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VISUAL INCAPACITATION OF AIRCREW BY NUCLEAR ANTI-AIRCRAFT WEAPONS

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VISUAL INCAPACITATION OF AIRCREW BY NUCLEAR ANTI-AIRCRAFT WEAPONS

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SUMMARY

An assessment is made of the likelihood of visual incapacitation of bomber aircrew by the explosion of nuclear anti-aircraft weapons. The existing medical data upon which this assessment is based have been accepted uncritically and the subject treated as a problem in applied physics.

It is estimated that for an average individual, retinal burns may be produced at ranges up to 60 miles at an altitude of 50,000 ft, and that for night operations, a pilot may be blind to instrument levels of brightness for several minutes. The operational significance of the results is not considered.

The accuracy of the existing data is believed to be questionable, and the various stages of the analysis are given in detail so that a re-assessment should be straightforward if further data became available.

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VISUAL INCAPACITATION OF AIRCREW BY NUCLEAR ANTI-AIRCRAFT WEAPONS

1 INTRODUCTION

The crew of a bomber aircraft may take steps to avoid blindness resulting from reflection of the light flash from a nuclear weapon which it has just delivered. In such a case, the time and position of the explosion are known. However, the crew may also be exposed to the unexpected flash of nuclear anti-aircraft weapons which explode too far away to be otherwise effective or which were aimed at other aircraft in the vicinity. Although such weapons are likely to have a low yield, appreciable thermal energy may fall upon the retina when detonation occurs within the visual field. There is a risk of permanent blindness of the area of the retina covered by the image, due to a retinal burn, and of temporary blindness or "dazzle" of other areas, which may last several minutes.

In this report an assessment is made of the hazard to aircrew for conditions typical of a V-bomber mission. The assessment is confined to the determination of critical conditions, and the effects on the performance of the crew are not discussed. It is hoped that the results may allow the military significance of blindness from this source to be assessed, and may assist in determining the need for protective equipment.

Several analyses of the problem of visual incapacitation by nuclear weapons have already been made, but these deal with the "nominal" (20 kt) weapon, usually at ground level conditions. It will be shown that the results are very different for low-yield weapons at high altitudes, and a re-assessment of the problem seems to be necessary. The most comprehensive analysis has recently been given by Bridges[1,2] and the methods employed in the present report have been largely based on those used by him. It is recognised that much of the data used is of questionable accuracy, and the various stages of the analysis are given in detail so that a further assessment should be straightforward if further data became available.

The matter is treated as a problem in applied physics, and no attempt is made to deal critically with the purely medical aspects.

2 THE EYE

It is pertinent to examine briefly the structure of the eye in so far as it affects the present work and so that any terms used subsequently will be recognised.

Fig.1 shows a horizontal section through a right eye, seen from above. Light, entering the protective cornea, passes through the aqueous humour and is focussed by the lens on to the retina. The shape of the lens, which is flexible, is adjusted by the surrounding muscles so that objects at different ranges may be brought into focus. Whenever a brightly-illuminated object is examined closely, the eye is adjusted so that its image falls upon the fovea centralis, a shallow depression in the retina subtending about 0.6° at the lens, where visual acuity is greatest.

The layer of optic receptors lies near the rear surface of the retina, in contact with the pigment epithelium layer which absorbs most of the light. The nerve fibres carrying the sensation of light pass forward to the front surface and across it to the optic disc, where they pass out through the back of the eye on the nasal side, forming the optic nerve. The optic disc itself is free from receptors and is insensitive to light.

The outer surface of the eye is attached to a system of muscles which move it as a whole so that a wide field may be seen.

The iris controls the amount of light entering the eye in the same way as that of a camera lens and the aperture or the part of the lens seen through it is the pupil. For an average individual the pupil diameter is about 0.4 cm in daylight and about 0.8 cm at night, but these values vary considerably from person to person. In addition to the variation with local illumination, the pupil diameter is subject to wide changes in response to the nervous systems. In particular, in times of nervous stress, the pupil may dilate.

The media which compose the eye do not uniformly transmit radiation of all wavelengths. They are almost completely opaque to radiation of wavelengths less than 0.38μ ($1\mu = 10^{-4}$ cm) or greater than 1.4μ. Within the transparent region the transmissibility is variable, having a maximum of 80% at about 0.85μ. The mean transmissibility over the whole range is about 40%.

Another mechanism favourable to the reduction of energy received by the retina is the involuntary blink reflex which occurs when the eye is stimulated by a brilliant light. The blink reflex time varies with the individual, but an average value is about 0.2 secs. In this report this value has been used, as well as a lower limit of 0.1 sec for comparative purposes, and it is assumed that upon exposure to a nuclear explosion, the individual blinks and turns away, receiving only the energy which arrives before the blink reflex occurs.

From the construction of the retina, it seems that a burn at one position could interfere with vision at another, through destruction or interruption of the nervous or vascular systems[1]. In particular, a burn on the optic disc would almost certainly blind other areas of the retina. Furthermore, tension set up in the retina by scars can cause distortion of vision or eventual detachment of the retina. Recovery of vision after a flash insufficient to cause a burn, though prolonged in some cases, is eventually complete.

There are two principal ways in which the radiant energy from the explosion can affect the eye. When the fireball is viewed directly, the optical system produces an image of it on the retina, varying in sharpness according to its position in the visual field, and the concentration of energy in this small area may give rise to a retinal burn. At the same time, an area round the fireball image will be temporarily blinded or dazzled by the glare effect. Temporary blindness can also result from the reflection of radiation from objects in the visual field when the fireball is not actually seen. The production of a retinal burn and "dazzle" will be considered separately.

3 RETINAL BURNS

3.1 Spectral distribution of radiant energy

Radiant energy of any wavelength contributes to the rise in temperature which results in a burn[8], but it is important to consider the distribution of energy of different wavelengths produced by the nuclear explosion. This is because selective transmission according to wavelength takes place in the atmosphere, in any other material between the explosion and the eye, and also in the eye itself.

Little information has been published concerning the spectral distribution of energy from the explosion as a function of time, but a curve has been given[3] of the equivalent radiating temperature of the fireball, that is, the temperature of a black body yielding the same energy distribution at any given time. This curve was prepared from an analysis of the energy in various wavebands, and in the absence of better data it appears to be legitimate to use this curve in order to calculate the spectral distribution, since the curve was itself prepared from such a distribution.

The time-history of the radiating temperature of the fireball is similar for all nuclear weapons when the time variable is scaled according to $W^{\frac{1}{2}}$ where W is the yield. The original curve, drawn for a 20 kt weapon, has thus been used to produce curves for weapons of other yields. Values of 1, 3 and 10 kt have been taken as representative yields for nuclear anti-aircraft weapons, and the deduced time-history of the radiating temperature is shown in Fig.2.

These curves strictly apply only to weapons burst at sea level conditions, and at high altitudes, the time of the first minimum may be significantly increased. However, it is generally assumed that the time-history of the burst is largely independent of altitude up to 50,000 ft, the altitude to which this report refers. There are as yet no experimental data for high altitude conditions, but should it be shown later that there is a significant effect at 50,000 ft, the curves of Fig.2 would then apply not to weapons of 1, 3 and 10 kt, but to other weapons, whose yield is at the moment indeterminate.

The amount of energy of wavelength λ emitted by unit area of a black body of absolute temperature T in unit time is given by Planck's equation

$$E(\lambda) = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} \qquad (1)$$

where C_1 and C_2 are suppressed constants depending on the units used.

Values of E(λ) have been calculated for a wide range of temperature and wavelength and are given in standard physical tables[12]. From the temperature-time curves of Fig.2, the amounts of energy of different wavelengths emitted in 0.1 and 0.2 secs were calculated and are plotted in Figs.3 and 4. To plot these curves, values of E(λ) were obtained from the equivalent radiating temperature at intervals of 0.01 sec, for wavelengths between 0.34μ and 1.46μ at intervals of 0.08μ. In Figs.3 and 4 the function

$$U(\lambda,t) = \int_0^t E(\lambda)\, dt \qquad (2)$$

is plotted against wavelength for t = 0.1 sec and 0.2 sec respectively. The integrations were carried out numerically.

Figs.3 and 4 represent the spectral distribution of radiant energy emitted by unit area of the fireball over periods of 0.1 and 0.2 secs for weapons of various yields. In the first 0.1 sec, most energy is released by the 1 kt weapon, the 3 kt and 10 kt weapons following in order. However, up to 0.2 sec, the order of magnitude becomes 3 kt, 10 kt and 1 kt. Ultimately it must become 10 kt, 3 kt and 1 kt, the order of the total duration. The reason for the variation lies in the relative position of the first minimum in the radiating temperature, which being only about 2200°K, does not allow a significant contribution to the total energy release. It may be seen in Fig.3 that the fireball of the 10 kt weapon is at a low temperature for most of the initial 0.1 sec period, whereas the 1 kt weapon reaches its peak temperature at about 0.05 sec. Also the 10 kt weapon gives maximum temperature during the period 0.1 - 0.2 sec, whereas the 1 kt and 3 kt bursts have passed the peak and are already cooling.

The position is complicated for larger weapons, for which the period before the first minimum becomes of dominating importance because of its very high temperatures, even though they act for very short periods. In the present study, it was found that the period before the first minimum was only significant for the 10 kt weapon.

3.2 Total energy received by the retina - no attenuation

The parameter U(λ,t) in equation (2) is the total thermal energy of wavelength λ emitted by unit area of fireball surface during the time interval 0 to t. Thus, if the fireball diameter is D, the total energy release is

$$U(\lambda,t) \,.\, \pi D^2$$

which is emitted uniformly into 4π steradians. Thus, the energy emitted into unit solid angle is

$$U(\lambda,t) \,.\, \frac{D^2}{4}$$

Now if the pupil diameter is r and the range R, the solid angle subtended by the pupil is $\frac{\pi r^2}{4R^2}$, and thus the energy falling upon the pupil is given by

$$u(\lambda,t) = U(\lambda,t)\, \frac{D^2}{4} \,.\, \frac{\pi r^2}{4R^2} \qquad (3)$$

This energy is ultimately brought to a focus on the retinal image of the fireball, of diameter d. The image diameter is related to the fireball diameter by the geometrical expression

$$\frac{d}{D} = \frac{r}{R} \qquad (4)$$

where r is the distance from the lens to the retina. Thus the fireball image is of area

$$\frac{\pi d^2}{4} = \frac{\pi D^2}{4} \cdot \frac{r^2}{R^2} \qquad (5)$$

Then the total quantity of radiation of wavelength λ falling within the image, q(λ,t), is, from equations (3) and (5)

$$q(\lambda,t) = U(\lambda,t) \cdot \frac{p^2}{4r^2} \qquad (6)$$

Thus, because the energy falling upon the pupil decreases with the square of the range, as does the area of the retinal image, the intensity of radiation within the image is independent of the range when no attenuation occurs. This analysis applies strictly only when the fireball is of constant size over the time t. Since, in fact, it increases with time, only the central portion of the retinal image receives the quantity per unit area implied by equation (6). However, this portion may be quite large since, as will be seen later, the fireball diameter is almost constant after 0.05 secs for all the weapons considered. The error is thus greatest for the initial 0.1 sec period.

In order to determine the total radiant energy of all wavelengths falling upon unit area of fireball image in the time t, equation (6) has to be integrated over the appropriate range of wavelength, i.e.

$$Q(t) = \int U(\lambda,t) \cdot \frac{p^2}{4r^2} \cdot d\lambda$$

$$= \frac{p^2}{4r^2} \int U(\lambda,t)\, d\lambda \qquad (7)$$

This gives the energy per unit area falling within the fireball image in the absence of attenuation.

3.3 Attenuation by the atmosphere

At sea level, attenuation of radiation by the atmosphere is due to scattering by air molecules and dust particles as well as by absorption at certain wavelengths by suspended water vapour and carbon dioxide. Oxygen and nitrogen do not absorb radiation of the wavelengths in which we are interested.

No experimental data are available for high altitude conditions. It seems unlikely, however, that a sufficient quantity of dust particles or absorptive media would be present to contribute significantly to the attenuation. It is therefore assumed that at high altitudes attenuation is due solely to Rayleigh scattering by air molecules. In this process, energy of wavelength λ in a collimated beam is reduced by a factor $e^{-h(\lambda)R}$ in travelling a distance R, where[4]

$$h(\lambda) = \frac{32\pi^3 (\nu-1)^2}{3n\,\lambda^4} \qquad (8)$$

ν is the refractive index of the air, and n the number of molecules per unit volume.

Now both $(\nu-1)$ and n are directly proportional to the relative density, σ, so that if the zero subscript refers to sea level conditions,

$$(\nu-1) = \sigma\,(\nu-1)_o \qquad (9)$$

and

$$n = \sigma\, n_o \qquad (10)$$

Thus, at altitude,

$$h(\lambda) = \frac{32\pi^3 \sigma\,(\nu-1)_o}{3n_o\,\lambda^4} \qquad (11)$$

and since $(\nu-1)_o = 2.9 \times 10^{-4}$, $n_o \doteqdot 2 \times 10^{19}$ cm^{-3} and $\sigma = 0.152$ at 50,000 ft,

$$\begin{aligned} h(\lambda) &= 2.12 \times 10^{-25}\,\lambda^{-4}\ \text{cm}^{-1} \\ &= 6.46 \times 10^{-21}\,\lambda^{-4}\ \text{kilofoot}^{-1} \\ &= 3.42 \times 10^{-20}\,\lambda^{-4}\ \text{mile}^{-1} \qquad (12) \end{aligned}$$

if λ is in centimetres.

