, it is almost a solid luminous area. However, for large acceptance angles, i.e. for high numerical aperture condensers, the front row shadows the rear row, with the result that the polar distribution



Radiation Lobe of C-13 Tungsten Filament

Fig. 7

falls off more rapidly than a cosine function. Fig. 8 shows the radiation lobe of the C-13D filament as measured by Wallin Optical Systems.

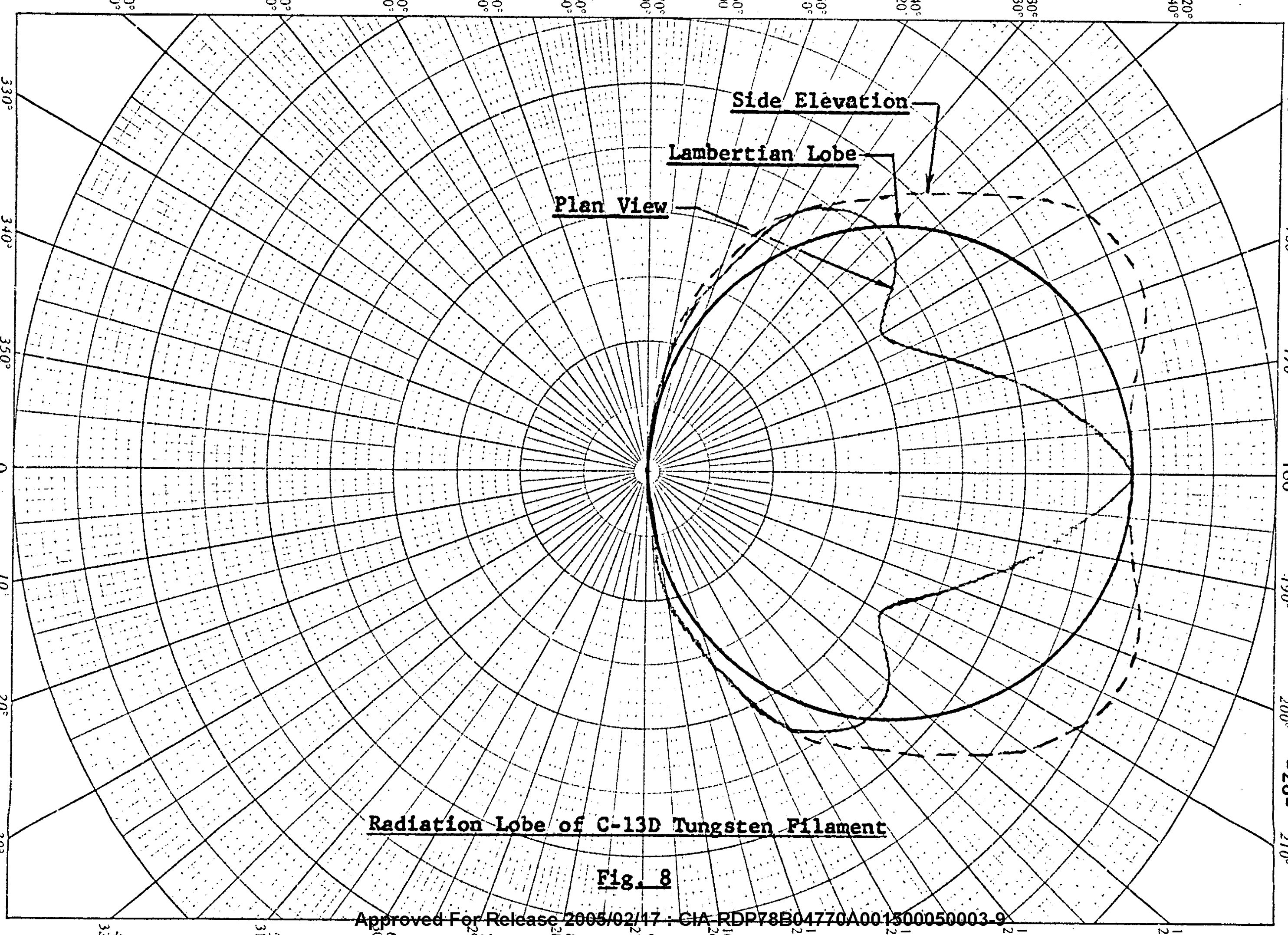
3.6 Filters

Three types of filters are available to eliminate the infra-red.

