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THE INTERACTION OF INFRARED RADIATION WITH THE EYE:

A REVIEW OF THE LITERATURE

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THE INTERACTION OF INFRARED RADIATION WITH THE EYE:

A REVIEW OF THE LITERATURE

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Prepared Under Contract NSR 36-008-108

The Aviation Medicine Research Laboratory
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INTRODUCTION

Infrared radiation is that part of the electromagnetic spectrum with energy levels generally considered to produce heating effects when absorbed by matter. Although the division is not absolute, the infrared range may be thought of as encompassing those wavelengths from 12,000 millimicrons (mu) to 770 mu, with 1,500 mu being an arbitrary point of division between long wave and short wave infrared (39).

If one is to be exposed to an electromagnetic radiation field which contains infrared radiation, he must be prepared to avoid any potentially dangerous effects of the radiation, including those possible harmful effects upon the ocular tissues. Because of this concern, the personnel of the Neurophysiology Laboratory of the Manned Spacecraft Center of the National Aeronautics and Space Administration have requested a compilation of data concerning the effects of infrared radiation upon the eye. Specific information is necessary in the following areas:

1. The transmission and absorption of infrared radiation by the ocular tissues.

2. The range of infrared radiation which is harmful to the ocular tissues.

3. The infrared radiation thresholds of the various ocular tissues.

4. The infrared radiation transmission and absorption of current optic materials.

It is the purpose, then, of this report to attempt to provide this information, insofar as it is now available in the biomedical literature.

Special acknowledgement is appropriate for the assistance of several persons. The suggestions from Dr. H. V. Ellingson of The Ohio State University, Department of Preventive Medicine, were most helpful as were the suggestions of Dr. Glenn A. Fry of The Ohio State University College of Optometry.

Finally, a special thanks to Mrs. Marsha Rayburn for her assistance in locating and securing reference materials, as well as in the typing and layout of the report.

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PART I: THE TRANSMISSION AND ABSORPTION OF INFRARED RADIATION BY THE TISSUES OF THE EYE

The effect of electromagnetic radiation on tissues is dependent upon the amount of energy which the tissue absorbs. If, then, one wishes to understand the effects of a particular type of radiation upon a tissue, one must have knowledge of the amount of this radiation which the tissue will absorb. It is, conversely, just as important in certain circumstances to know what radiation is transmitted through a particular tissue or structure, for when these structures are aligned as are the ocular tissues, the amount of radiation reaching one particular tissue may be wholly dependent upon the transmittability of the structures interposed between the radiation source and the tissue in question. For this reason, this section is devoted to a review of those studies which have examined the question of the transmission and/or absorption of infrared radiation by the ocular tissues.

Aschkinass, experimenting with both cattle and human eyes suggested near the end of the last century that at wavelengths of 1,400 mu or longer, all penetration of radiation through the eye stopped (3). As a result of his studies, he concluded that the absorption of the eye is similar to that of an equal thickness of water.

A decade later, Vogt published his findings concerning transmission of infrared radiation by the eye (92,93). Using an incandescent lamp with a carbon filter as a light source, he reported that of the rays falling on the cornea, 20 to 25% passed into the anterior chamber and only about 3% reached the retina. Although no specific spectral transmission curves were developed, Vogt stated generally that only the energy from "white hot bodies" - i.e., those bodies producing much short wave, high energy infrared radiation - could penetrate the ocular media to the iris, while longer wave infrared radiation affected the external parts of the eye. Additionally, Vogt commented that infrared radiation is absorbed more completely (and selectively) by the lens than by any other ocular tissue. (This latter belief set the stage for a long-term controversy concerning the etiology of the so-called "glassblowers' cataract," which is covered in detail elsewhere in this report.)

One of the earliest and most carefully done studies examining the interaction of infrared radiation with the eye was that performed by Hartridge and Hill (50). Their experiments were designed to answer two basic questions. First, in what amount do infrared radiations of different wavelengths gain access to the deeper structures of the eye and, second, what percentage of these radiations is absorbed in transmission through the lens? Using techniques somewhat similar to those of Aschkinass, these investigators measured the absorption bands of the different ocular media. They found that for different structures of the eye, the absorption curves were quite similar to those of the eye measured in whole, and further confirmed the similarity between the absorption curves of water and the ocular structures. These results are shown in Table 1. Then, relating the absorption of standard thicknesses of water, as shown in Table 2, with those of the eye, the investigators calculated the absorption of various parts of the eye. These calculations are shown in Table 3.

Hartridge and Hill made several pertinent observations about their calculations. They point out that besides absorption by the eye structures a small amount of infrared radiation is lost by reflection and scattering at the different surfaces of the structures of the eye. The authors estimate that of heat incident upon the cornea, approximately 5% of the total is lost by reflection and scattering. In addition, they point out that, according to their calculations, heat radiation from 1,100 mu to 700 mu passes into the eye almost unchecked, with most of the energy reaching the retina, thereby confirming the results obtained by Vogt.

Other early investigators also reported findings suggesting that the absorption of infrared radiation by the ocular media is similar to the absorption by water. Among these were von Mandach (94) and Berner (10), the latter also reporting that the absorption of the lens varies slightly depending upon the age of the animal from which the eye is taken.

Taking advantage of the fact that when infrared radiation is absorbed by a medium, the temperature of that medium rises, Fischer et al, al., (31) took a somewhat more clinically oriented approach to measuring ocular absorption of infrared radiation than had been taken previously. In examining the damage caused by infrared rays, the eyes of rabbits were exposed to monochromatic radiation from a carbon arc. The effect measured was an aqueous flare - a vasodilatation in the anterior uveal vessels. Establishing a "harm factor" ($f\lambda$) of unity for radiation at 1,000 mu, the most effective spectral band was found to be at 900 mu, suggesting that maximum ocular absorption occured at this frequency. The threshold dose necessary to excite a reaction expressed as intensity times duration (or, more simply, a time-dose relationship) as a function of wavelength is shown in Table 4.