It is evident from this relation that atmospheric attenuation at this altitude is only significant for short wavelengths and long ranges. For example, the atmosphere transmits 87% of radiation of wavelength 0.4μ over a distance of 10 miles. At the same range, the transmission for wavelengths greater than 1μ is virtually 100%.

3.4 Attenuation by aircraft windscreens

Although called upon to transmit most of the visible radiation (ca. $0.4\mu - 0.7\mu$) aircraft windscreens are totally opaque to ultraviolet and transmit infrared radiation rather poorly. A typical V-bomber windscreen may be considered to consist of two glass-vinyl-glass laminates separated by a dry air space. Each laminate is composed of two sheets of glass 3/16 in. thick and a vinyl sheet ⅛ in. thick.

No accurate data are available concerning the spectral transmission of such a windscreen, and it has accordingly been calculated from the published properties of its constituents. The transmissibility of 3/16 in. plate glass and ⅛ in. vinyl have been given for the infrared region[5]. In the visible range the curve for vinyl has been assumed to be the same as for perspex, as it is in the infrared[5,6]. The curve for glass was extrapolated in this region to a transmissibility of 98% in the 0.5μ region. The position of cut-off at ultraviolet wavelengths depends critically on the composition of the glass, and has been taken to be about 0.30μ[13,14]. These curves are shown in Fig.5 together with the calculated transmissibility of the whole windscreen, carried out on the assumption that 5% of radiation of all wavelengths is reflected at each glass-air surface.

Specification DTD 218B requires a normal transmissibility in the visible range of not less than 70% for windscreens of this thickness, and DTD 869 requires values up to 84%, so the values calculated are of the right order.

Because of the slope of the windscreen in modern aircraft, the line of sight is not usually normal to the surface, and in the V-class bombers, it may be as great as 60^o to the normal. From the basic data of Fig.5, it is possible to determine the transmissibility at any angle, and the curve for 60^o has been given in addition to that for normal transmission. It may be noted that although the transmissibility in the visible region is reduced by less than 10% at 60^o to the normal, the values in the infrared region are considerably diminished.

3.5 Attenuation within the eye

In Fig.6 is given the transmissibility of the eye media as deduced from Bridges' data[1]. (This curve should not be confused with the spectral sensitivity of the retina, which is much more restricted.)

As for the windscreen material, the transmission is low at both ends of the spectrum, and in particular the ultraviolet is severely attenuated. The intensity of the fireball is highest in this region (see Figs.3 and 4) and thus a considerable reduction is effected in the energy actually reaching the retina.

3.6 Intensity of radiation reaching the retina

From equation (6) it is seen that the intensity of radiation of wavelength λ reaching the retinal image during a time t when attenuation is ignored is given by

$$q(\lambda,t) = U(\lambda,t) \cdot \frac{p^2}{4r^2} \qquad (6)$$

The fraction of this transmitted by the atmosphere is $e^{-h(\lambda)R}$ and if the fractions transmitted by the windscreen and pre-retinal media of the eye are $\omega(\lambda)$ and $m(\lambda)$ respectively, the intensity of radiation of wavelength λ at the retina is

$$q(\lambda,t) = \frac{p^2}{4r^2}\, \omega(\lambda)\, m(\lambda)\, e^{-h(\lambda)R}\, U(\lambda,t) \tag{13}$$

Of the attenuation factors, only that due to the atmosphere is a function of range, and its effect at high altitudes is found to be very small. In Fig.7 is given an overall transmission, covering all sources, as a function of wavelength. It will be seen that there is very little difference between the curves for zero and 50 miles range, but that the maximum transmission is only about 45%.

It is now possible to calculate the total intensity of radiation falling in a given time upon the retinal image. This is done by integrating equation (13) with respect to wavelength, viz:

$$Q(t) = \frac{p^2}{4r^2} \int_{\lambda_1}^{\lambda_2} \omega(\lambda)\, m(\lambda)\, e^{-h(\lambda)R}\, U(\lambda,t)\, d\lambda \tag{14}$$

Thus, the whole process, substituting for $U(\lambda,t)$ from equation (2), is expressed mathematically as

$$Q(t) = \frac{p^2}{4r^2} \int_{\lambda_1}^{\lambda_2} \omega(\lambda)\, m(\lambda)\, e^{-h(\lambda)R} \int_0^t E(\lambda)\, dt \cdot d\lambda \tag{15}$$

For convenience of evaluation, the expression

$$\omega(\lambda)\, m(\lambda) \int_0^t E(\lambda) \cdot dt = \omega(\lambda)\, m(\lambda) \cdot U(\lambda,t) \tag{16}$$

has been plotted in Figs.8 and 9 for t = 0.1 sec and 0.2 sec respectively. To obtain the thermal dose received through any pupil at any range, the ordinates of these figures must be multiplied by $e^{-h(\lambda)R}$, the resulting curves integrated and the integral multiplied by $p^2/4r^2$ (vide equation (14)). It should be noted that the curves shown in Figs.8 and 9 may be used for any conditions of altitude and range, if the appropriate atmospheric transmission is known as a function of wavelength.

Representative values of total thermal dose are given in Table 1 for pupil diameters of 0.4 cm and 0.8 cm, assuming a constant length r, from lens to retina, of 1.7 cms. The results are strictly for zero range, but they are not very different for ranges up to 25 miles.

TABLE 1

Total thermal dose received within retinal image of fireball - cals cm^{-2}

Line of sight normal to windscreen

Yield kt		1		3		10	
Pupil dia. cms		0.4	0.8	0.4	0.8	0.4	0.8
Blink reflex time secs	0.1	1.04	4.16	0.89	3.56	0.53	2.12
	0.2	1.75	7.00	2.09	8.36	1.87	7.48

3.7 Thermal energy required to produce a retinal burn

Bridges has discussed in detail eight cases of retinal burns produced by nuclear explosions at distances up to 10 miles, as well as others produced by the sun[1]. In none of the cases involving nuclear explosions has the yield of the weapon or the atmospheric transmission been stated, and it has not been possible to deduce from the results anything more than the clinical effects. Also, in the case of solar retinal burns, the time required is much longer than the blink reflex time.

A number of experimental retinal burns have been produced in rabbits, both by solar and nuclear sources. The rabbit eye has a larger pupil diameter and shorter focal length than the human eye, and its optical blink reflex time is longer, so that a retinal burn may result at greater distances from an explosion. In one trial, all the exposed rabbits had retinal burns out to 27 miles, and some burns were recorded at 42.5 miles.

These experiments have not yielded a reliable value for the threshold of energy required to produce a retinal burn. The process is complicated by the conduction of heat away from the irradiated area, an effect which must depend upon the size of the fireball image.

The smallest thermal dose which has produced a retinal burn in the rabbit is 0.14 cals cm^{-2} at the retina delivered in 0.03 secs (4.7 cals cm^{-2} sec^{-1}) and this value has been taken by Bridges to be the critical dose for all cases, irrespective of the size of the image or the time of irradiation[1]. In fact, the critical dose would be expected to increase with the time of irradiation, because of heat loss by conduction. Since heat loss is more significant for small than for large areas, it would also be expected that the critical dose would increase as the irradiated area is decreased.

The experimental data on the production of retinal burns in rabbits, cover the ranges of thermal dose obtained in the previous sections. Some of these data are given in Table 2[7,8].

These results have been selected for analysis since they are threshold values; other results have been discarded where it was not established that a smaller dose would not have produced a retinal burn.

TABLE 2

Critical thermal dose for retinal burns in the rabbit

Dose cals cm^{-2}	Time of irradiation secs	Diameter of irradiated area cm	Remarks
0.14	0.03	0.10	
22.5	30	0.14	Average of several trials
72.0	720	0.30	Electric arc
360.0	120	0.015	Unmagnified solar image

It is impossible to make a theoretical analysis of thermal conduction in the layers of the retina and choroid because of their complex construction and unknown thermal properties. However, it was found from the experimental results given above that there is a correlation between the critical or threshold dose and the factor ($^t/d$), where t is the time of irradiation and d is the diameter of the irradiated area. The results, plotted in Fig.10 on logarithmic axes, fit a straight line which suggests a relationship of the form

$$Q_{crit} = K \left(\frac{t}{d}\right)^x \qquad (17)$$

where, from the existing data,

$$K = 0.32 \quad \text{and} \quad x = 0.72, \quad \text{approximately.}$$

The diameter of the irradiated area in the present analysis is inversely proportional to the range, as given in equation (4), and it is thus possible to determine the extreme range at which a burn will be produced - the critical range. In a virtually transparent atmosphere, it is only the increase in critical dose with decreasing size of image which results in a critical range at all. If the critical dose were independent of the size of the image, as was assumed elsewhere[1], a retinal burn would result from the weapons considered even at an infinite range, if atmospheric attenuation were negligible.

3.8 Critical range

If it is assumed that the human retina is structurally and materially similar to that of the rabbit, the critical range at which a burn is just produced may now be calculated. This is strictly an iterative process, since the value of Q is itself a function of range. Thus, the value of Q for zero range is obtained from Table 1, and the appropriate value of ($^t/d$) is found from Fig.10. The value of d obtained from this is inserted in equation (4) to give the range, and then a closer approximation to Q may be obtained by correcting for atmospheric attenuation. The process is then repeated. In view of the anticipated accuracy, the correction is only necessary for very long ranges, and the values of Q given in Table 1 were used directly where the range was less than 25 miles. Even at 50 miles, the dose received is about 85% of that at zero range.

Although this method applies strictly only to irradiation occurring at a uniform rate, it is considered that because of the simplifying assumptions made, it is legitimate to take t to be the total time of exposure and D the diameter of the fireball at time $t/2$. The variation of fireball radius with time is illustrated in Fig. 11 for the weapons concerned. This figure was prepared from a curve for the 1 kt fireball[9] with radii scaled according to $W^{1/3}$ and times according to $W^{\frac{1}{2}}$ after the first minimum. It may be seen that the assumption that the diameter of the image (and thus of the fireball) is constant is more nearly true for the larger values of t.

The principal results of the analysis are given in Table 3, corrected to the nearest mile.

TABLE 3

Critical range for retinal burns - miles

Line of sight normal to windscreen

Yield kt		1		3		10	
Pupil dia. cm		0.4	0.8	0.4	0.8	0.4	0.8
Blink reflex time secs	0.1	5	31	5	31	4	26
	0.2	5	32	9	51	11	60

These results apply to the production of retinal burns when the explosion is viewed directly and transmission takes place normally to the windscreen surface. The hazard will be less for other circumstances, and should be calculable for any particular case. In view of the number of variables, however, only the direct transmission case has been considered in detail. The most important variable to be considered in a practical assessment is the angle made by the line of sight to the normal through the windscreen. By following the foregoing method, the critical ranges for angles other than zero can be determined. In order to indicate the importance of the angle of transmission, the critical ranges for a line of sight making an angle of 60° to the normal have been computed and are given below in Table 4. An appreciable reduction in the critical range is indicated.

It should always be checked that for none of the solutions is the range sufficient for the fireball to be seen as a point source. Beyond this range, the image is of constant size but the intensity of radiation within it diminishes with the square of the range. For this to be so, the fireball must subtend at the eye an angle of less than $\frac{1}{2}$ minute, and the appropriate range in the present cases would be several hundred miles, owing to the large size of the source.

TABLE 4

Critical range for retinal burns - miles

Line of sight 60° to normal through windscreen

Yield kt		1		3		10	
Pupil dia. cm		0.4	0.8	0.4	0.8	0.4	0.8
Blink reflex time secs	0.1	3	21	4	24	3	16
	0.2	3	22	6	33	7	41

4 FLASH BLINDNESS OR "DAZZLE"

4.1 The "glare" effect

As well as producing a retinal burn in many cases, a nuclear weapon detonated within the visual field will cause dazzling of other parts of the retina. This is due to the "glare" effect of the source which affects areas beyond the actual image, probably by scattering within the eye. The effect diminishes as distance across the retina increases from the image, but it will be seen that following an explosion, appreciable areas of the retina may be blinded for several minutes under certain circumstances.

The time taken to recover vision after exposure to a given stimulus depends upon the brightness of the objects which have to be seen. It appears that at daylight levels of brightness, recovery of vision after the flash would take only a few seconds, although an after-image may persist until the following day when the intensity within the image is high, but insufficient to cause a burn[10]. Flash blindness is therefore hazardous only at night, and the degree of incapacitation depends upon whether the subject is required to see out of the cockpit or to read illuminated instruments.