The so-called cold mirror is a multi-layer interference filter that transmits the near infra-red and ultraviolet and reflects the visible radiation. In a folded system, this type of filter permits transmitting the infra-red into a heat sink.

The reverse type of interference filter, known as a hot mirror, can be used when no fold in the optical path is desired. In that case, the near infra-red and ultraviolet are reflected off to the side into a heat sink, and the visible passes straight through.

In both cases, the effectiveness is only for the near infra-red. Good data are not available beyond 1 micron, but it may be presumed that the effectiveness fails somewhere between 1 and 2 microns. Since tungsten and Xenon have a considerable portion of their radiation in the longer infra-red, it is advisable to use a heat absorbing glass in conjunction with the interference filter. In such a case the interference filter should be nearer to the lamp in order to reject as much of the unwanted radiation as possible before it is absorbed by the heat absorbing glass, because a portion of what is absorbed will be re-radiated as longer wavelength infra-red.



Radiation Lobe of C-13D Tungsten Filament

Fig. 8

Filtering capability is illustrated in Fig. 9. The Balzer heat reflecting filter transmits about 90% of the visible and about 6% of the near infra-red. There is no data on the far infra-red. The transmission drops steeply above 0.64 microns.

The Corning Glass infra-red absorbing, visible transmitting filter absorbs about 97% of the infra-red above 1 micron.

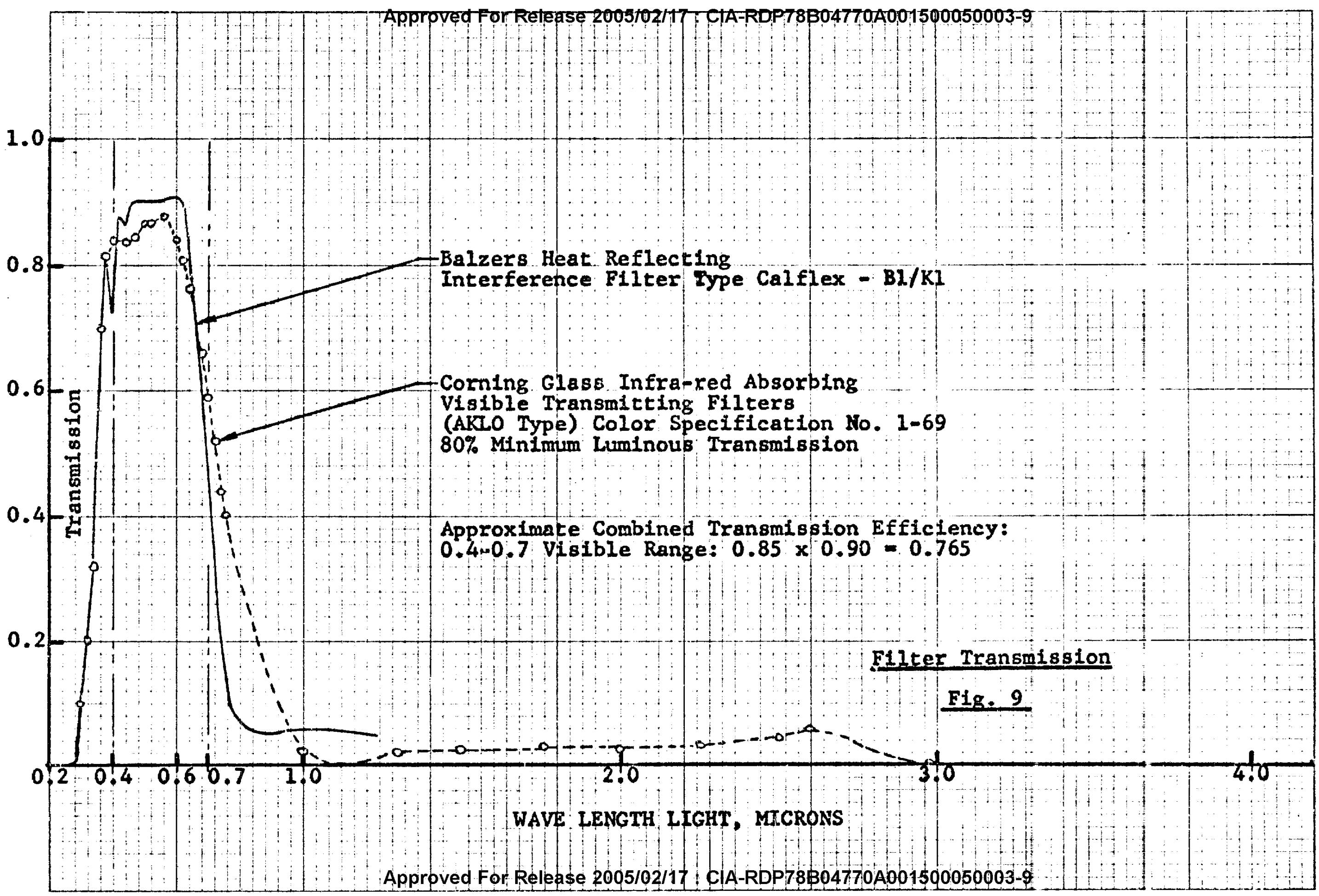
3.7 Lamp Tolerances and Replacement Time