Studies performed in 1927 by Roggenbau and Wetthauer were concerned with the transmission of infrared radiation by the refractive media of cattle eyes (84). Similar investigations were performed by Ludvigh and McCarthy, but using human eyes and investigating the so-called visible part of the electromagnetic spectrum (64). However, the latter study extended to 820 mu which may be considered to be in the very short wave infrared part of the electromagnetic spectrum. Both of these studies indicated that the refractive parts of the eye do indeed transmit short wave infrared quite efficiently.

In 1946 an excellent presentation of the knowledge available at that time concerning the transmittability of infrared radiation by the

Table 1. Comparative Values of Amount of Infra-red Energy of Different Wave-length Transmitted by the Lens and Aqueous and Vitreous Humours and by an Equivalent Thickness of Water.*

Wave-length in A.U.	Water	Deflection of galvanometer		
		Aqueous	Vitreous	Lens
		mm.	mm.	mm.
13,500	14	13	15	22.8
13,000	44	40	50	53.5
12,500	50.5	48	56	54.1
12,000	41	38.5	44	44
11,500	48.5	45	53	49.5
11,000	78.5	75	89.5	75
10,500	71.5	68.5	83	71
10,000	51	50	59	49
9,500	42.5	38.5	46	42.5
9,000	44	40	47	38.5
8,500	35	31.5	37	31
8,000	26.5	24	30	25
7,500	18	16.5	21.5	15.5

*From Hartridge and Hill[50]

Table 2. Absorption by Water in Percentage of Incident Heat Energy*

A.U.	Thickness	Readings				Mean	Log of reciprocal
	mm.	p.c.	p.c.	p.c.	p.c.		
7,000	30.6	102.5	97	98	101	99	0.0044
7,500	-	95	93	96	94.5	94.5	0.0246
8,000	-	91.2	89.8	95	92	93	0.0362
8,500	-	90	92.1	91.3	90.7	91	0.0410
9,000	-	88	86.9	86.6	87.1	87	0.0605
9,500	10.5	72.3	72.6	73	71.8	72.4	0.1403
9,750	-	67.5	67	67.3	67.4	67.3	0.1720
10,000	-	74	74	73.1	74.2	73.8	0.1319
10,500	-	90.2	91.4	91.5	90.3	90.9	0.0414
11,000	-	85.5	85.3	85.4	84.5	85.2	0.0696
11,500	-	42.2	43	42.6	43.5	42.8	0.3686
12,000	-	30.7	31.3	30.3	30.4	30.7	0.5129
12,500	-	33.2	33.9	33.3	33.6	33.5	0.4750
12,750	-	33.5	33.6	34.3	33.1	33.6	0.4737
13,000	-	27.6	26.3	26.4	26.8	26.8	0.5719
13,500	3	43.1	43	43.2	43.2	43.1	0.3655
14,000	1	24	24.4	23.6	23.9	24	0.6198
14,500	-	56	5.5	5.36	5.6	5.5	1.2596
15,000	-	13.5	13.3	13.45	13.5	13.4	0.8729
15,500	-	29.4	29.2	28.2	29	29	0.5376
16,000	3	12.2	12.4	12.45	12.15	12.3	0.9101
16,500	-	16.5	16.3	16.45	16.9	16.5	0.7825
17,000	-	14.3	13.6	13.7	14.1	13.9	0.8570
17,500	-	8.35	8.6	8.4	8.3	8.4	1.0757
18,000	1	20.5	20.9	20.4	20.65	20.6	0.6861
18,500	-	52	5.1	4.8	4.95	5	1.3010
19,000	-	-	-	2	-	2	1.7000
19,500	-	-	-	2.5	-	2.5	1.6021
20,000	-	-	-	4.5	-	4.5	1.3470
20,500	-	-	-	6	-	6	1.2218
21,000	-	-	-	7.5	-	7.5	1.1249
21,500	-	-	-	7	-	7	1.1549
22,000	-	-	-	5	-	5	1.3010
22,500	-	-	-	2.5	-	2.5	1.6021
23,000	-	-	-	0	-	0	-
23,500	-	-	-	0	-	0	-
24,000	-	-	-	0	-	0	-

The absorption by water at different wave-lengths is given in Table 2. The values were obtained by first measuring the deflection of the galvanometer.

*From Hartridge and Hill[50]

Table 3. Calculated Values of Heat Radiation Penetrating the Eye in the Human Subject*

Wave-length in Å.U.	I Percentage of heat energy transmitted by cornea of that incident on cornea.	II Percentage of heat energy reaching the anterior surface of lens of that incident on cornea.	III Percentage of heat energy reaching the posterior surface of lens of that incident on cornea.	IV Percentage of heat energy reaching retina of that incident on cornea.
7,000	97.5	95	95	94.3
7,500	97.5	95	94.6	91.3
8,000	97.5	94.5	93.6	89.6
8,500	97.5	94.2	93	89
9,000	97.2	93.6	91.9	86.1
9,500	94.4	85.4	76.2	48
9,750	93.6	83.1	72.5	41.2
10,000	94.5	85.8	77.2	50.3
10,500	96.6	92	89	77.6
11,000	95.9	90	85.1	67.7
11,500	89.4	71.5	53.2	15.9
12,000	86.4	63.7	42.2	7.9
12,500	87.0	65.7	44.9	9.5
12,750	87.3	65.6	44.8	10.6
13,000	85.4	61	37.7	6.55
13,500	75.0	36.4	13.4	0.24
14,000	23.5	0.72	-	-
14,500	5.5	0.00	-	-
15,000	12.9	1.1	-	-
15,500	28.0	1.37	-	-
16,000	48.2	8.7	0.73	-
16,500	53.3	12.2	1.44	-

Continued -

Table 3. Calculated Values of Heat Radiation Penetrating the Eye in the Human Subject - Con't.