4.2 Equivalent brightness

If the illumination at the eye is J foot-candles, the glare effect at points in the retina subtending an included angle of θ^o at the lens is equal to that produced by a uniform brightness field of B equivalent foot-candles (e.f.c.) where according to Bridges[2]

$$B = \frac{48\ J}{\theta^2} \qquad (18)$$

The illumination at the eye, J, is a function of time and depends on the intensity of the fireball. If the intensity at any time is I(t) candles, the illumination at range R feet is

$$J(t) = \frac{I(t)}{R^2} \text{ foot-candles} \qquad (19)$$

and the equivalent brightness for the retinal location θ is, from equation (18)

$$B(t) = \frac{48\ I(t)}{R^2\ \theta^2} \tag{20}$$

The factor which is related to recovery time is the product of brightness and time, which is embodied in the photochemical law and which has been shown to hold even at very high brightness values[10] It will thus be assumed that for a source which varies in intensity during the exposure, the recovery time will be related to the integral of brightness with respect to time. Thus, the measure of the stimulus will be taken to be the "equivalent integrated brightness" given by

$$\int_0^t B(t)\ dt = \frac{48}{R^2\ \theta^2} \int_0^t I(t)\ dt \tag{21}$$

4.3 Fireball intensity

The intensity of the fireball I(t) at any instant is the product of the brightness of the surface and its apparent area. It should be noted that there are no absolute units of luminous energy, the brightness of an object being defined subjectively according to its effect on the eye when compared with some standard illuminator. Tables have been prepared of the brightness of a black body radiator at various temperatures, as seen by a standard observer[11]. Using the temperature (Fig.2) and radius (Fig.11) history of the fireballs considered, the intensity I(t) was calculated up to t = 0.2 secs. This is shown for the three typical weapons in Fig.12.

4.4 Equivalent integrated brightness

Using Fig.12 and equation (21) the equivalent integrated brightness was calculated for various values of $R^2\ \theta^2$. To allow for reflection and absorption by the windscreen the normal transmission at $\lambda = 0.55\mu$ from Fig.5 was used, corresponding to the middle of the visible spectrum. The transmission of the eye is included in the definition of intensity, and no allowance was made for atmospheric attenuation, since the eye acts as a wide angle receiver and would also receive some of the small amount of light scattered by the atmosphere.

In Figs.13 and 14 the equivalent integrated brightness is given in e.f.c.-secs as a function of the range in miles and retinal location in degrees, the two figures applying to the periods up to 0.1 sec and 0.2 sec respectively. It may be seen that although there is little difference between the three weapon yields up to 0.1 sec, the order of the integrated brightnesses is always that of the yields.

4.5 Recovery time

It was mentioned in paragraph 4.1 that the recovery time depends upon the brightness of the objects which have to be seen. Whiteside and Bazarnik[10] have carried out experiments upon their own eyes, using the sun as a source, in order to determine the time required to see a typical dial hand of brightness 0.03 e.f.c. as a function of the integrated brightness to which the eye had been exposed. The range covered is somewhat greater than is required here, and the authors have given, for a flash centred on the fovea, recovery times for the fovea itself and for another retinal location. Naturally, these effects vary from individual to individual, but the results of the two authors are in close agreement.

Bridges[2] has collected other data on the subject and considered the problem in detail. When objects have to be seen against a background of the moonlit sky, with a brightness of about 3×10^{-4} e.f.c., the recovery times have been measured over a wide range of integrated brightness. These values will be used in the subsequent work, together with those of Whiteside and Bazarnik for objects with a brightness of 3×10^{-2} e.f.c., the value appropriate to the dial of an instrument illuminated by standard ultraviolet lamps. The latter data have been reduced to the equivalent integrated brightness, as previously defined, by assuming a glare angle of 10°. In the original report, the data is said to refer to the "periphery". It has been ascertained from one of the authors that the point considered subtended an included angle of about 10°. The data used are shown in Fig.15.

4.6 Typical values

Using Figs.13, 14 and 15, the recovery time for any retinal location and any range can be determined for the two object brightnesses given.

The recovery time to read an instrument dial after seeing a 3 kt explosion at various ranges is shown, as an example, in Fig.16. This refers to a retinal location subtending an included angle of 10° at the lens, and probably represents the limit at which numbers can be seen sharply enough to be identified. It may be seen that the recovery time is greater than 30 secs for ranges of less than 5 miles. Although a serious hazard, this is less than might be expected, from an examination of Whiteside and Bazarnik's analysis for the 20 kt explosion, even when the smaller yield is taken into account. This is partly due to the increased importance, for the larger weapon, of the period before the first minimum, but mainly because allowance has been made in the present report for the decrease in apparent size of the fireball with range (vide equation (21)). Whiteside and Bazarnik were aware that this could have an important effect, and drew attention to it, but made no allowance in their results, which are accordingly pessimistic.

In Fig.17 the degree of incapacitation of various parts of the retina is illustrated, as an example, for a 1 kt explosion at 2 miles and 10 miles range when night vision is required outside the cabin.

As in Section 3, the only cases considered are those in which the fireball is viewed directly. The hazard will be less in all other cases. Incapacitation by diffuse reflection from cloud when the fireball is not viewed directly is thought to be unlikely for the conditions of a bombing mission. With the rare exception of cumulo-nimbus tops in thundery weather, the only cloud likely to be encountered above 40,000 ft is cirrus, which is very tenuous and likely to have a low reflectivity. Reflection from a cloud layer below the aircraft, say at the tropopause, will be limited by the restriction of the visual field in the downward direction.

5 CONCLUSIONS

An assessment has been made of the likelihood of retinal burns and dazzling resulting at high altitudes (50,000 ft) when nuclear anti-aircraft weapons are detonated within the visual field. The most severe case has been considered, i.e. when the fireball is viewed directly along a normal to the windscreen, and comparative solutions have been determined for a situation in which the line of sight makes an angle of 60^o to the normal.

For an average individual, with a blink reflex time of 0.2 secs, it is found, for example, that a 3 kt weapon would produce a retinal burn at a range of 9 miles in daylight (0.4 cm pupil) and 51 miles at night (0.8 cm pupil) for transmission normal to the windscreen. The corresponding ranges for a line of sight making an angle of 60^o to the normal are 6 miles and 33 miles respectively. The accuracy of these solutions depends primarily on the validity, when applied to man, of experimental data obtained from tests with rabbits. It does not seem likely that results for the human retina will ever become available, and this restriction must be accepted, but the existing data is far too sparse and should be supplemented by further experimental results if an accurate assessment is required*.

The degree of flash blindness or dazzle produced by a nuclear explosion depends on the brightness of the objects which have to be seen. At daylight levels of brightness, dazzle may only last for a few seconds, but the time required to see instruments in a darkened cockpit at night may be several minutes. The recovery times have been correlated, in laboratory tests, with the product of the brightness of the source and the time[10]. For a nuclear explosion, the brightness varies widely during the period of exposure, and the integral of brightness with respect to time has been assumed to apply. The accuracy of the results depends on the validity of this assumption, which could be checked fairly easily in the laboratory.

No attempt has been made in this report to assess the military significance of visual incapacitation, but the results given should permit such an assessment to be made.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of the Libraries of the Flying Personnel Research Committee and the London School of Hygiene and Tropical Medicine, who permitted the author to see certain rare documents.

Some conversations on medical aspects with Sqd Ldr T.C.D. Whiteside of the RAF Institute of Aviation Medicine were of particular value to the author.

ADDENDUM

Since this report was prepared, a paper was presented to the 1957 Tripartite Conference on the effects of Atomic Weapons by Lt Col S.A. Bach, of the U.S. Armed Forces Special Weapons Project entitled "Flash blindness and retinal burns". It was stated that this paper was based on new and unpublished experimental work on the production of retinal burns in rabbits by Dr W.T. Ham of the Medical College of Virginia.

The results of this new work bring out strongly the dependence of the critical thermal dose on image size, as shown herein, but the conditions of the experiments - notably the times of exposure - are not stated clearly enough to permit a curve to be plotted to replace Fig.10. When these new data are published in full, it should be possible to make a more reliable assessment of the hazard of retinal burns than has been possible here.

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* See addendum to this report.

The author of the U.S. paper concludes that retinal burns would not occur at sea level at ranges greater than 18 miles for weapon yields up to 20 kt. Although it is not stated specifically in the text of the paper, it appears that the results apply to the dark-adapted eye, and if so, this represents a considerable relaxation of the hazard compared with that determined here.

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NOTATION

Symbol	Meaning
$E(\lambda)$	Energy of wavelength λ emitted per unit area of black body per unit time
$h(\lambda)$	Rayleigh scattering coefficient for radiation of wavelength λ
$\omega(\lambda)$	transmissibility of windscreen to radiation of wavelength λ
$m(\lambda)$	transmissibility of pre-retinal media of eye to radiation of wavelength λ
$U(\lambda,t)$	Energy of wavelength λ emitted per unit area of fireball surface in time t
$u(\lambda,t)$	Energy of wavelength λ emitted by fireball in time t into solid angle subtended by pupil
$q(\lambda,t)$	Intensity of radiation of wavelength λ falling within retinal image in time t
$Q(t)$	Intensity of radiation of all wavelengths falling within retinal image in time t
$J(t)$	Illumination at the eye from fireball at time t
$B(t)$	Equivalent brightness at time t
$I(t)$	Intensity of fireball at time t
D	Diameter of fireball
R	Range
Q_{crit}	Critical thermal intensity for the production of a retinal burn
p	Diameter of pupil
r	Posterior nodal distance of eye
d	Diameter of fireball image
t	Time of irradiation; optical blink reflex time
n	Number of air molecules per unit volume
n_o	Value of n at sea level
θ	included angle subtended at lens by given retinal location
ν	refractive index of air
ν_o	value of ν at sea level

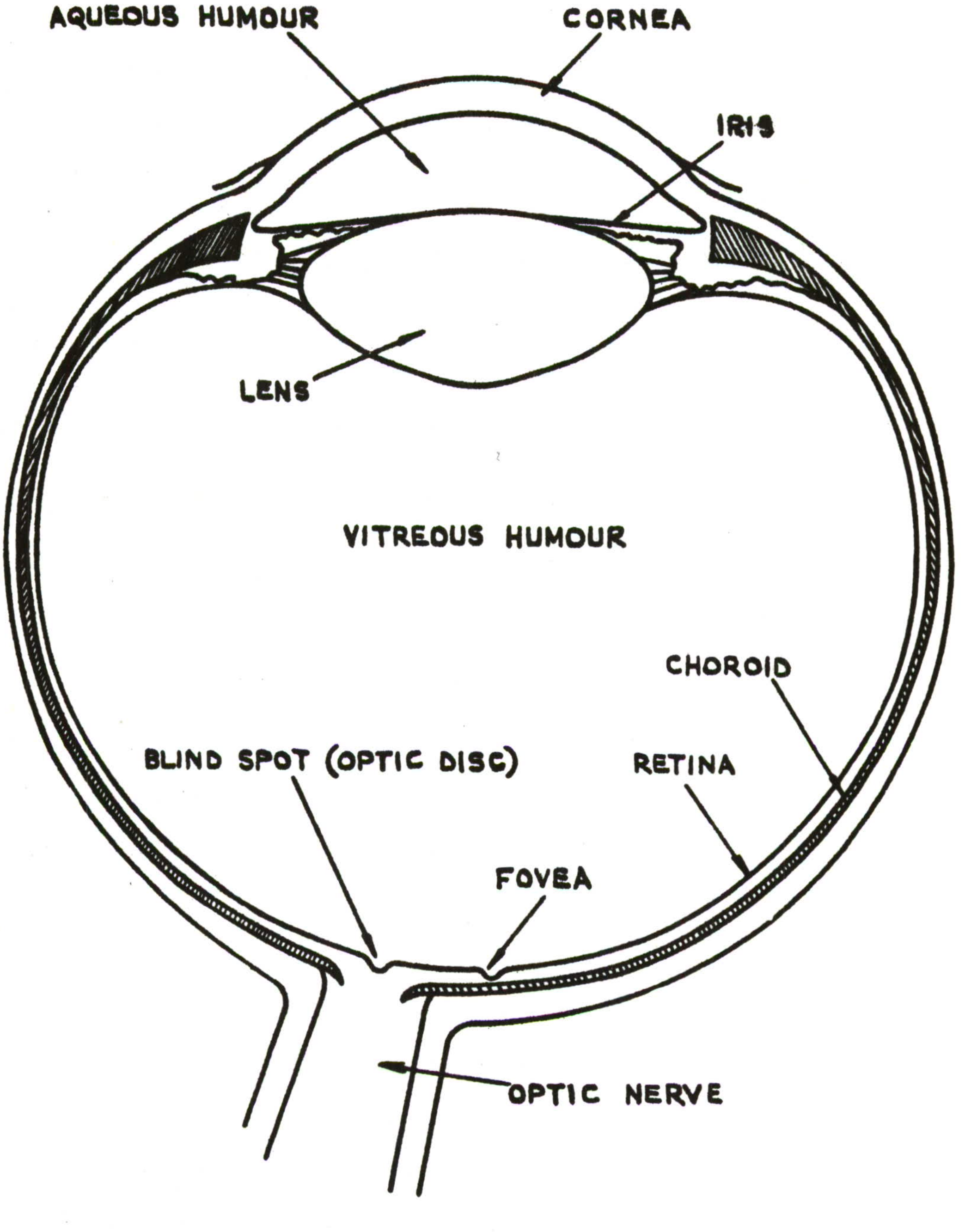

Fig. 1--Horizontal section through an adult human eye (after Bridges[1])