No attempt has as yet been made to take into account the fact that replacement cost includes not only the purchase price of the lamp, but also the labor cost of making the replacement. In high numerical aperture condensing systems, use is necessarily made of aspheric elements, which tend to make alignment extremely critical. Thus, where dimensional tolerances of the lamps are known, those lamps made to the tighter tolerances are favored. Replacement time is highly specific to a particular projector design. No suitable general assumption has been found so far.

3.8 Spectral Distribution

Tungsten lamps in the higher wattages have very close to a black body spectral distribution with color temperatures ranging from 2800° to 3400°K. Some are available with rated lives as long as 50 hours, while 25 hours is more common.

The carbon arc has the very desirable property of a black body distribution whose color temperature can be increased to that of sunlight by operating under pressure.



Filter Transmission

Fig. 9

According to Sylvania's literature on their RF lamp, it has a gray body distribution, and its color temperature can be varied, with a corresponding difference in lamp life. This relationship is tabulated as follows:

^{o}K	Hours Life
2700	1000
2800	750
2900	600
3000	500
3100	400
3200	300
3300	250
3400	180
3500	125
3600	100
3700	50
4100	Melting Point

Xenon and Xenon-Mercury lamps are characterized by having a line spectrum superimposed on an approximation to a black body distribution of about 5500 to 6000^{o}K. According to Hanovia data, a Xenon lamp has 23.6% of its radiated energy in the visible region while a Xenon-Mercury lamp has 41% in the visible. While these data make the Xenon-Mercury lamp sound attractive, it becomes less attractive when one considers that the quality of the light is blue-green.

3.9 Screen Illumination from B and A_s

Evaluation of a lamp cannot actually be made without reference to the optical system with which it is used.

One method of expressing the illumination falling on the screen is:

$$E = \frac{k \ B \ A_L}{m^2 \ t^2}$$

where:

k = Transmission factor of the entire optical system
B = Lamp brightness
A_L = Utilized area of the entrance pupil of the projection lens
t = Distance from film to projection lens
m = The projection magnification to the screen

The equation deceptively makes it appear that the brightness is the only lamp parameter of importance.

Actually if the condenser magnification does not fill the projection lens with the source image, A_L must depend on A_s, the projected area of the source. In case of a compact arc the image of which is unlikely to fill the lens in either direction, the relationship is simply

$$A_L = m_c^2 \ A_s$$

where:

m_c = Condenser magnification
A_s = Projected area of the source

For a long narrow source, A_L will be roughly rectangular limited by the projection lens diameter along its length, while its width is the product of the source width and the condenser magnification.

Considering the case of the compact arc, the screen illumination is then

$$E = \frac{k\ B\ m_c^2\ A_s}{m^2\ t^2}$$

The condenser magnification may be expressed as

$$m_c = \frac{NA}{\tan uL}$$

where::

NA = Numerical aperture of the condenser
uL = Half field angle of the projection lens

In turn:

$$\tan uL = \frac{y}{t}$$

where: y = semi-diagonal of film

Thus:

$$E = \frac{k\ B\ A_s\ (NA)^2}{m^2\ y^2}$$

But for a square screen, $m^2\ y^2$ is half the area of the screen. Thus calling the screen area A_I, the illumination is

$$E = \frac{2\ k\ B\ A_s\ (NA)^2}{A_I}$$

In the above equation, the characteristics of the projection lens and film size have been completely eliminated, and it is seen that for a source that does not fill the projection lens, the screen illumination depends on the numerical aperture of the condenser, on the screen size, and on the transmission factor of the entire optical system.