Wave-length in A.U.	I	II	III	IV
17,000	51.4	10	0.95	-
17,500	43.5	5.6	0.30	-
18,000	20.3	0.42	-	-
18,500	4.9	-	-	-
19,000	2	-	-	-
19,500	2.5	-	-	-
20,000	4.4	-	-	-
20,500	6	-	-	-
21,000	7.6	-	-	-
21,500	7.1	-	-	-
22,000	5	-	-	-
22,500	2.5	-	-	-
23,500	0	-	-	-

*From Hartridge and Hill[50]

Table 4. The Harm-factor to the Inner Eye of Infra-red Radiation*

λ in A.U.	Threshold dose erg/cm^2	f λ
20,000	$1{,}500.0.10^5$	0.005
16,000	$25.0.10^5$	0.30
14,000	$18.0.10^5$	0.41
12,000	$10.0.10^5$	0.74
11,000	$9.2.10^5$	0.80
10,000	$7.4.10^5$	1.00
9,000	$6.5.10^5$	1.14
8,000	$14.0.10^5$	0.53

*From Fischer et al[31].

eye was made by Kutscher (58) and reiterated by Minton in 1949 (12). Kutscher commented as follows:

> "In general all radiations longer than 30,000 A.U. are completely absorbed by the cornea. A slow progressive increase of corneal transmission is observed until at about 19,000 A.U. a marked increase occurs. This continues with one exception until at about 11,000 A.U. 96% of the incident energy is transmitted.
>
> "Absorption by the lens begins rather abruptly at 18,000 A.U. and continues in varying degrees until at 10,000 A.U. nearly all infra-red is transmitted....The iris absorbs all wave lengths of infra-red that fall upon it. Upon absorption it is translated into heat....By far the major portion of infra-red incident upon the cornea is absorbed by the cornea, aqueous, iris and lens. The vitreous filters out most of the remainder so that little reaches the retina. Only in very unusual circumstances does the retina suffer a thermal burn as the result of infra-red radiation."(58, p. 314)

Figure 1 is adapted from Kutscher's summary of the absorption of infrared by ocular structures.

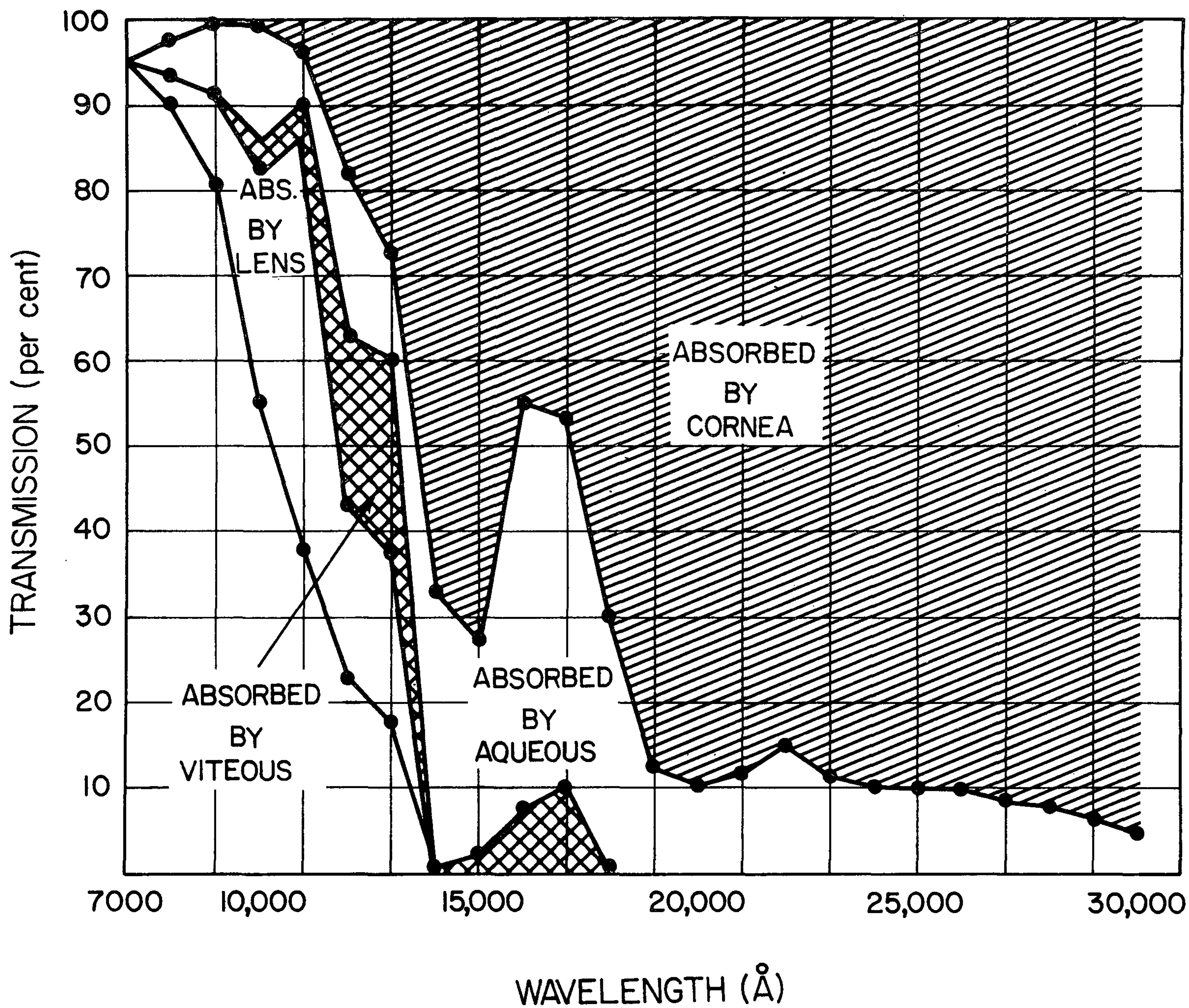
This summary was, in general, concurred with by Cogan in his 1950 report, when he stated:

> "Infra-red rays penetrate the transparent portions of the eye as they do a water-phantom: The relatively long rays (e.g., those longer than 2,000 millimicrons) are absorbed almost entirely by the cornea and aqueous humor, while the relatively short infra-red rays encountering the iris are absorbed by the pigment, and those which, having passed through the pupil, reach the retina are similarly absorbed by the pigmented epithelium." (20, p. 146)

LeNoble and Le Grand (61) added further information when reporting their studies in 1954 which indicated that the absorption of infrared radiation by the lens depends upon the water content of the lens.