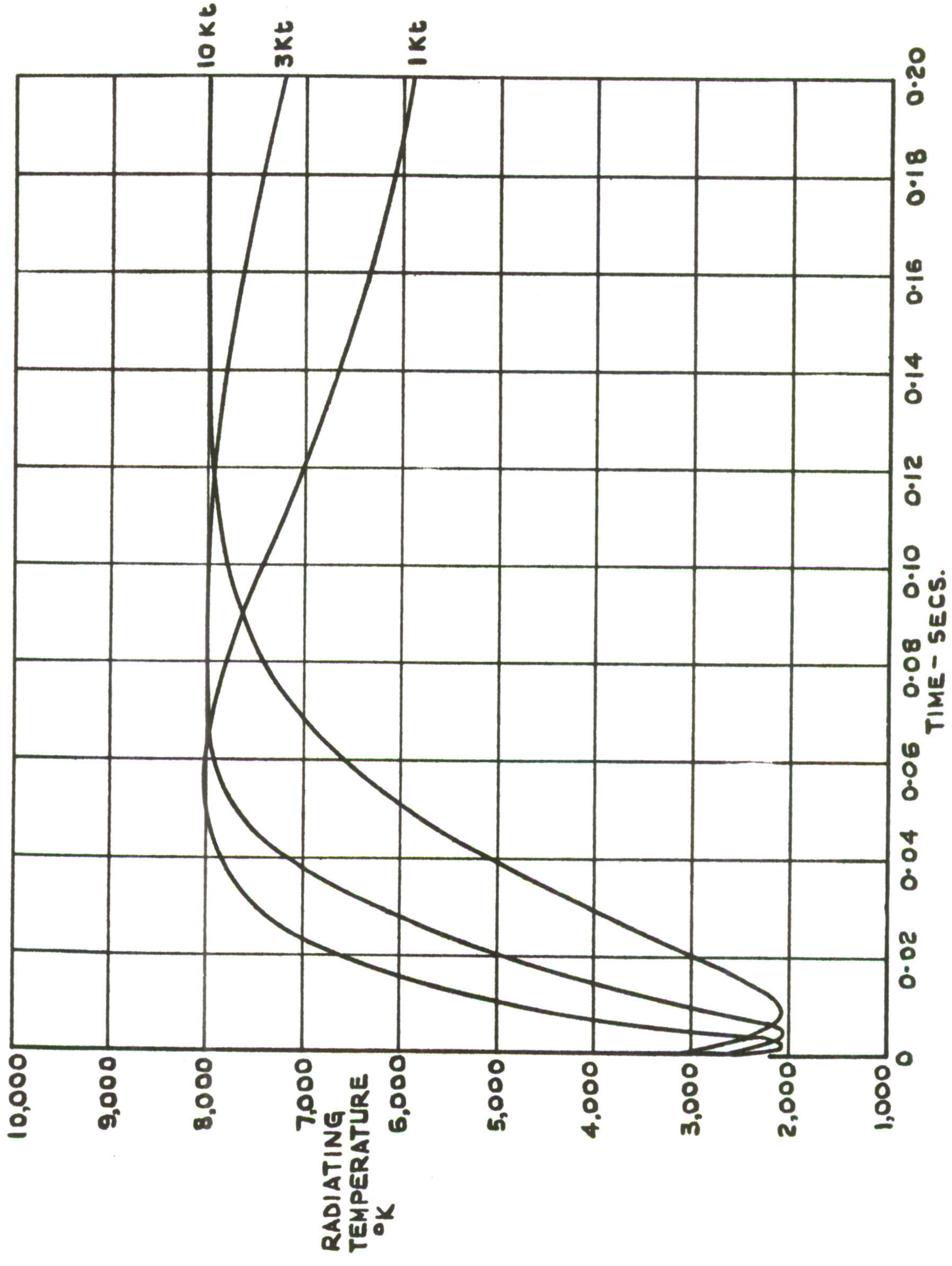

Fig. 2--Variation of fireball radiating temperature with time.

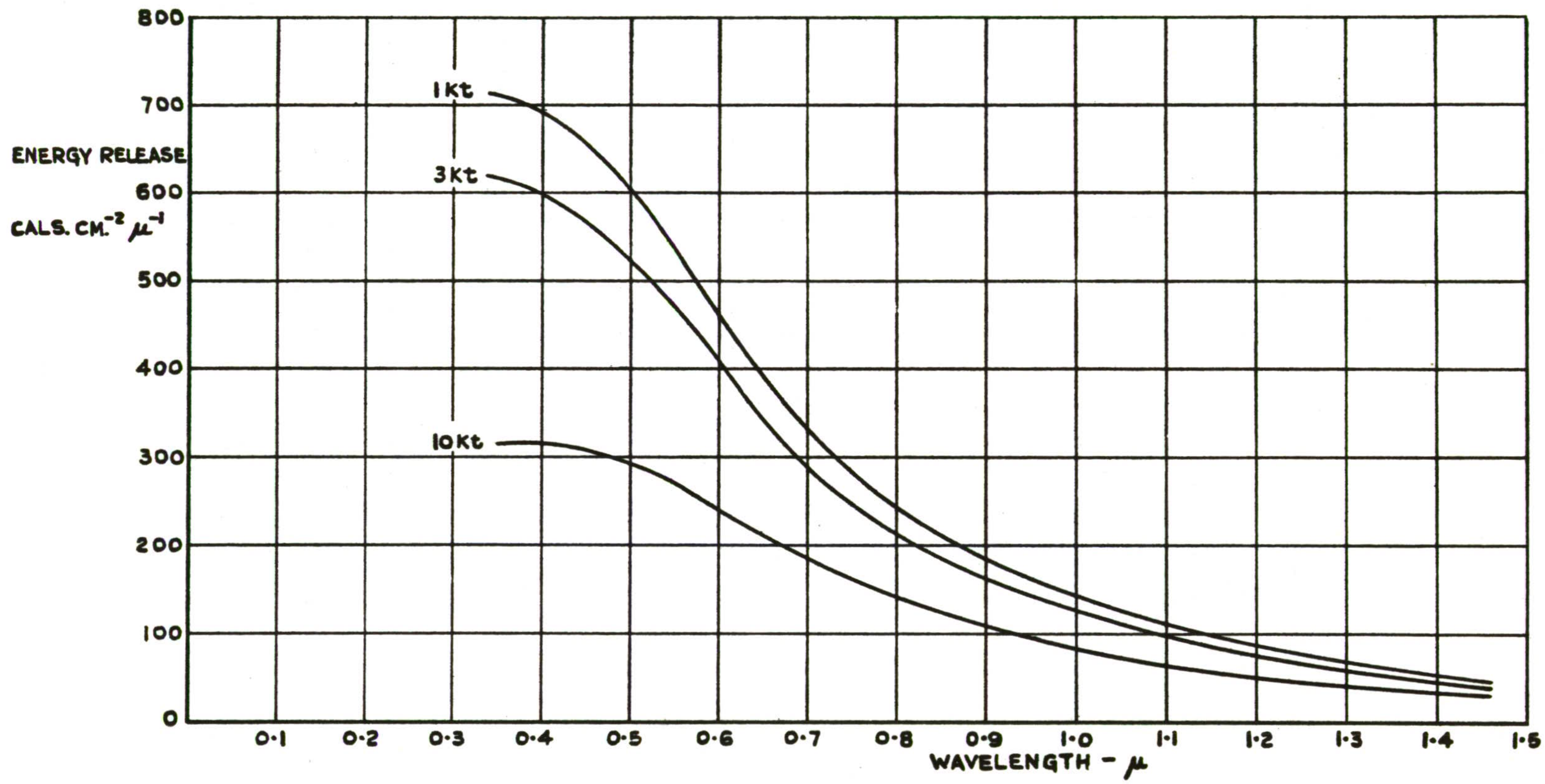

Fig. 3--Spectral distribution of thermal energy release from unit area of fireball - 0-0.1 sec.

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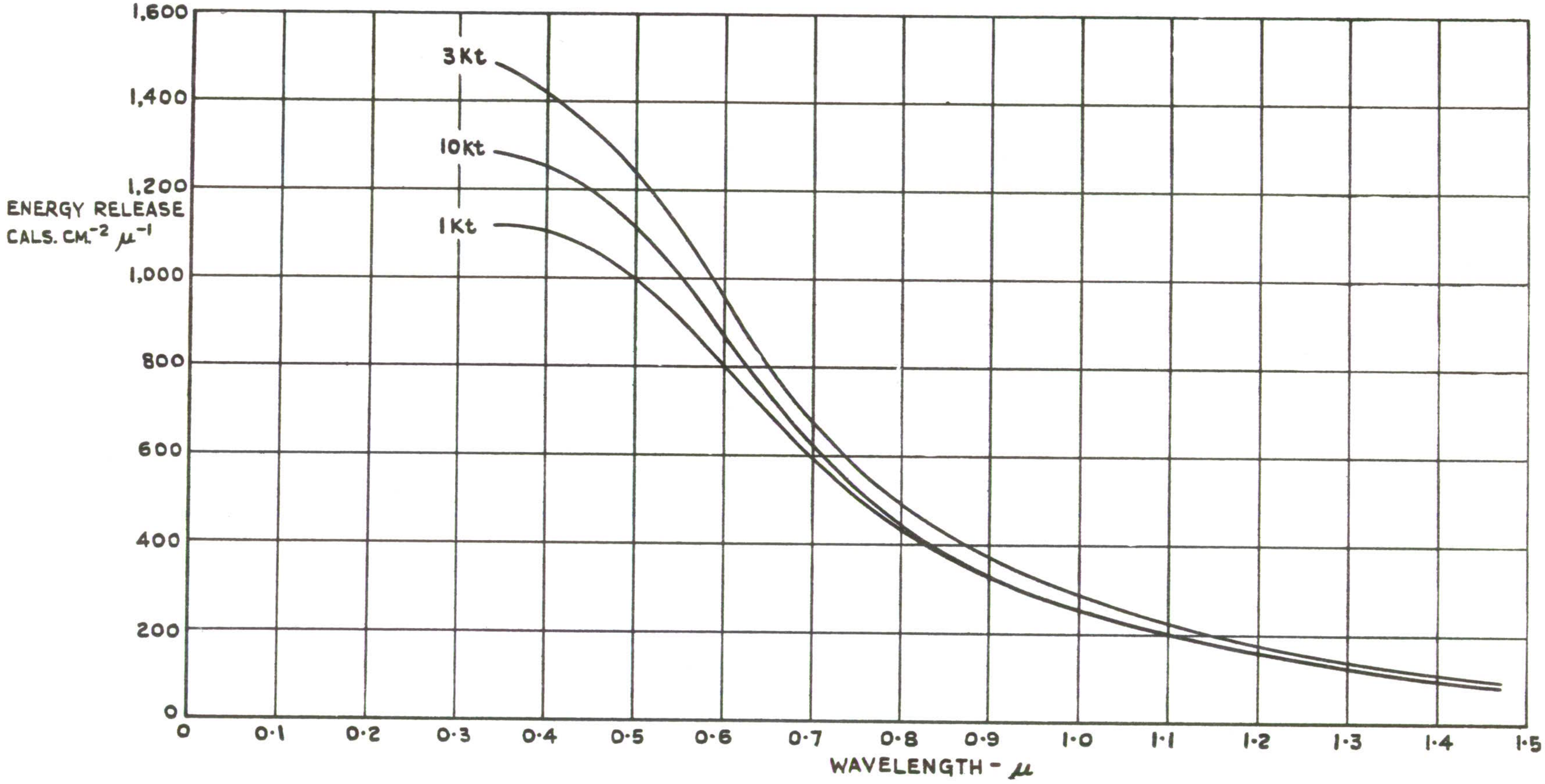

Fig. 4--Spectral distribution of thermal energy release from unit area of fireball - 0–0.2 sec.