The necessary diameter of the projection lens will be

$$D_L = d_s m_c$$

where:

d_s = Length of the source

Replacing m_c as before,

$$D_L = \frac{d_s \quad (NA) \quad t}{y}$$

But from a paraxial relationship

$$t = \frac{(1 + m)}{m} f \qquad \text{and } y_I = my$$

where:

y_I = Semi-diagonal of the screen

Thus the f/no of the projection lens must be

$$f = \frac{y_L}{d_s \quad (NA) \quad (m + 1)}$$

While a faster lens may be used, this f/no is adequate, and a faster lens does not increase screen brightness.

When a C-13 or C-13D filament is used it is generally possible to fill the projection lens aperture, and the available lens speed becomes the limiting factor. In that case the screen illumination may be expressed

$$E = \frac{\pi \quad k \quad B}{4(1 + m)^2} \left(\frac{D}{f}\right)^2$$

The trade off that follows from the preceding discussion is that with a small source of high brightness, the condenser should be of high numerical aperture, but a relatively slow projection lens may be used. With a large source, having a lower brightness, a lower condenser magnification and accordingly a lower numerical aperture of the condenser lens will serve to fill the aperture of existing projection lenses, but the burden is imposed on the projection lens, which must be of correspondingly higher speed.

In order to evaluate and compare screen brightness obtainable from the various lamps, certain standard conditions were assumed. For the equation:

$$E = \frac{2 \ k \ B \ A_s \ (NA)^2}{A_I}$$

assumptions were:

- E = Illumination falling on screen, lm/ft^2
- k = Total transmission factor of the entire optical system = 0.3
- B = Source brightness from manufactures data, lm/mm^2
- A_s = Source area from manufactures data, mm^2
- NA = Numerical aperture of condenser lens = 0.707 for a 90° collecting angle
- A_I = Screen area = 6.25 ft^2 for a 30" square screen

When screen brightness was computed, it was found that tungsten lamps were several times brighter than the Xenon or Xenon-Mercury lamps and this result was not consistent with the comparative total luminous flux output of the lamps as quoted by the manufactures.

The B and A_s data were suspect. For the compact arc lamps, the average source brightness, B, is dependent upon what source area, A_s, the brightness is averaged over. The manufactures data for B and A_s varied greatly for lamps which, it appeared, should be nearly equal.

The total lumen output data for the lamps appeared to be more consistent and probably more reliable since measurement by the lamp manufacturer was relatively easy in an integrating sphere. Therefore an alternate method of computing screen illumination was sought.

3.10 Screen Illumination from Total Lamp Luminance

The alternate method of predicting screen illumination consists of determining the fraction of the total lumens collected and transmitted and dividing by the area of the screen over which it is spread.

$$E = \frac{k\ F}{A}$$

where:

E = Density of the luminous flux falling on the screen, lumens/ft^2

k = Total collection and transmission factor, dimensionless

A = Area of the screen, ft^2 = 6.25 ft^2 for a 30 inch square screen

The density of the luminous flux falling on a screen in lumens/ft^2 is numerically equal to the brightness in ft. lamberts of a perfectly transmitting (or reflecting) and perfectly diffusing screen.

To determine the collection factor we will consider two idealized radiation patterns for which nearly all actual lamps will be well approximated.

One pattern consists of two tangent spherical lobes. It is representative of planar type tungsten filaments. In both plan view and side elevation, the lobes are lambertian distributions. The total radiation is the volume of the two spheres. For each sphere this is

$$\frac{4}{3}\pi r^3$$

where:

r = The radiation intensity vector

The radiation collected is represented by a right circular cone with apex at the filament and the base at the condenser lens. The collected radiation is thus the intersection volume of the cone and the sphere. The intersection volume is:

$$V = \frac{2}{3}\pi r^3 \sin^2 (2u) \cos^2 u + \frac{4}{3}\pi r^3 \sin^4 u \, (3 \sin 2u - 2 \sin^2 u)$$

where:

V = Volume of intersection = collected flux
r = Radius of the lambertian sphere
u = Half angle of the collection cone

To permit a standardized comparison of lamps, we have arbitrarily selected a condenser lens with a 90° plane collection angle. Thus:

$$NA = 0.7 \text{ and } u = 45^\circ$$

and the collected flux is:

$$V = \frac{1}{3}\pi r^3 + \frac{2}{3}\pi r^3 = \pi r^3$$

The fraction collected will therefore be the ratio of volume of intersection to the total volume of the two spheres:

$$\text{Collection factor} = \frac{\pi r^3}{2(\frac{4}{3}\pi r^3)} = 0.375$$

The other radiation pattern to be considered is a toroidal shape.