Perhaps the single best study to that time measuring the transmission of light through the ocular media was that reported by Wiesinger, et al., in 1956 (96). This investigation involved measuring the transmission of light through freshly enucleated rabbit eyes. Using a highly sophisticated technique, measurements were made from 380 mu through 1,350 mu. The results of their findings are noted in Table 5, and shown graphically on Figure 2. In the figure, the mean percentage transmission for the eyes studied is plotted against the wavelength in mu, and, for purposes of comparison, the percentage transmissions through 1 cm. of distilled water and through 1 cm. of physiologic saline solution are

Figure 1* - ABSORBTION OF INFRA-RED HEAT RAYS COMPOSITE GRAPH



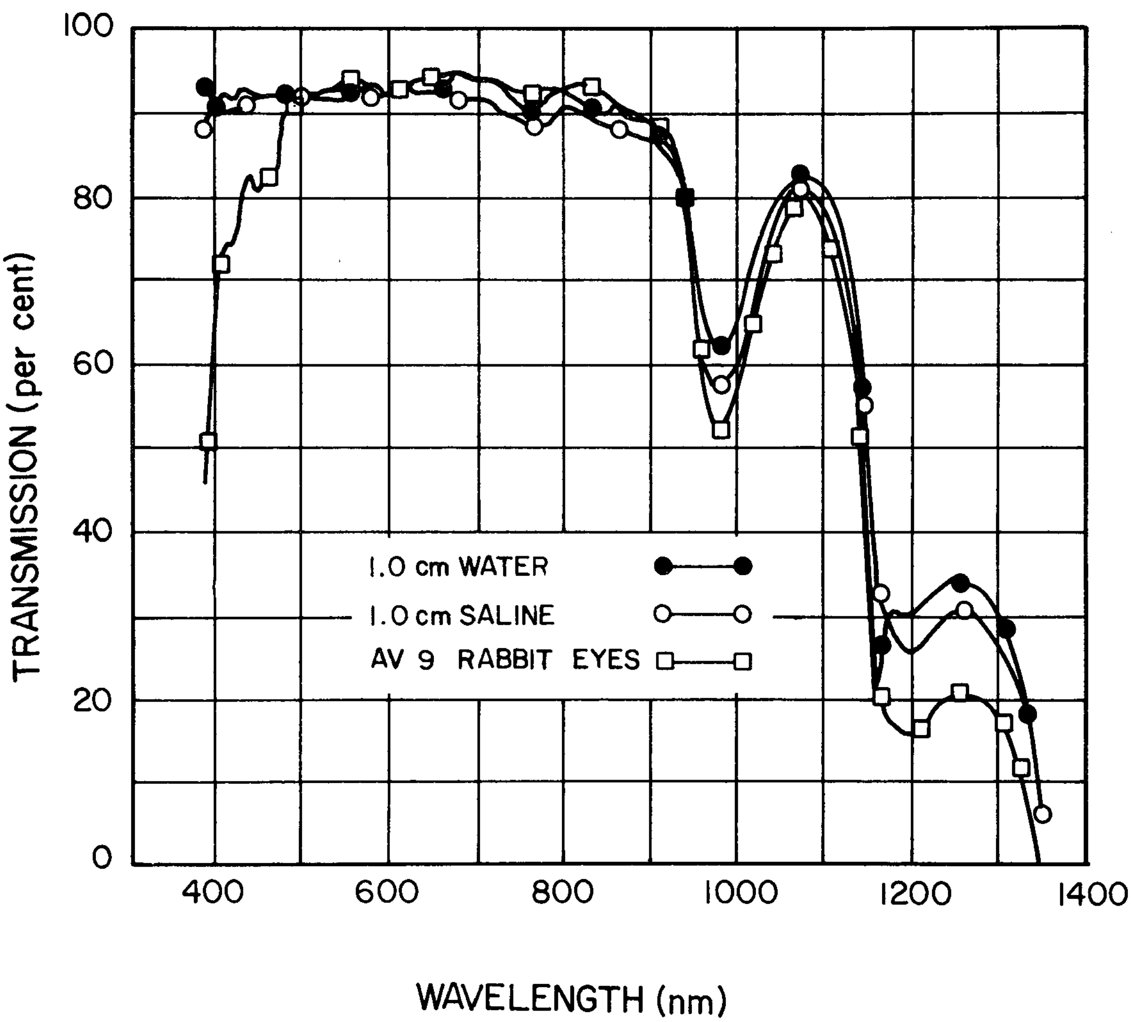
*From Kutscher, C.F. (58).

Table 5. Transmission Data for Nine Rabbit Eyes*

Wave-length (in mu)	Mean Percent Trans-mission for Nine Eyes.	Standard Deviation	Coefficient of Varia-tion (%)	Wave-length (in mu)	Mean Percent Trans-mission for Nine Eyes	Standard Deviation	Coefficient of Varia-tion (%)
380				780	93.2	1.15	1.2
390	46.5	4.50	9.7	800	93.2	1.43	1.5
400	61.0	3.02	5.0	820	93.8	1.52	1.6
410	71.4	3.67	5.1	840	92.4	1.35	1.5
420	75.4	3.01	4.0	860	91.5	1.08	1.2
430	79.1	3.14	4.0	880	90.4	1.64	1.8
440	82.9	2.32	2.8	900	88.2	0.84	1.0
450	85.2	2.16	2.5	920	86.3	1.45	1.7
460	87.9	3.06	3.5	940	78.1	1.19	1.5
470	88.7	2.68	3.0	960	61.5	2.94	4.8
480	90.5	2.45	2.7	980	51.9	1.00	1.9
490	90.8	2.06	2.3	1000	57.5	6.30	11.0
500	92.4	1.80	1.9	1020	64.3	5.81	9.0
520	92.9	2.56	2.8	1040	71.4	1.11	1.6
540	93.5	2.15	2.3	1060	77.7	0.95	1.2
560	94.4	1.73	1.8	1080	79.8	1.10	1.4
580	93.5	0.87	0.9	1100	76.5	1.20	1.6
600	93.5	1.57	1.7	1120	70.3	1.27	1.8
620	93.5	0.92	1.0	1140	53.5	2.46	4.6
640	94.4	1.07	1.1	1160	22.8	3.10	13.6
660	94.7	1.25	1.3	1180	16.8	0.44	2.6
680	95.2	1.32	1.4	1200	15.6	0.69	4.4
700	94.6	1.63	1.7	1250	20.9	0.91	4.4
720	94.4	1.24	1.3	1300	18.1	0.88	4.9
740	92.8	1.44	1.6	1350	2.4	0.22	9.2
760	92.6	1.95	2.1				

*From Wiesinger, et al[96].