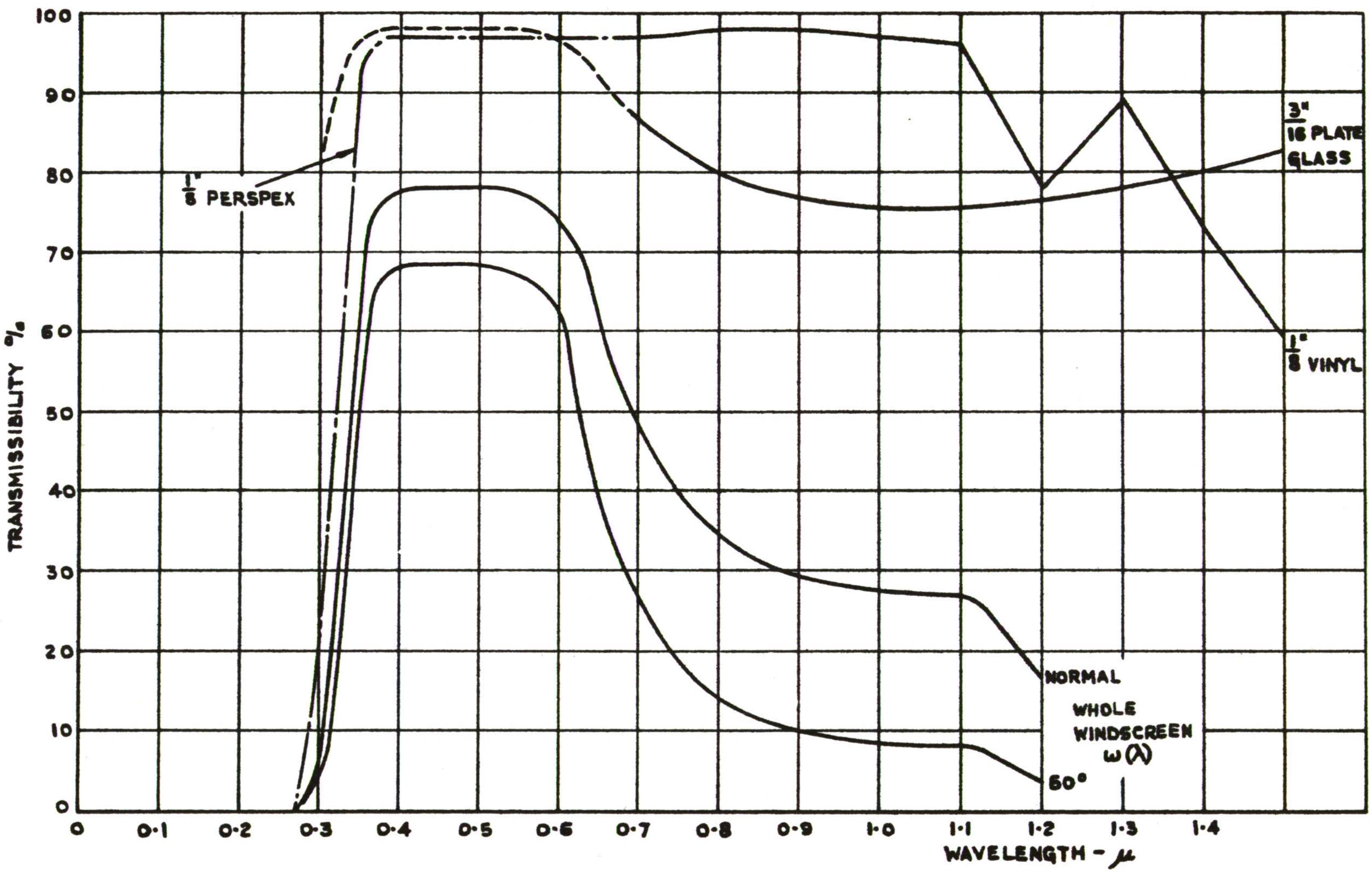

Fig. 5--Transmissibility of typical aircraft windscreen and components.

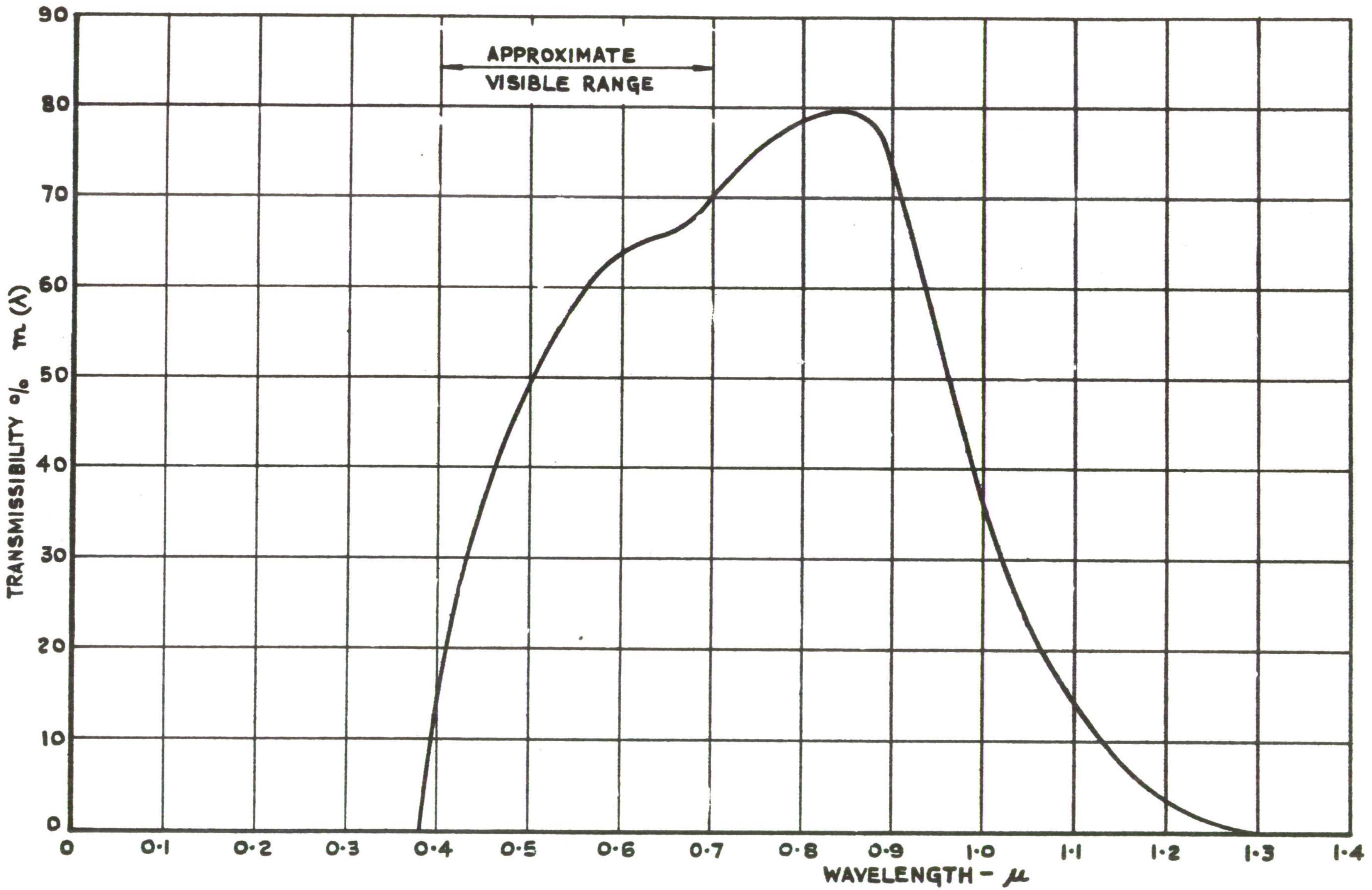

Fig. 6--Transmissibility of preretinal media of the eye.

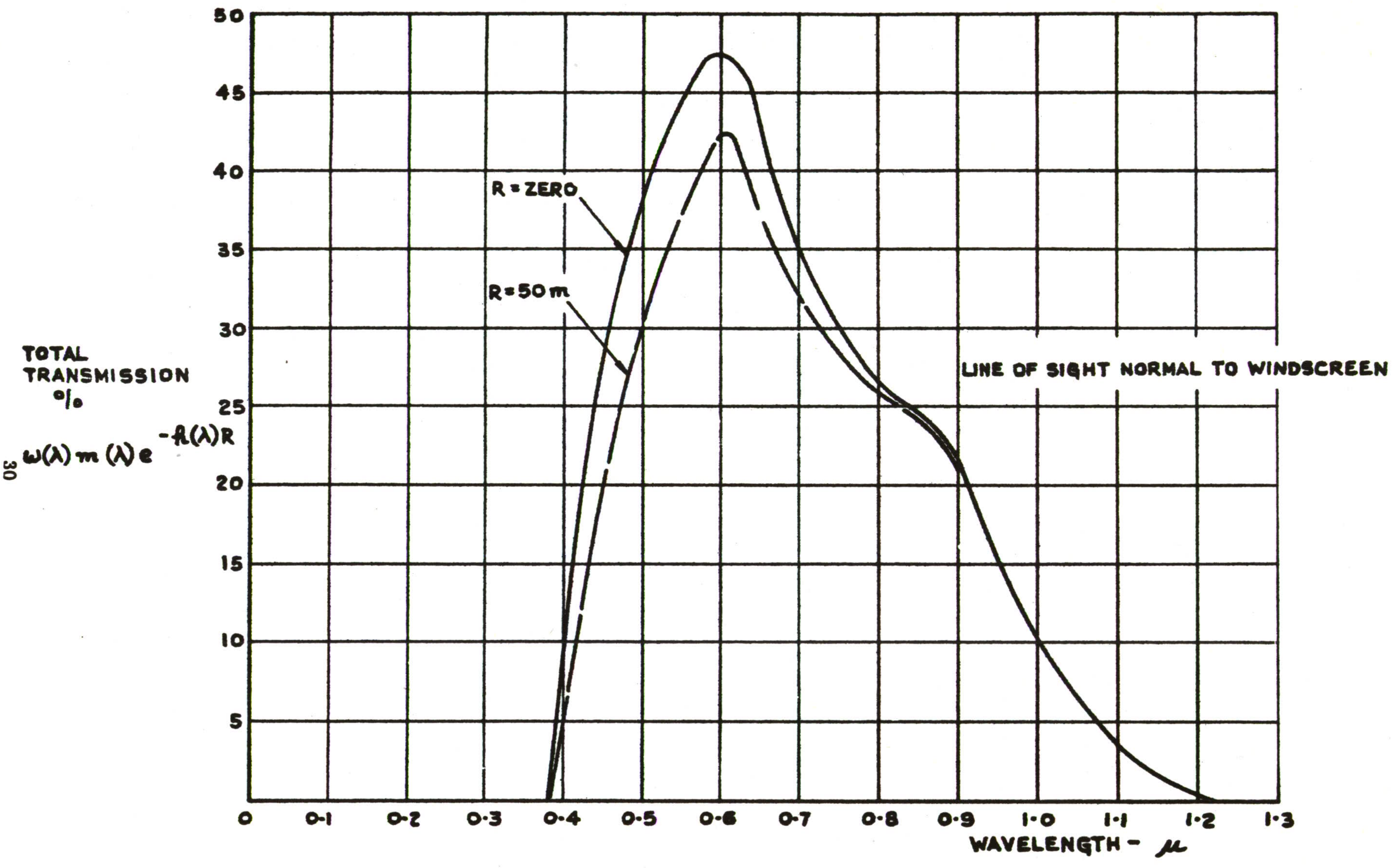

Fig. 7--Total transmission function for ranges of zero and 50 miles at 50,000 ft.

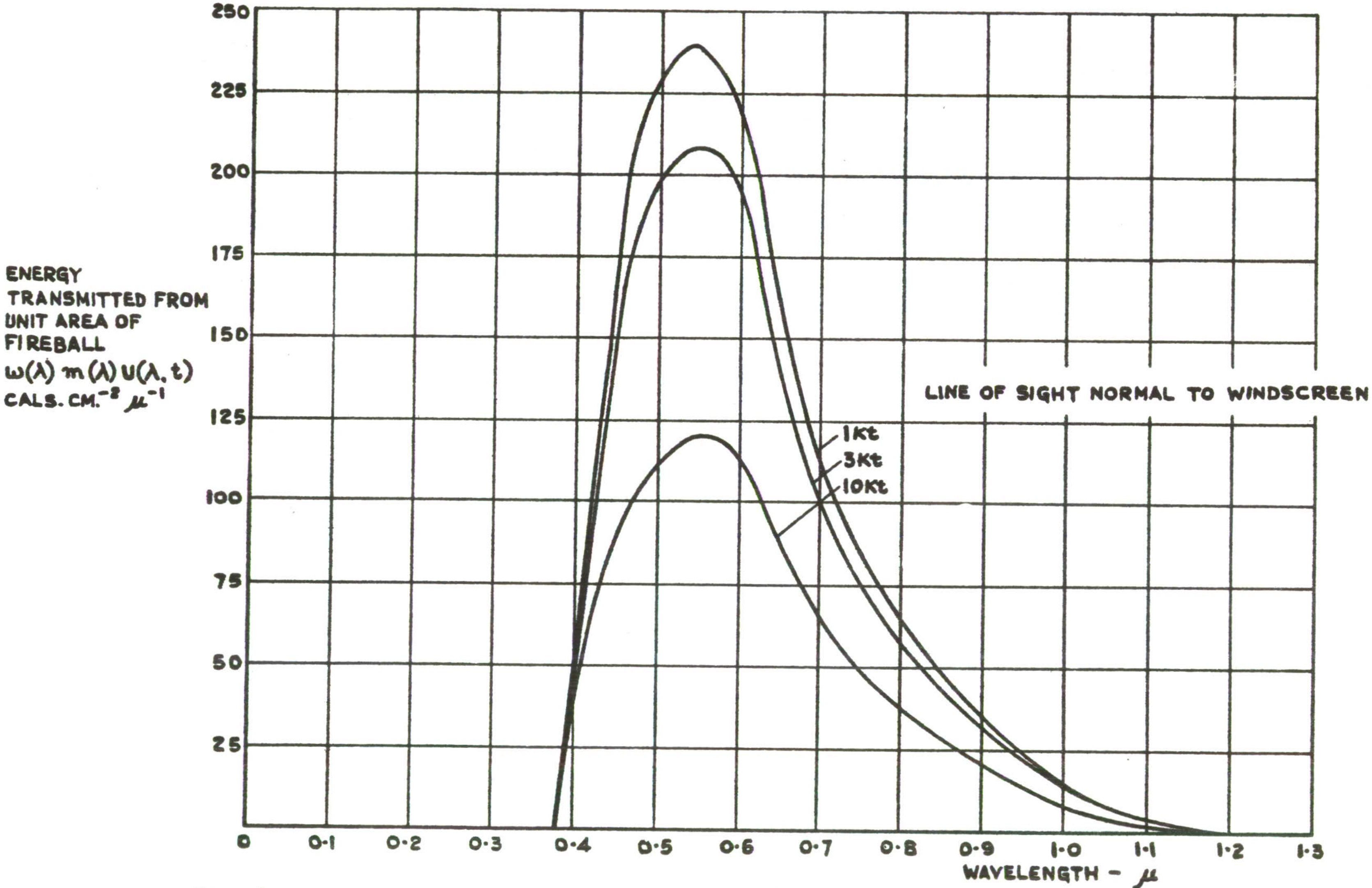

Fig. 8--Spectral distribution of energy reaching retina at zero range - 0-0.1 sec.