A compact arc radiates uniformly through 360° in the plane normal to its axis, while in the meridional section (side elevation) the distribution is roughly Lambertian. Thus the total radiation may be represented approximately by a toric volume.

$$V = 2\pi^2 r^3$$

where:

V = Volume of toroid = total flux
r = Radius of lambertian cross section and radius of revolution of the toroid

The flux collected is that portion of the torus intercepted by the cone of acceptance of the condenser.

A condenser of NA.7 has a 90° collection cone. A 90° plane wedge would take in 0.25 of the flux. Thus the 90° cone is accepting approximately (and somewhat less than) 25% of the flux.

Two other factors must be considered in collection. One factor is the light blocked by the film format shape which we call format blocking. For a square film format inscribed in circular condenser lens the flux falling in the circular segments outside the square format is not used. The flux falling inside the square format is found by:

$$\text{Format blocking factor} = \frac{(2r/\sqrt{2})^2}{\pi r^2} = \frac{2}{\pi} = 0.637$$

where:

r = Radius of condenser lens

also:

r = Semi-diagonal of film format

The other factor to be considered is projection lens aperture blocking. When the condenser magnifies the source so that it fully fills the projection lens aperture (as it normally does for tungsten filament lamps), then the flux falling outside the circular projection lens aperture is not used. For a square filament shape, such as C-13 and C-13D, the flux falling inside the projection lens circular aperture is found by:

$$\text{Aperture blocking factor} = \frac{\pi r^2}{(2r)^2} = \frac{\pi}{4} = 0.786$$

The aperture blocking factor is not applicable to the compact arc lamps since the image of the source normally lies wholly within the projection lens aperture. For other source shapes, the factor will be the area of the source image. falling inside the lens aperture divided by the total area of the source image at the projection lens aperture.

3.11 Summary of Screen Illumination and Heat Rejection Factors

Visible Light	Tangent Lambertian Spheres (Planar Filament)	Lambertian Toroid (Compact Arc)
1. Collection Factors		
Condenser Collection Factor without mirror	0.375	0.25
85% Refectance mirror	1. 85	1.85
Format Blocking Factor (square format)	0.637	0.637
Aperture Blocking Factor (square filament)	0.786	1. 0
Product	0.348	0.294
2. Filter Factors, Visible Light		
Dichroic hot mirror	0.90	0.90
Heat absorbing glass	0.85	0.85
Product	0.765	0.765
3. Transmission Factors		
12 surface condenser with 2% per coated surface reflectance loss	0.785	0.785
25 cm of condenser glass with 1% per cm absorption loss	0. 75	0.75
Projection lens estimated transmission efficiency	0. 90	0.90

Two projection mirrors, one dichroic, one rear surface coated	0. 79	0.79
Screen Transmission	0. 75	0.75
Product	0.315	0.315
4. All Factors Product	0.084	0.071

Infra-red	Tangent Lambertian Spheres	Lambertian Toroid
1. Collection Factors		
Condenser collection factor	0.375	0.25
10% reflecting cold mirror	1. 10	1.10
	0.413	0.275
2. Filter Factors		
Dichroic hot mirror	0. 06	0.06
Heat absorbing glass	0. 03	0.03
	0.0018	0.0018
3. Transmission Factors		
12 surface condenser	0.785	0.785
25 cm condenser glass	0. 75	0. 75
	0. 59	0.59
4. All Factors Product	0.000438	0.000266

LAMP MANUFACTURER AND DESIGNATION	LAMP TYPE
General Electric #DPW Sylvania Type 1m/t20p	1000 Watt C-13 Tungsten

POWER 115-120 VAC Line Power
8.7 AMPS, Hot

LIFE 50 Hours

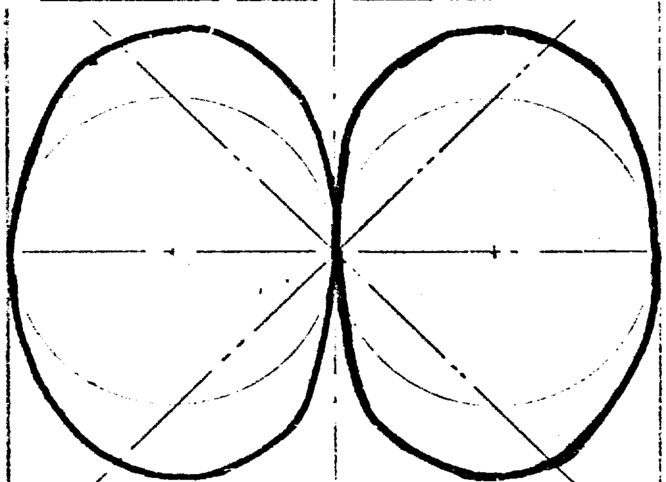
PROJECTION FACTORS

Collection	0.69
Filter	0.76
Transmission	0.32
Format Blocking	0.64
Aperture Blocking	0.79
PRODUCT	0.084