Figure 2* - Transmission curve for rabbit eyes.



*From Wiesinger, H., et al, (96).

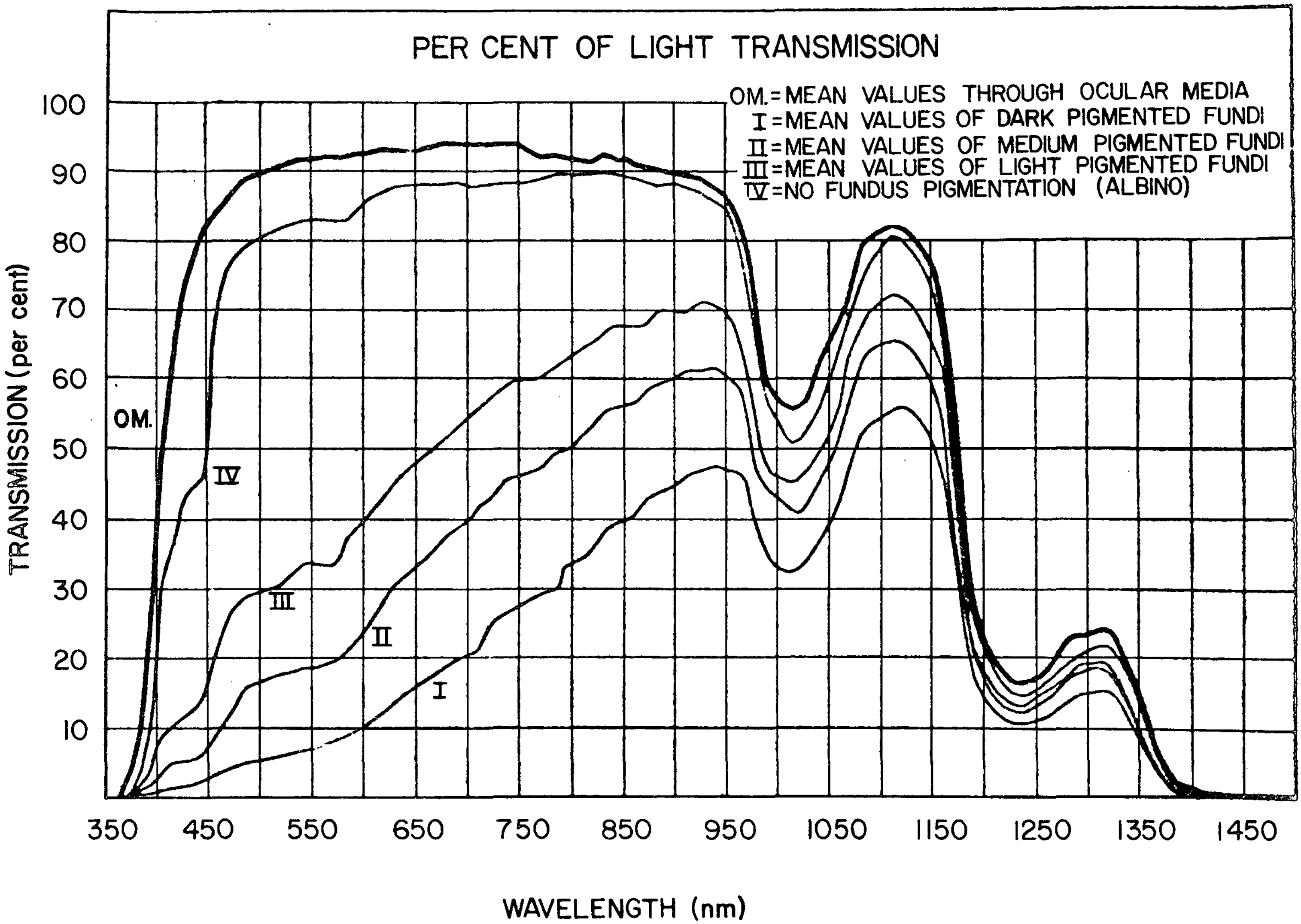
also plotted. Wiesinger, et al., point out that although the optic media of the rabbit eye has a thickness greater than 1 cm., the transmission curves are still remarkably similar in all three cases. Although the studies by Pitts examining the transmission of light through bovine eyes extended only to wavelengths of 700 mu (78) the similarity between his findings and those of Wiesinger et al. (at the lower frequencies) lend credence to Wiesinger et al.'s findings at longer wavelengths in the infrared range. Still further support has been offered by the comments of Lieb and Geeraets (63).

Geeraets et al. (37) measured the transmission of electromagnetic radiation through the ocular media, including the retina and choroid and then repeated the same measurement, but with the retina and choroid having been removed. These studies were performed in an attempt to clarify the spectral absorption characteristics of the ocular fundus so that data could be gathered to assist in realistic evaluation of the retinal burn capabilities of nuclear weapons and for a more thorough exploitation of the clinical uses of light coagulation. Studies were performed upon 30 eyes from Chinchilla-gray rabbits, ten albino rabbit eyes and two human eyes. Wavelengths from 350 to 1,500 mu were studied by the investigators. Figure 3 illustrates the measurements at different wavelengths and shows the effects of variation in the pigmentation of the fundi upon the amount of light absorbed in the eye. It should be noted however, that this variation begins to diminish as we enter the short wave infrared part of the range, so that above about 1,100 mu the role played by the pigmentation of the choroid plays a considerably less significant role in the absorption of radiation. Figure 4 shows similar curves for the human eyes studied. The estimation of corrected values for transmission of radiation through the human eyes was felt to be necessary, since the studies were performed about four hours post-mortem and the inner retinal layers were noted grossly to be cloudy, indicating that some degree of degeneration had already begun.

Noting that rabbits are frequently used as test animals in evaluating thermal hazards to the human fundi, the authors felt it of importance to compare the transmission characteristics of the rabbit eyes studied with those from the human eyes. This comparison is shown in Figure 5 for the ocular media alone. Figure 6 shows a similar comparison for the retina and choroids of rabbits with those of humans, where it should be noted that human fundi appear to act very much like those of the rabbits with dark fundi.