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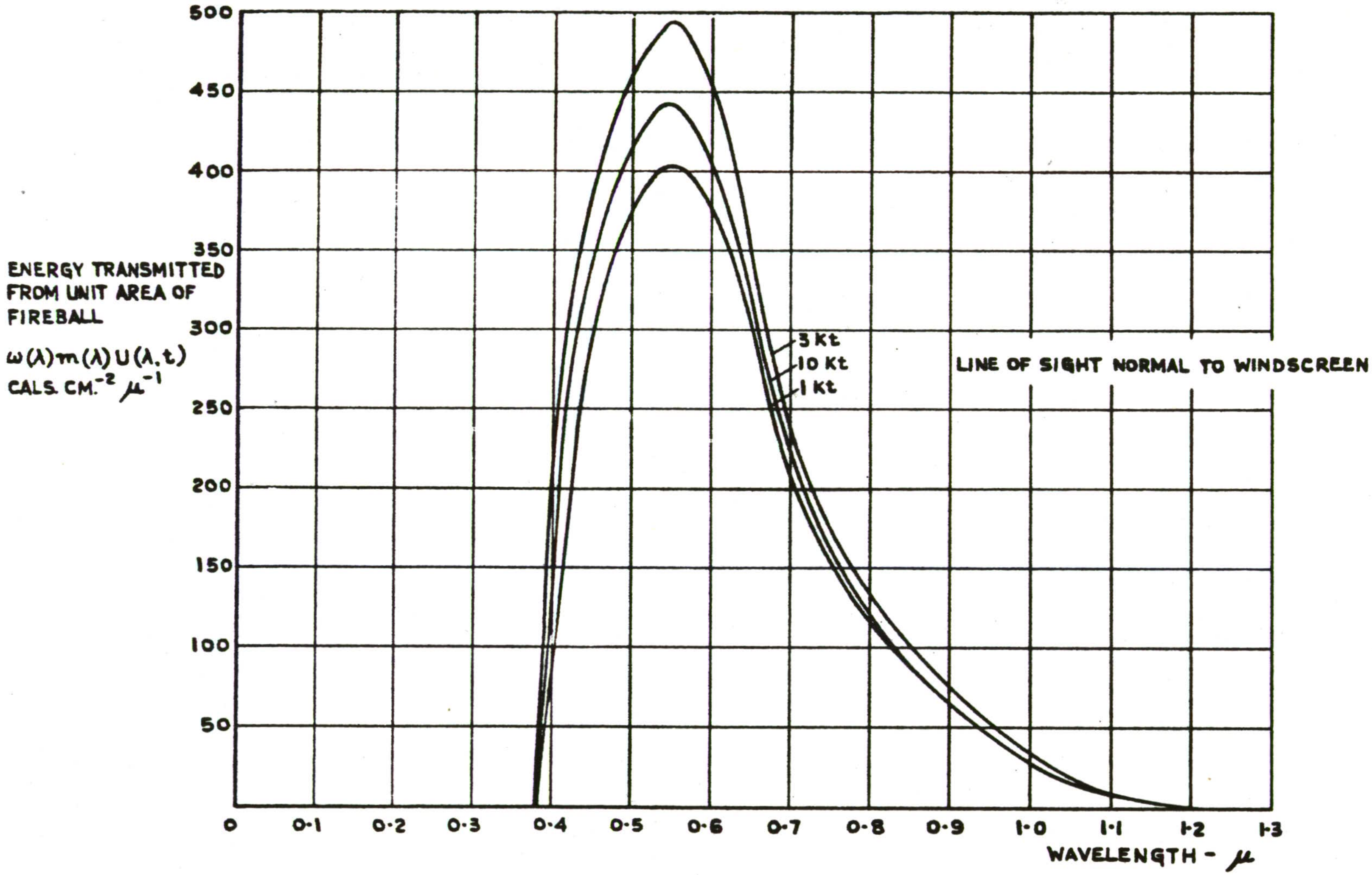


Fig. 9--Spectral distribution of energy reaching retina at zero range - 0-0.2 sec.

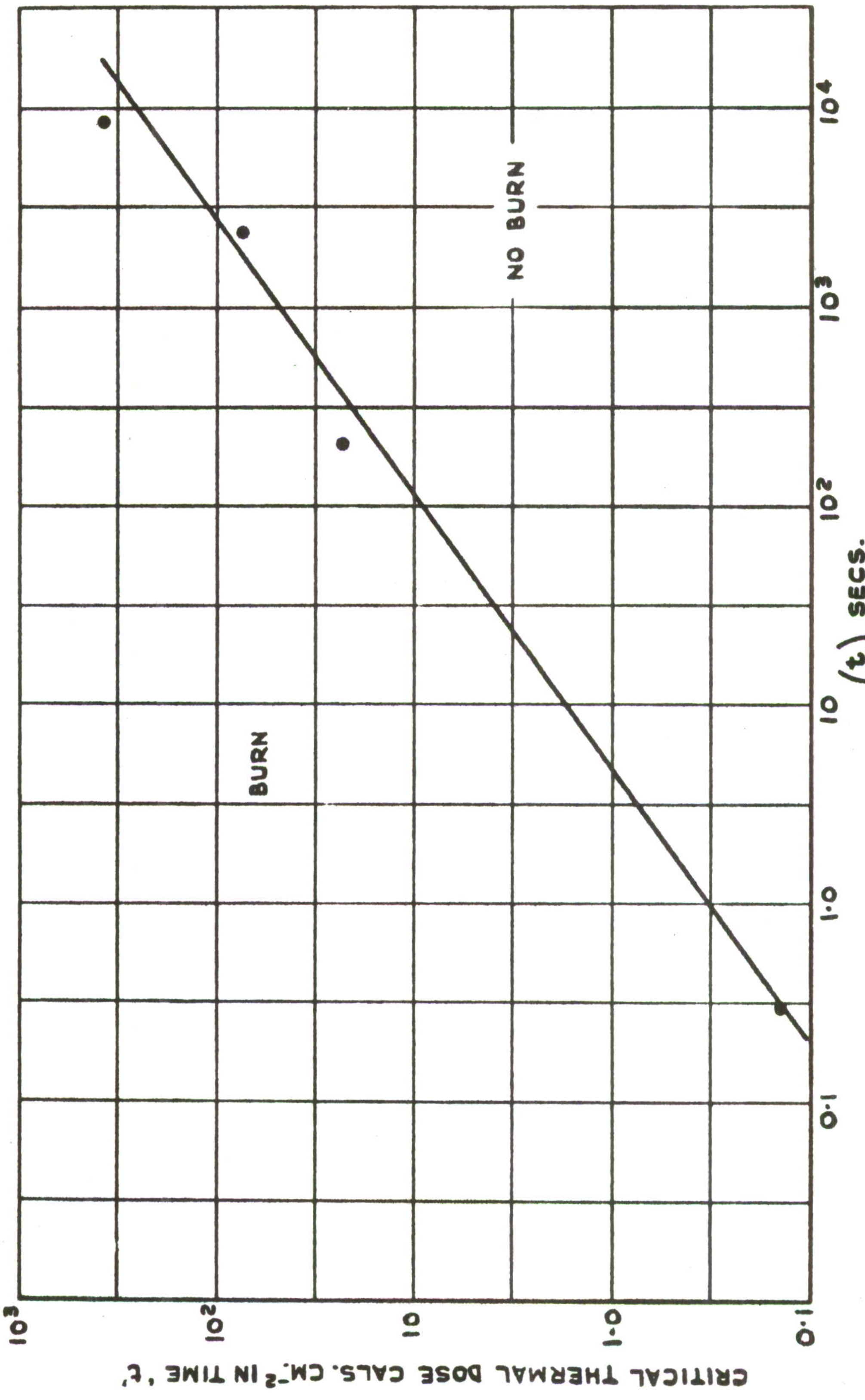


Fig. 10--Assumed critical thermal dose for retinal burns.

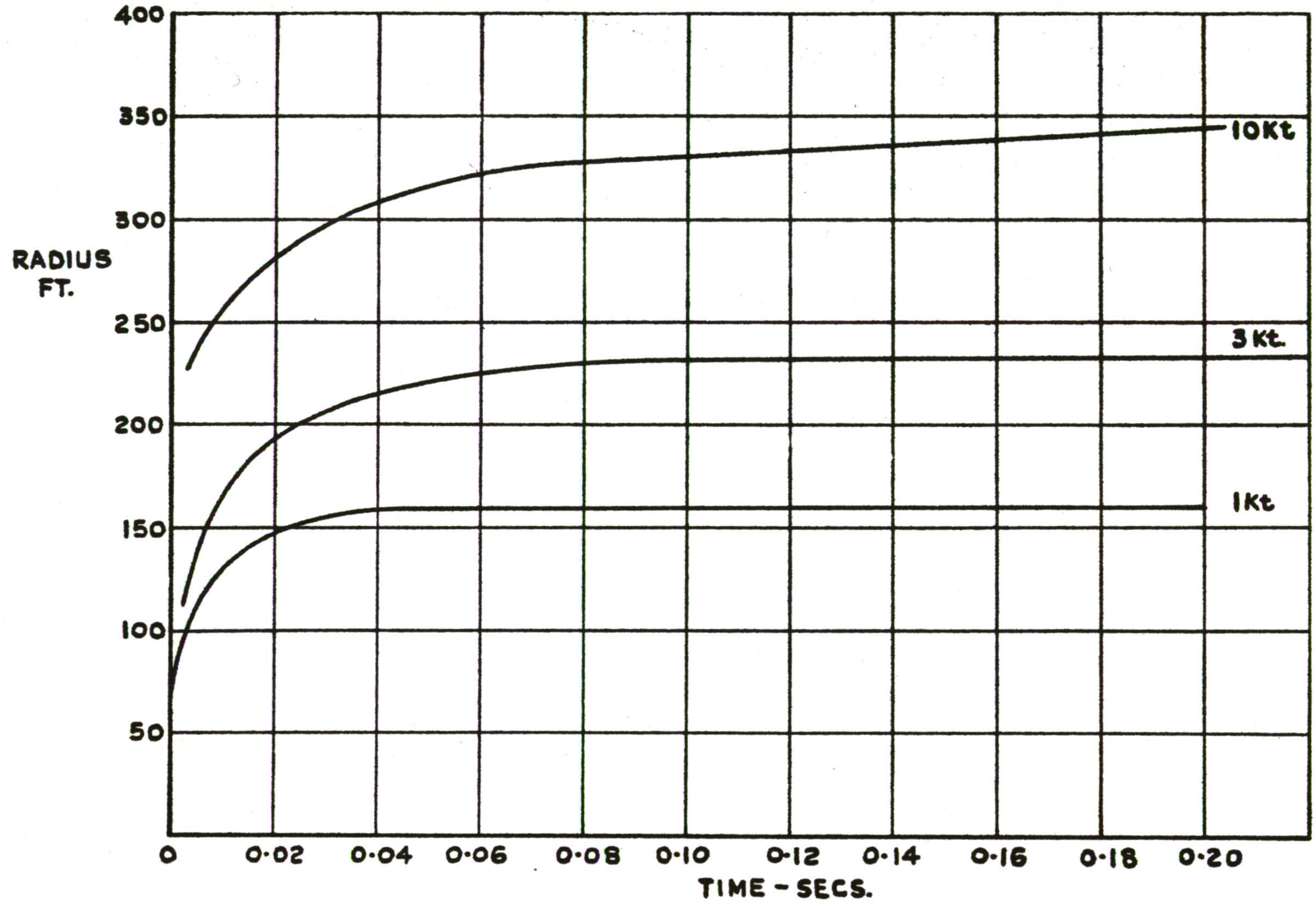


Fig. 11--Variation of fireball radius with time.