PHOTOMETRIC DATA

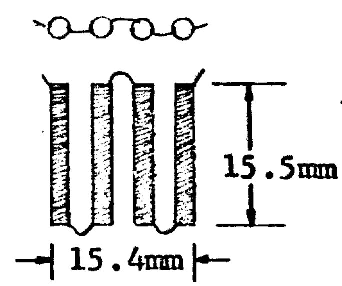
Color Temperature	3200°K
Luminous Flux	28,000 lumens
Intensity	
Brightness	21.1 candles/sq. mm.
Area	238 sq. mm.
Utilization of Area or Brightness	0.78

RADIATION LOBE, PLAN VIEW

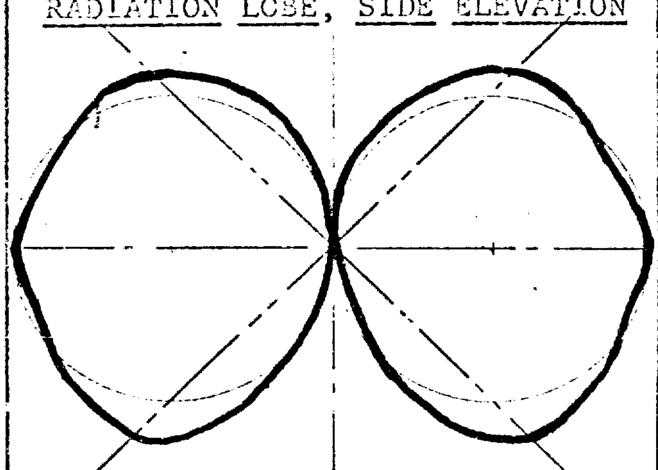


SOURCE :

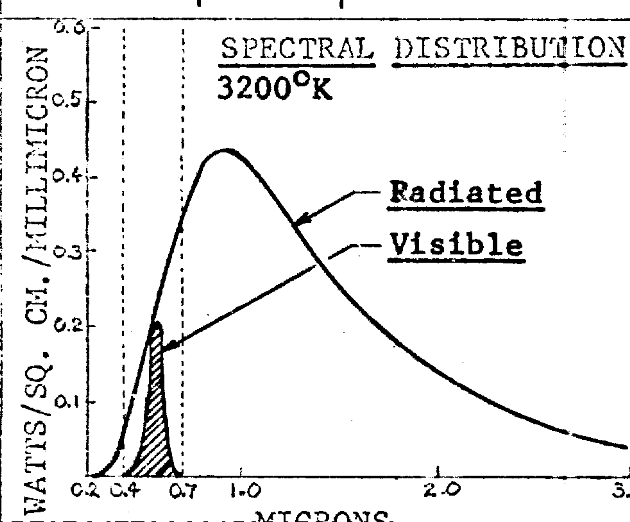
Monoplane Tungsten Coil



RADIATION LOBE, SIDE ELEVATION



SPECTRAL DISTRIBUTION
3200°K



LAMP MANUFACTURER AND DESIGNATION

General Electric ASA #DFD
Sylvania Type 1m/t12p

LAMP TYPE

1000 Watt
C-13D Tungsten

POWER 115-120 VAC Line Power
8.7 AMPS, Hot

LIFE 10 Hours

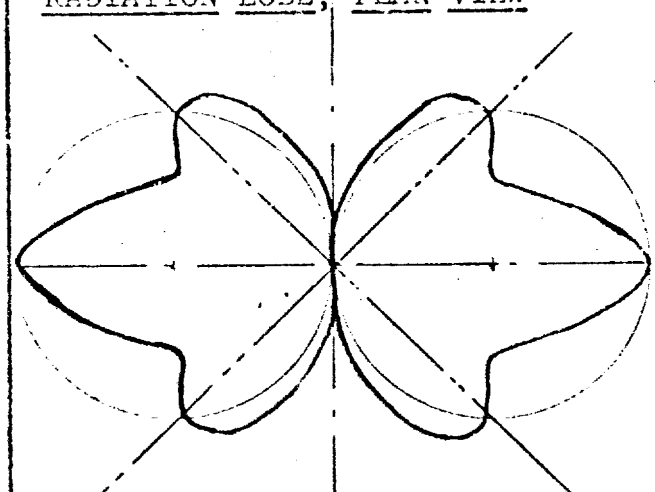
PROJECTION FACTORS

Collection	0.69
Filter	0.76
Transmission	0.32
Format Blocking	0.64
Aperture Blocking	0.79
PRODUCT	0.084