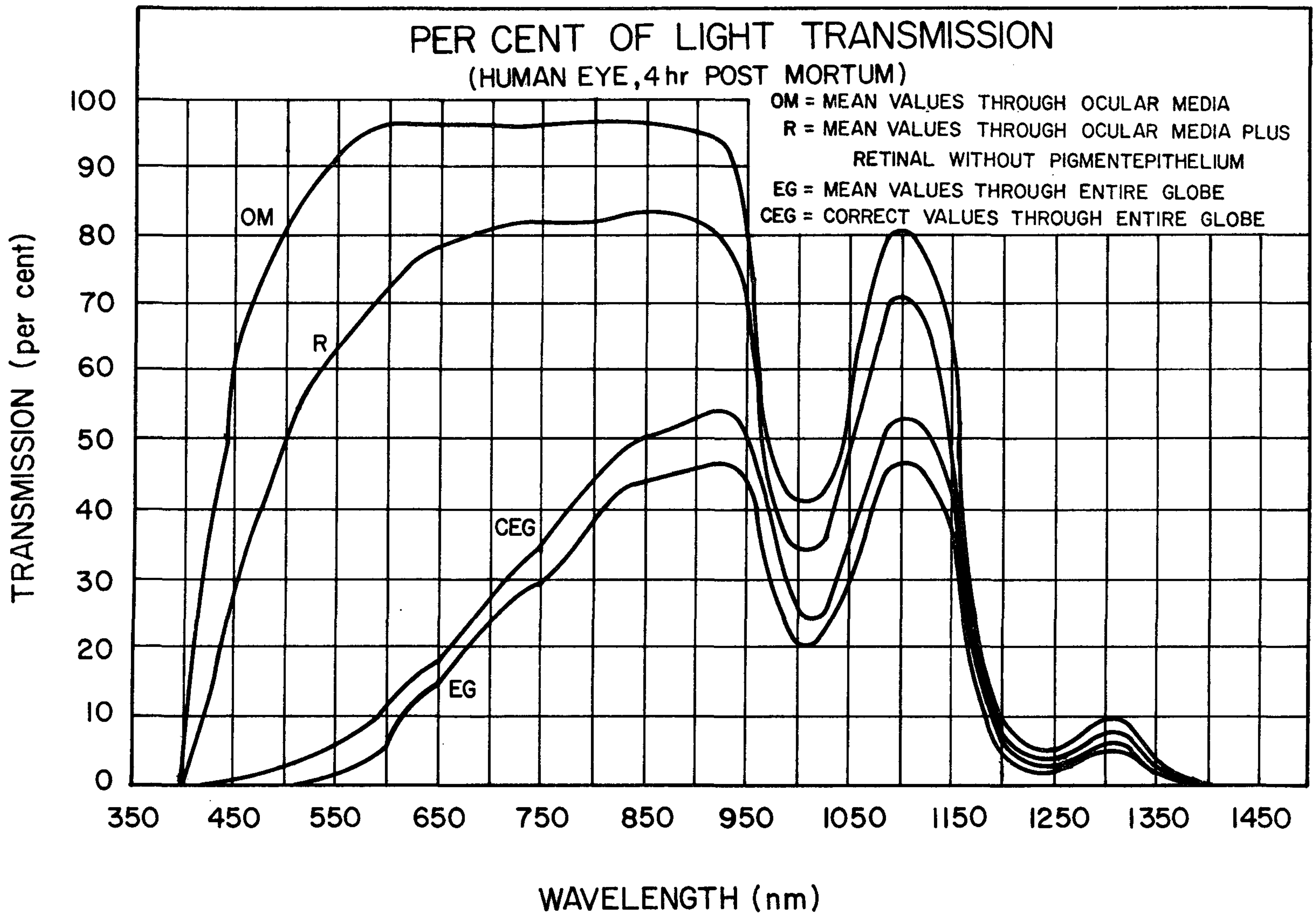
Boettner and Wolter, pointing out the scarcity of information on the transmittance characteristics of human eyes and, more particularly, on the transmittance of the separate components of the eye, reported on studies of nine human eyes (11). In the report, two sets of transmittance measurements of the individual components were described. One is a measure of "direct transmittance" - i.e., the light passing through the medium - and the other is a measure of both the direct and a portion of the "forward-scattered" light. The latter refers to that light which is scattered in the medium but still emerges from or passes through the

Figure 3* - Percentage transmission in the ocular media and the fundus for rabbit eyes with varying degrees of pigmentation for light incident on the cornea.