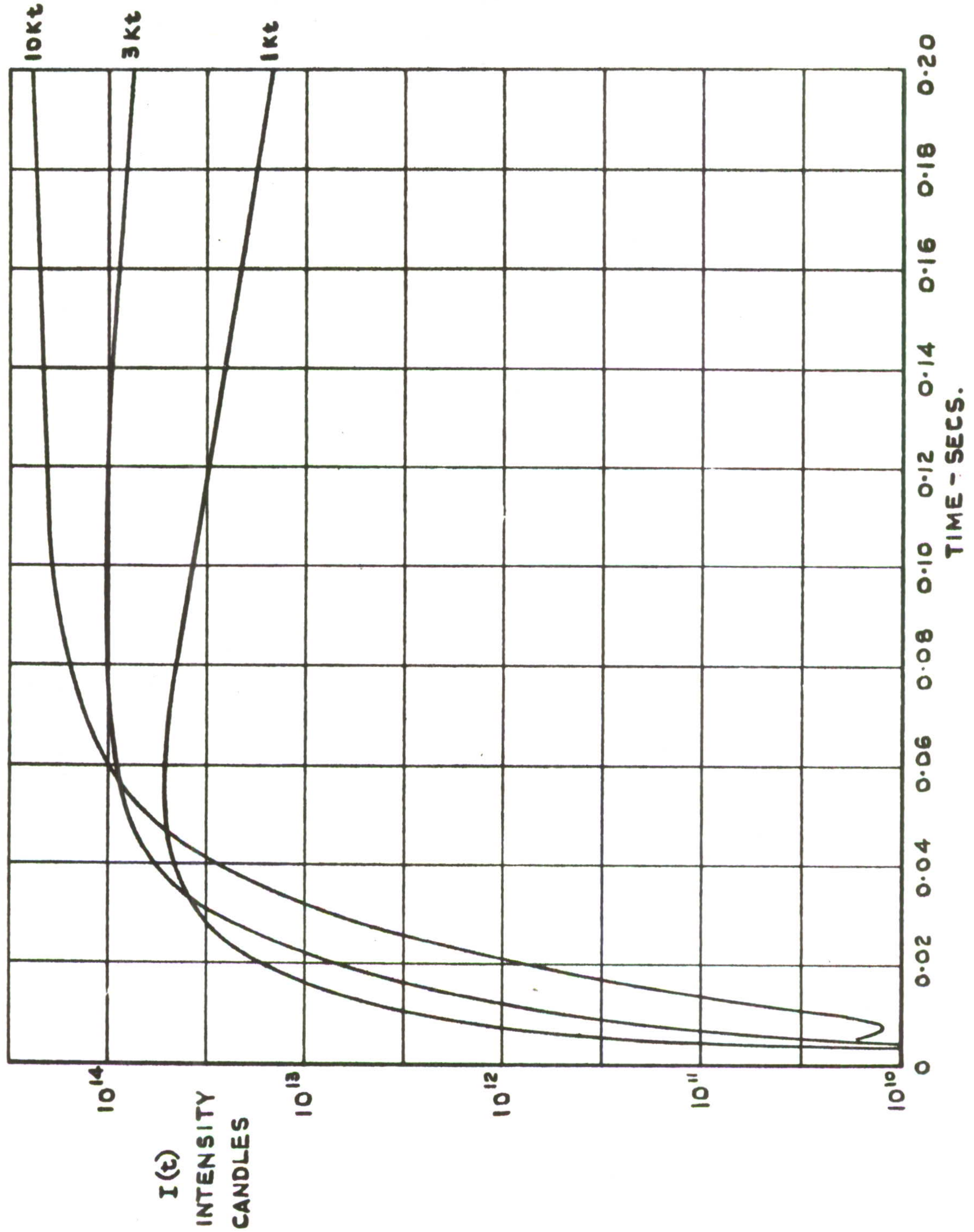


Fig. 12--Variation of fireball intensity with time.

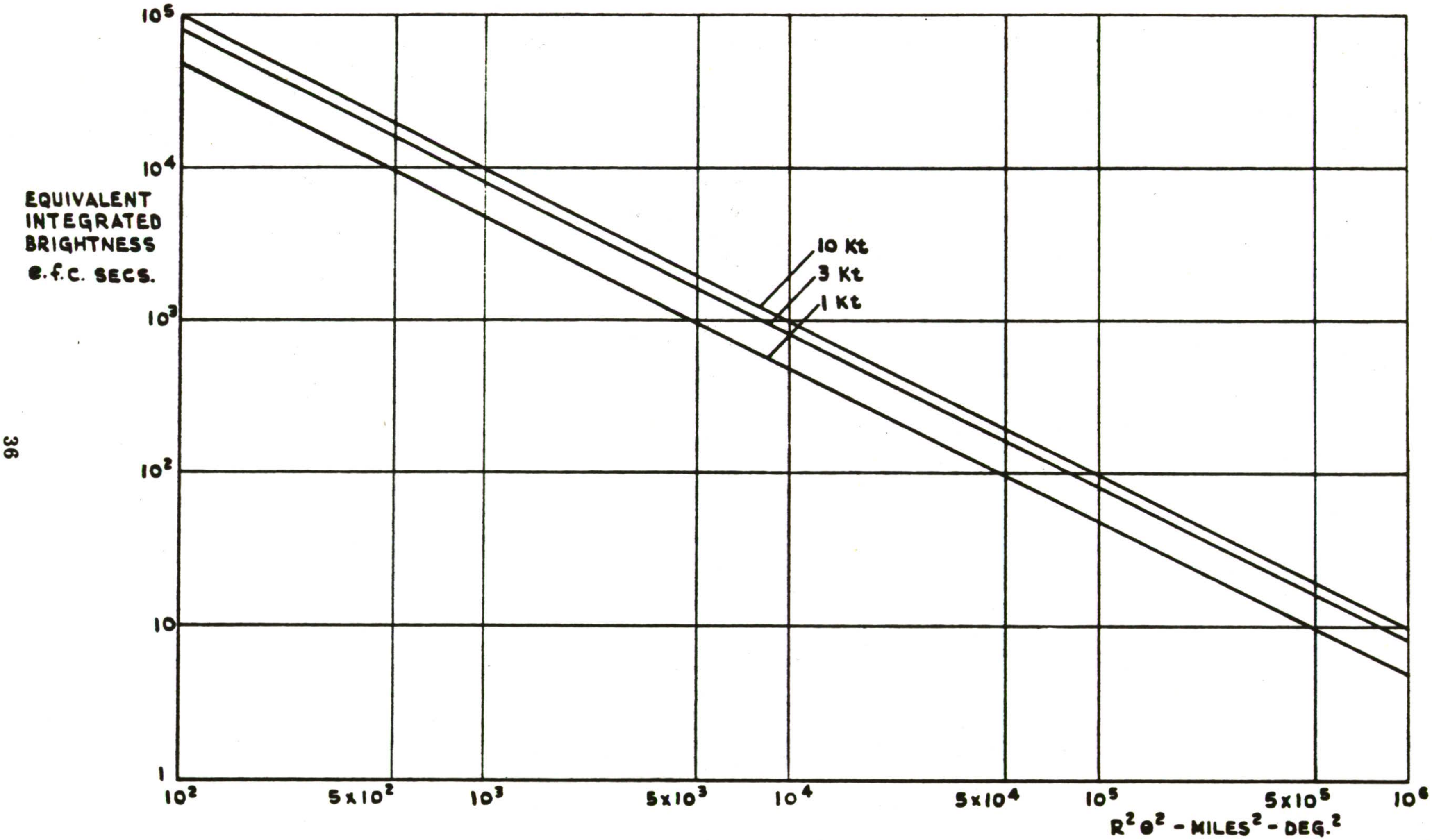


Fig. 13--Equivalent integrated brightness for various ranges and retinal locations. 0-0.1 sec.

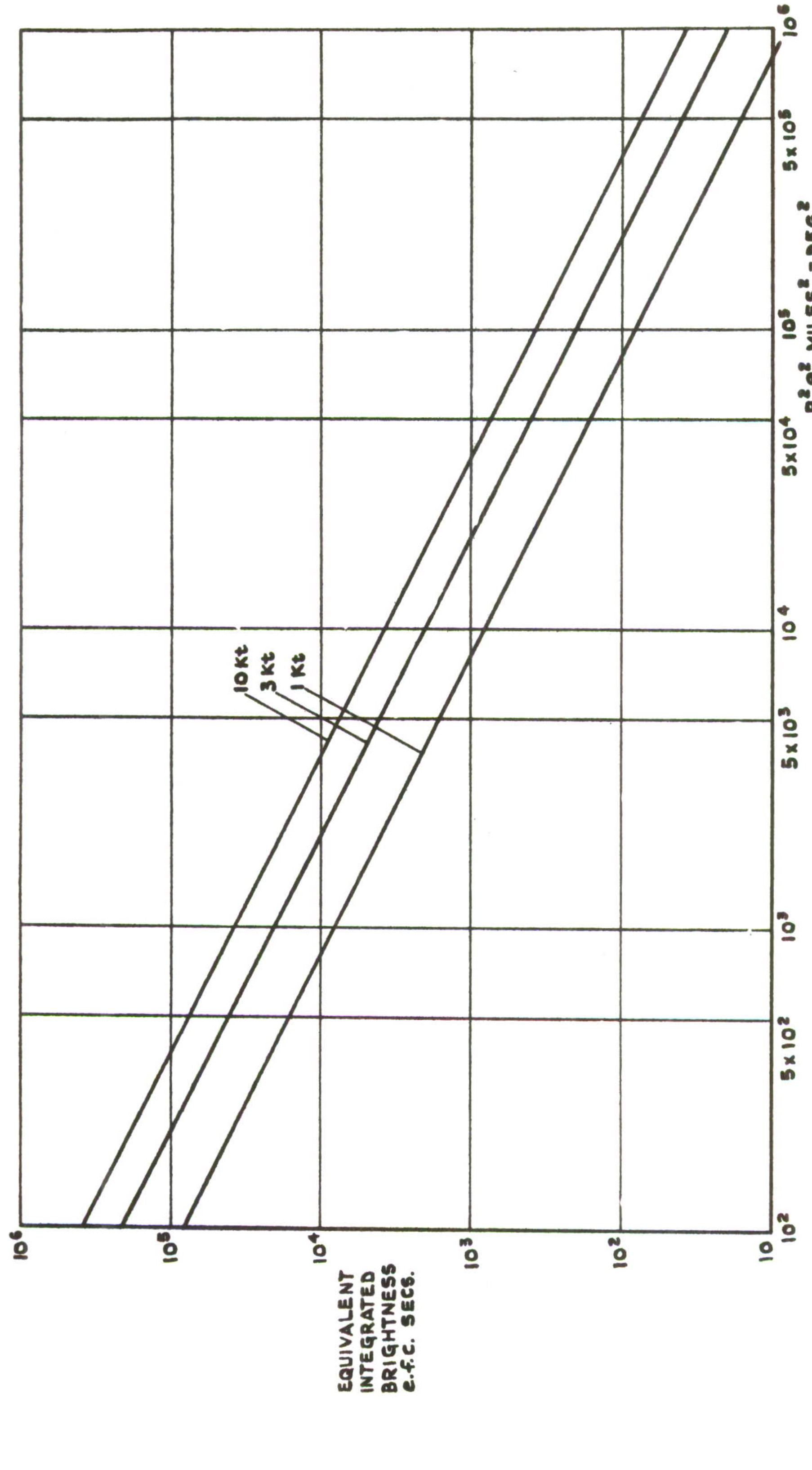


Fig. 14--Equivalent integrated brightness for various ranges and retinal locations. 0-0.2 sec.