PHOTOMETRIC DATA

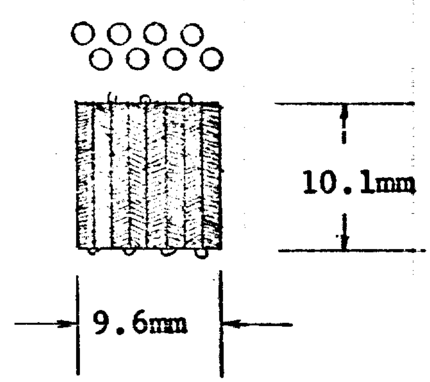
Color Temperature 3375°K
Luminous Flux 30,500 lumens
Intensity
Brightness 24 candles/sq. mm.
Area 97 sq. mm.
Utilization of Area or Brightness 0.95

RADIATION LOBE, PLAN VIEW

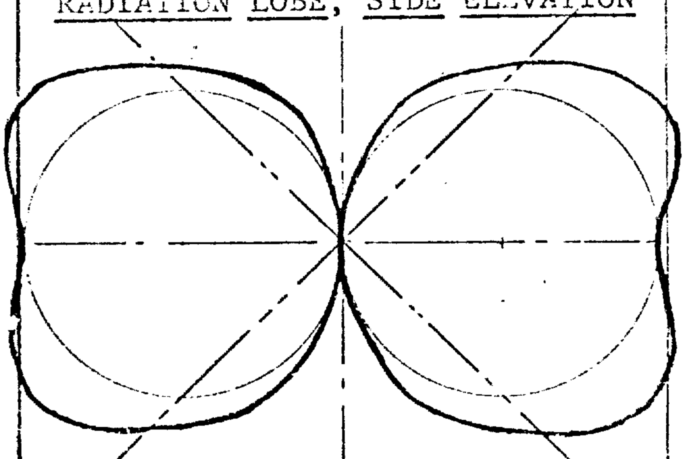


SOURCE :

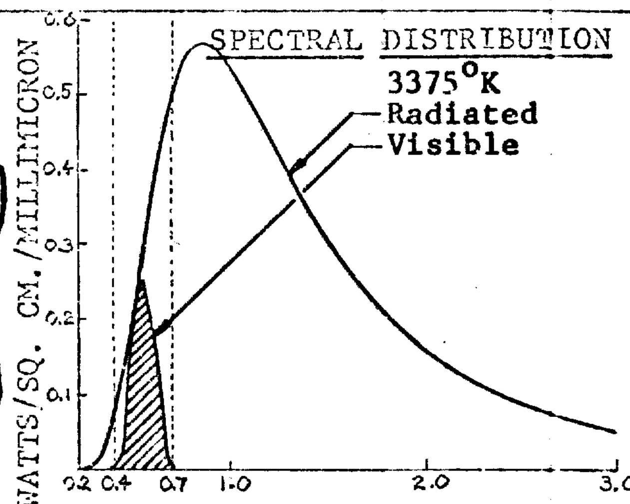
Biplane Tungsten Coil



RADIATION LOBE, SIDE ELEVATION



SPECTRAL DISTRIBUTION



LAMP MANUFACTURER AND DESIGNATION
OSRAM XBO 900W

LAMP TYPE
900 Watt
Xenon

POWER SUPPLY — **COST :**

70-110 Volts with 30 to 50 amps.
D.C. Power Supply.