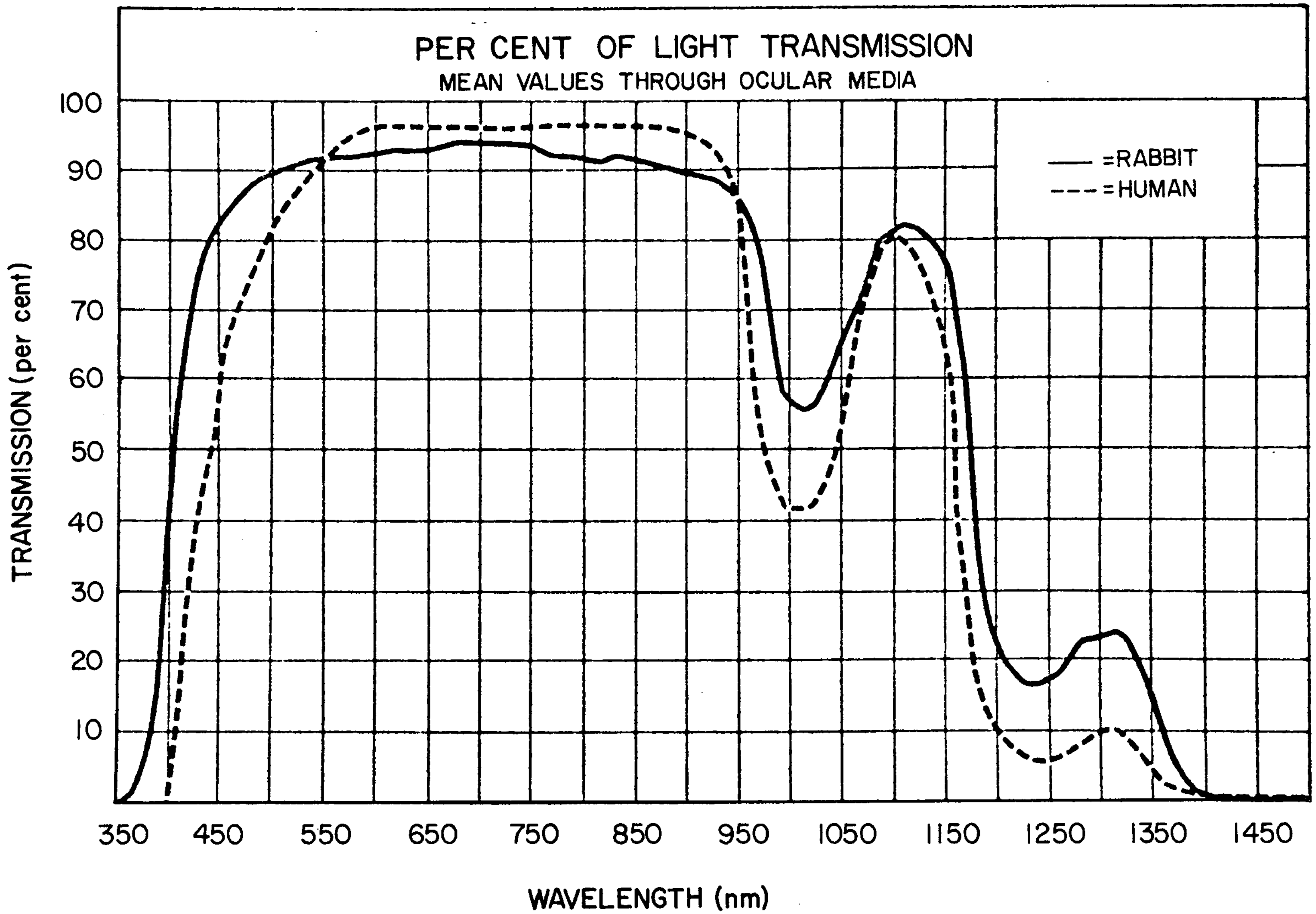
*From Geeraets, W.J., et al (37).

Figure 4* - Percentage transmission in the ocular media, retina, and entire globe for two human eyes.



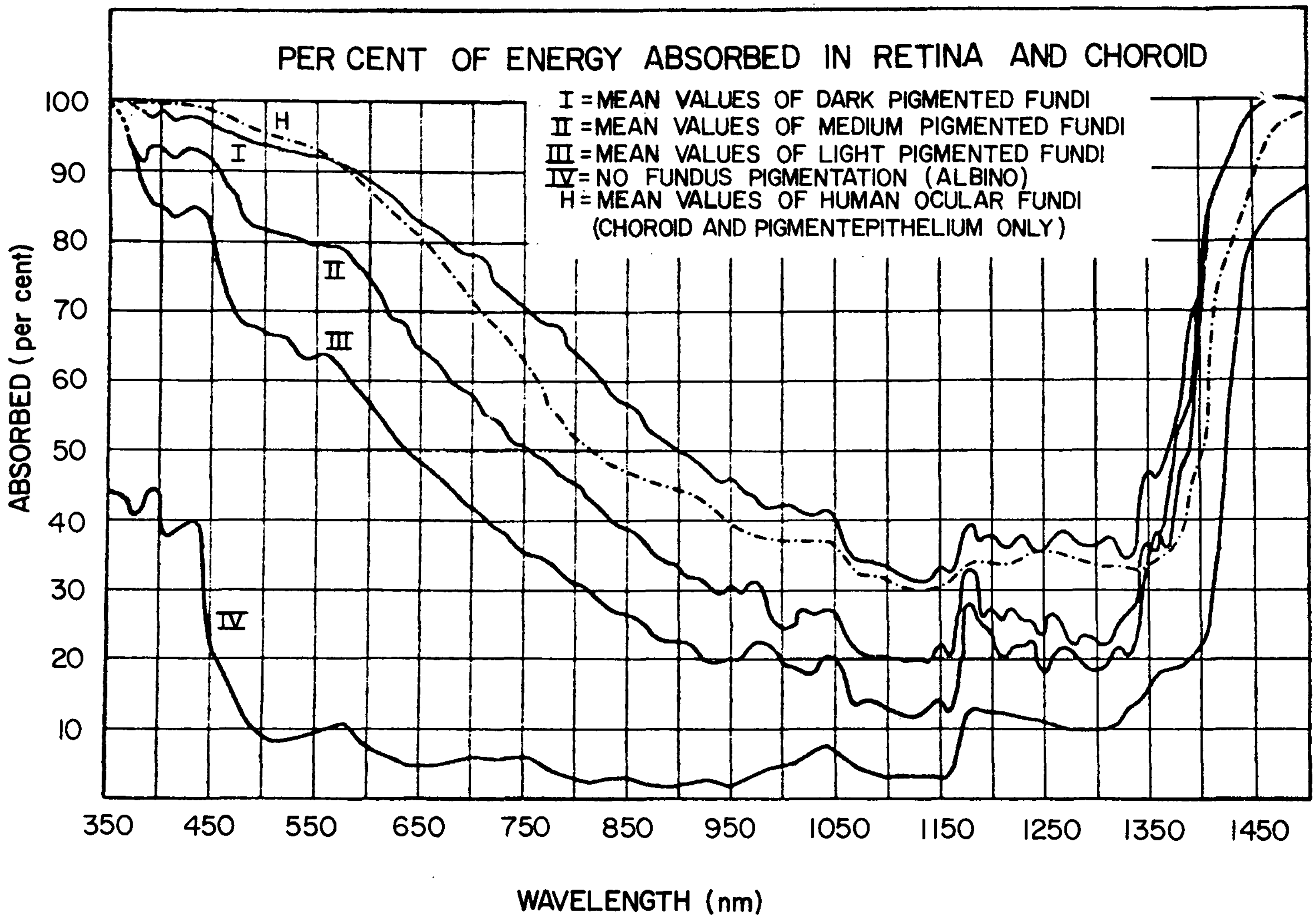
*From Geeraets, W.J., et al (37).