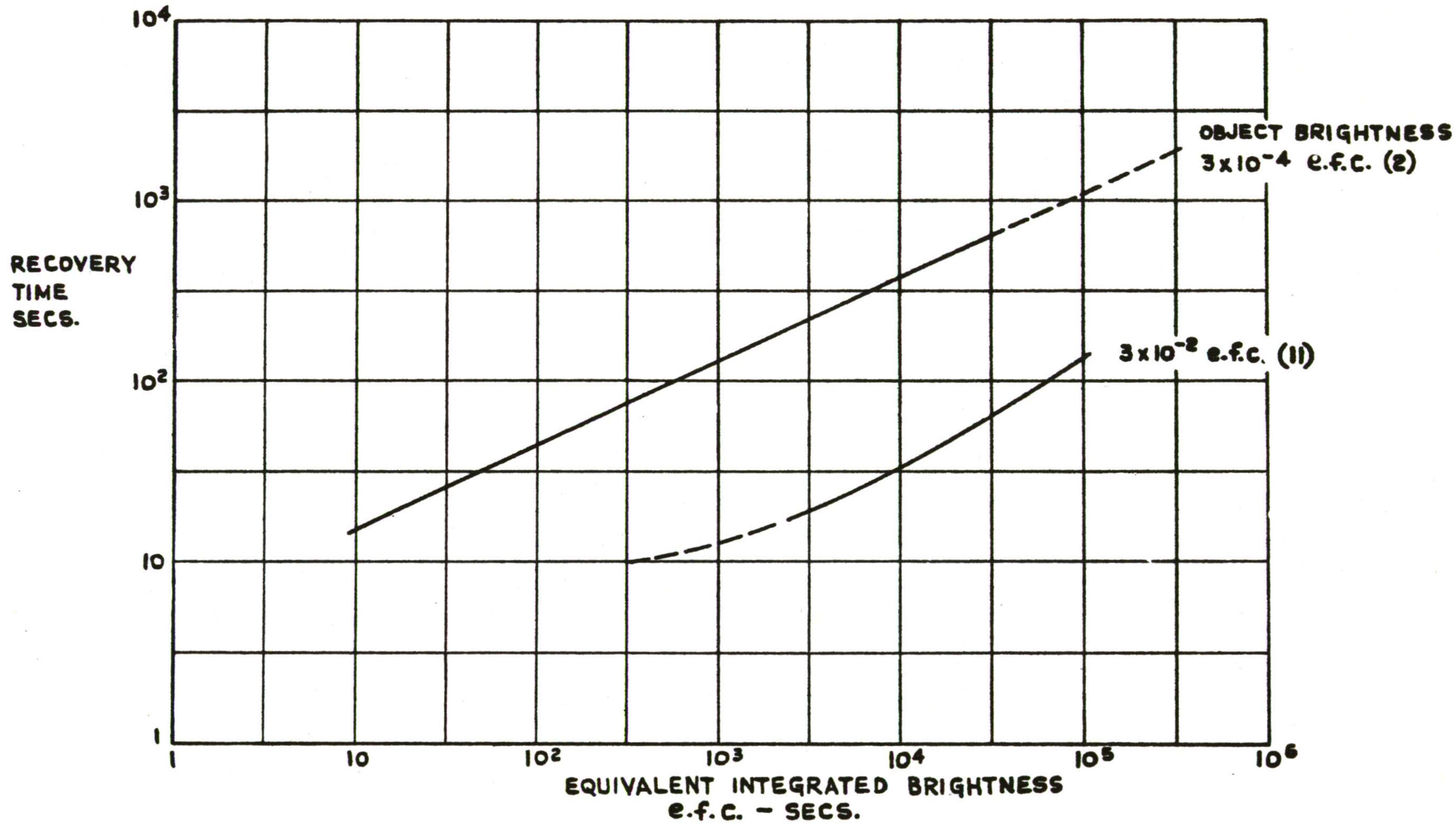


Fig. 15--Visual recovery time for two values of background brightness.

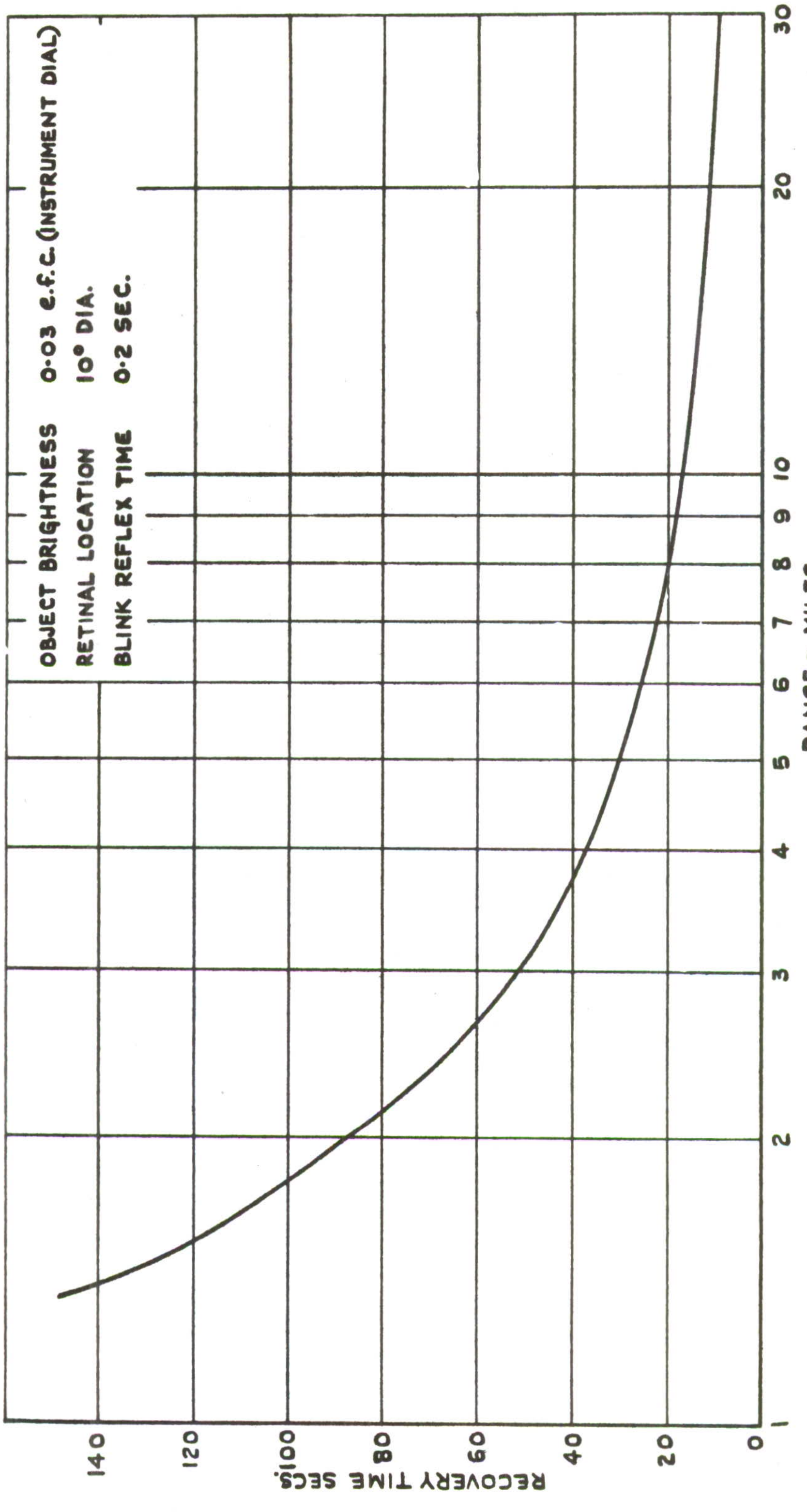
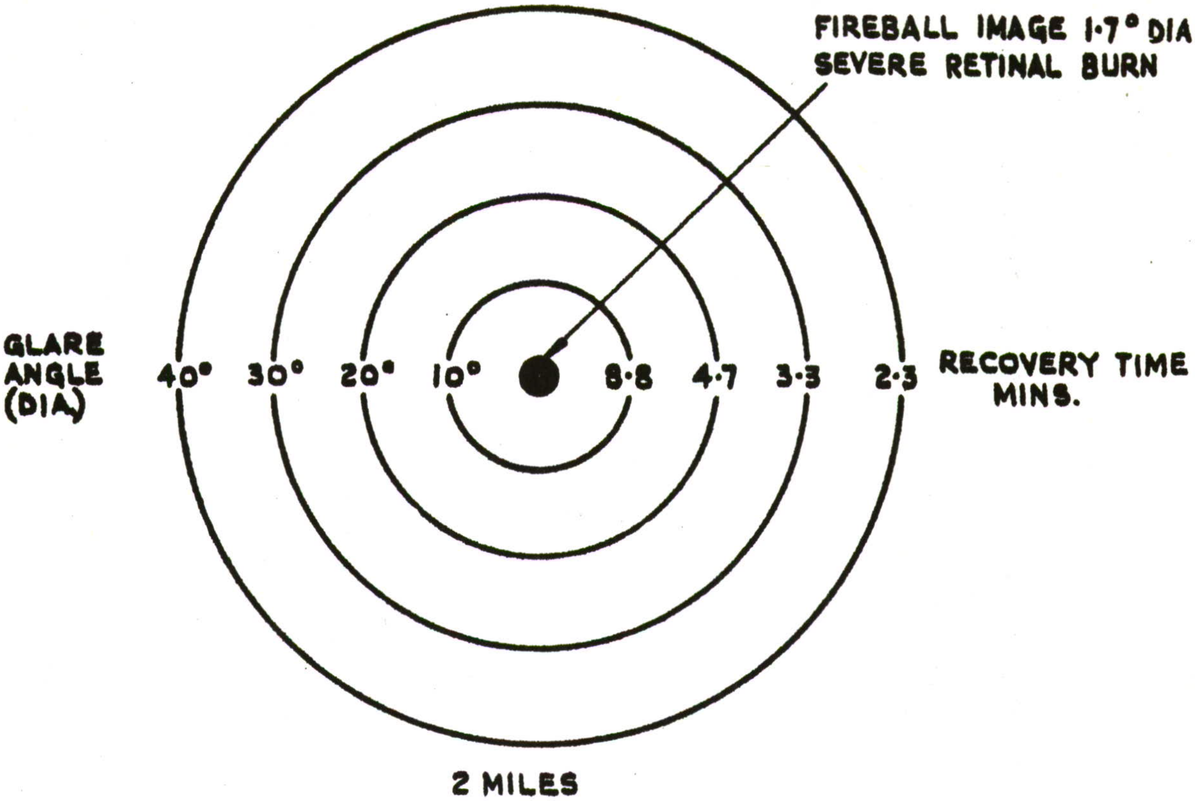


Fig. 16—Recovery time to read an instrument after a 3 kt explosion at various ranges.



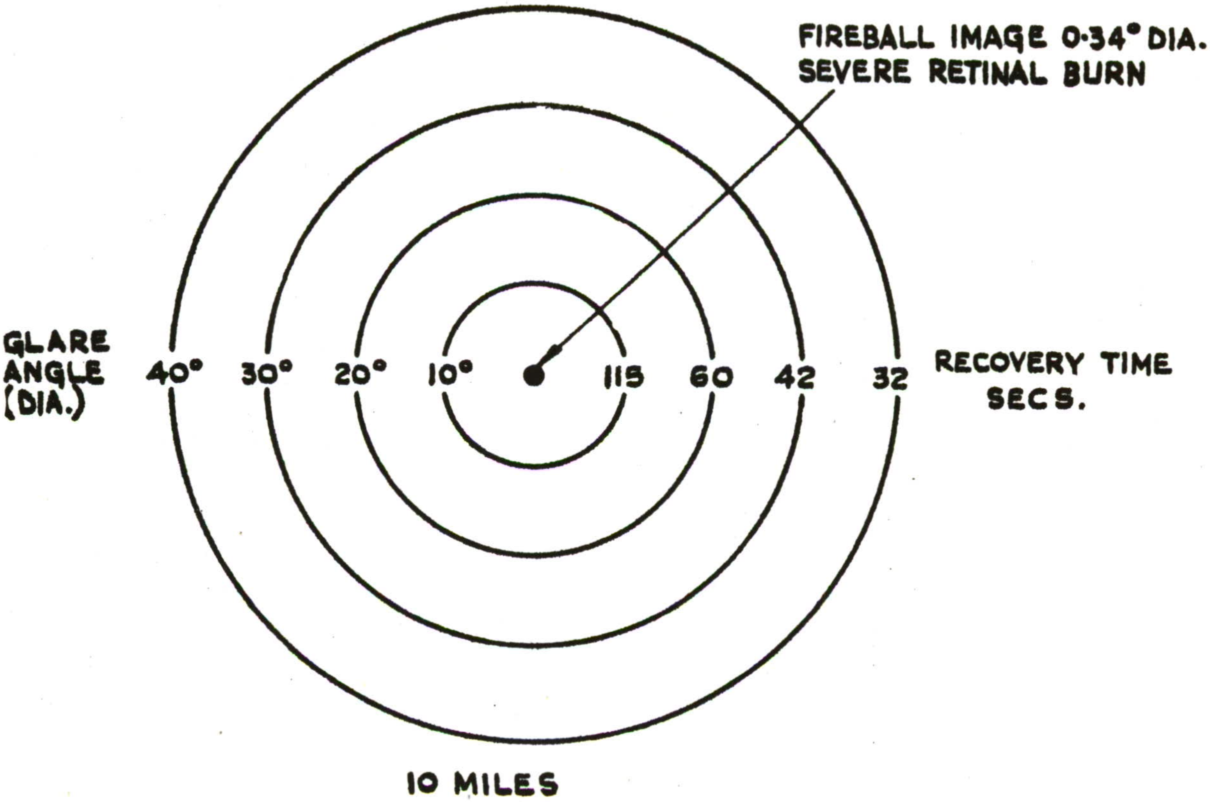


Fig. 17—Permanent and temporary blindness from 1 kt explosion (pupil dia 0.8 cm, blink reflex time 0.2 sec, object against moonlit sky).

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