IGNITER	OSRAM #Z5103 igniter with #L726, 33,000 Volt Spark Gap.	$180.00
LAMP LIFE	Warranted 1500 Hrs. Average 2000 Hrs.	$245.00

PROJECTION FACTORS

Collection	0.462
Filter	0.765
Transmission	0.315
Format Blocking	0.637
Aperture Blocking	1.0
PRODUCT	0.071

PHOTOMETRIC DATA:

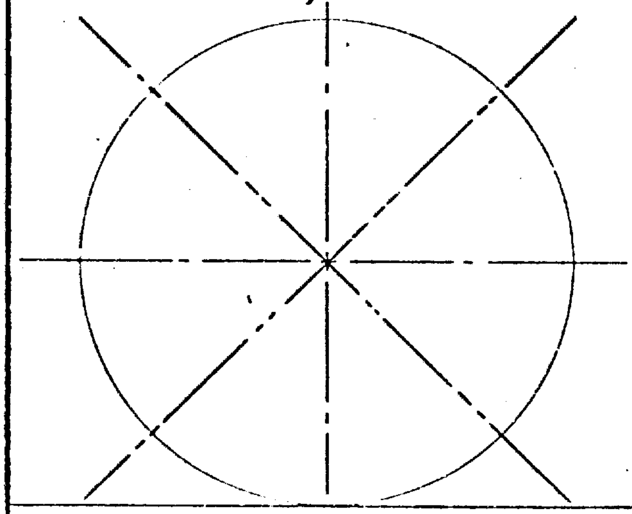
	Rated	Maximum	
Current	42	50	AMPS
Luminous Flux	30,500	41,500	LM
Intensity	3,300	4,100	LM/STER
Brightness	550	730	cd/sqmm
Area	6.6	6.6	sq.mm.

Utilization of Area or Brightness

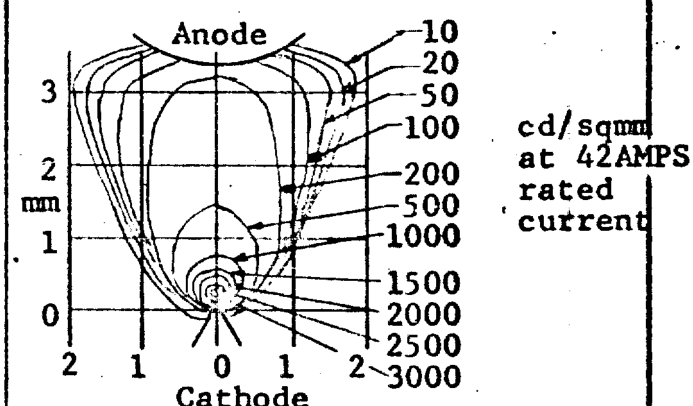
SPECTRAL DATA

UV 0.2-0.38µ	3%
Visible 0.38-0.76µ	14%
IR to 1.3µ	22%
IR Beyond 1.3µ	14%
Envelope, Leads, Etc	47%
Input	100%

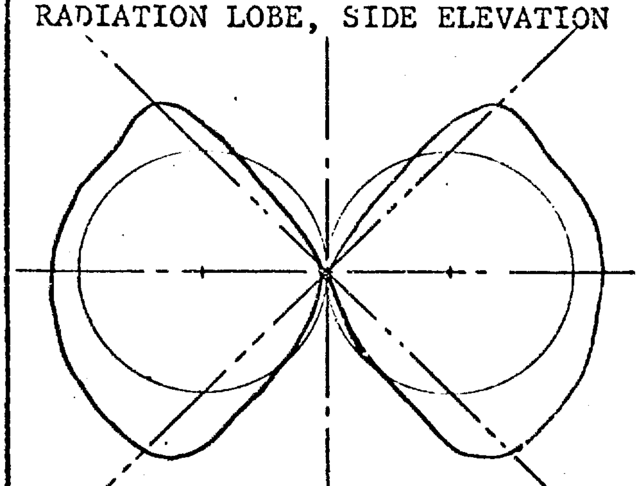
RADIATION LOBE, PLAN VIEW



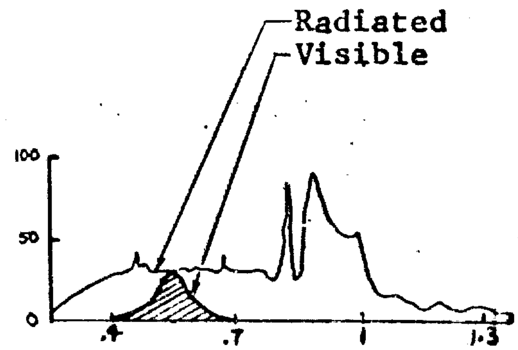
SOURCE : Xenon Compact Arc



RADIATION LOBE, SIDE ELEVATION



SPECTRAL DISTRIBUTION



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