Figure 5* - Percentage transmission curves comparing human and rabbit ocular media.



*From Geeraets, W.J., et al (37).

Figure 6* - Absorption characteristics of human and four groups of rabbit fundi for light incident on the fundus.



*From Geeraets, W.J., et al (37).

medium, rather than being "back scattered" or, in a sense, reflected. It should be recognized that this scattered light results in a degree of general illumination within the eyeball.

The results of Boettner and Wolter's studies can be shown well on a series of figures. It should be noted that the range of investigation extended from approximately 200 to 300 mu to a maximum wavelength of about 2,500 mu. Although we are not concerned primarily with the transmission of the visible parts of the spectrum in this report, the curves are presented in their entirety for the purpose of completeness.

Figure 7 presents curves for corneal transmittance. Curves of specific eyes are presented in order to illustrate the effect of age on transmittance. As the authors note, the cornea ".... transmits radiation from 300 mu in the ultraviolet to 2,500 mu in the infrared. The total transmittance increases rapidly from 300 mu and reaches about 80% at 380 mu, and from 500 mu to 1,300 mu is greater than 90%. Beyond 1,300 mu, two absorption bands of water appear (1,430 and 1,950 mu) but the transmission between the bands remains high" (11).

The total transmittance curve is representative of six eyes, while the two direct transmittance curves shown represent (1) the best transmittance observed and (2) the average of eight eyes. As indicated on Figure 7, the maximum transmittance of the direct measurements is at 1,100 mu. Boettner and Wolter point out that the cornea is the only ocular component having its maximum transmittance this far into the infrared.

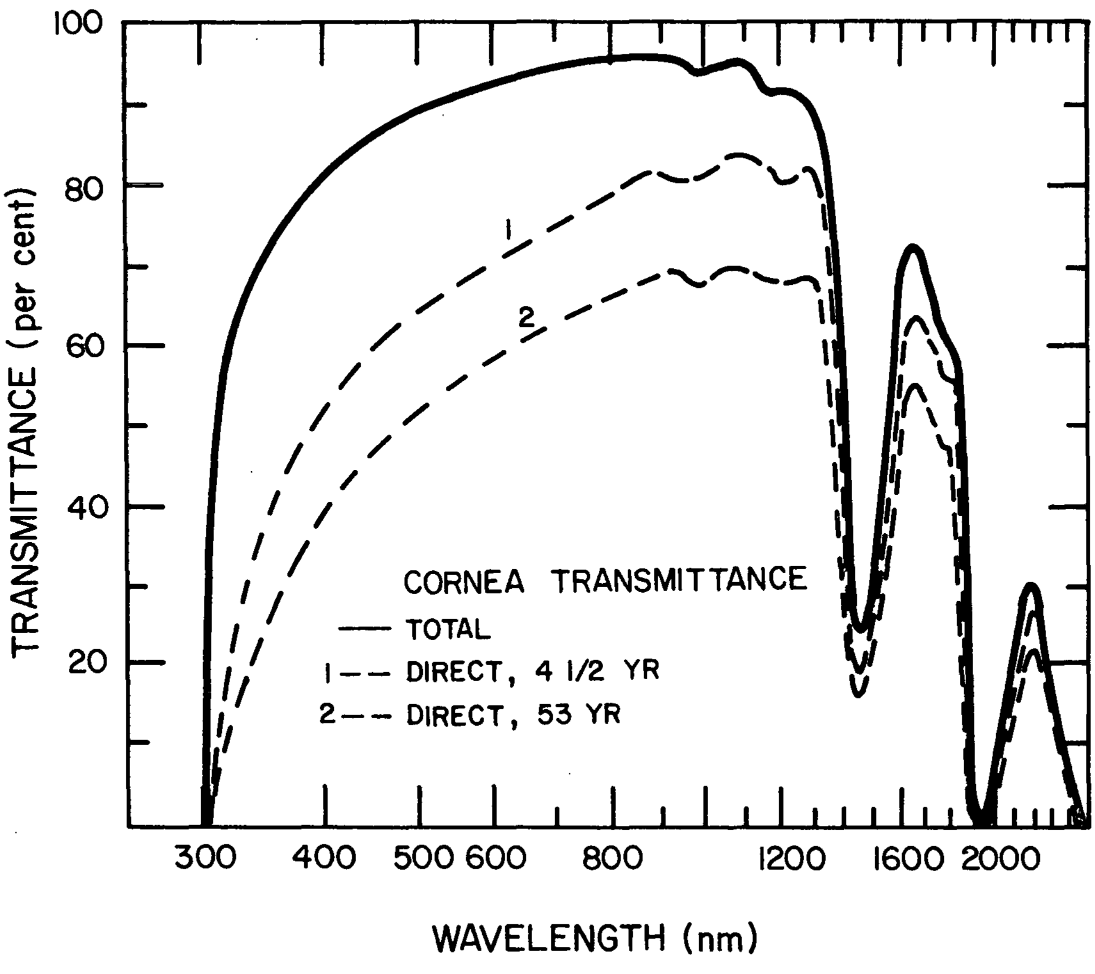
Figure 8 shows the transmittance curves for aqueous humor. Through the visible range the transmittance is high, being only slightly less than an equal thickness of water, while transmission in the infrared is decreased by water absorption band at 980, 1,200, 1,430 and 1,950 mu. The transmittance at 2,200 mu is only 0.1% and beyond 2,200 mu the absorption is complete. No age differences were found for the aqueous and virtually no evidence of a scattering phenomenon was found.

Lens transmittance is shown in Figure 9 and the marked differences according to age of the lens is indicated. In general, lens transmittance begins to increase rapidly at about 390 mu (with the rate of increase varying with the age of the lens), and maintains a fairly high transmission through the near infrared to about 1,400 mu but exhibiting the typical water absorption bands at 980, 1,200 and 1,430 mu.

Vitreous transmission is shown in Figure 10. Although total transmittance in the visible range is greater than 90%, transmittance drops rapidly in the infrared with complete absorption occurring beyond 1,400 mu.

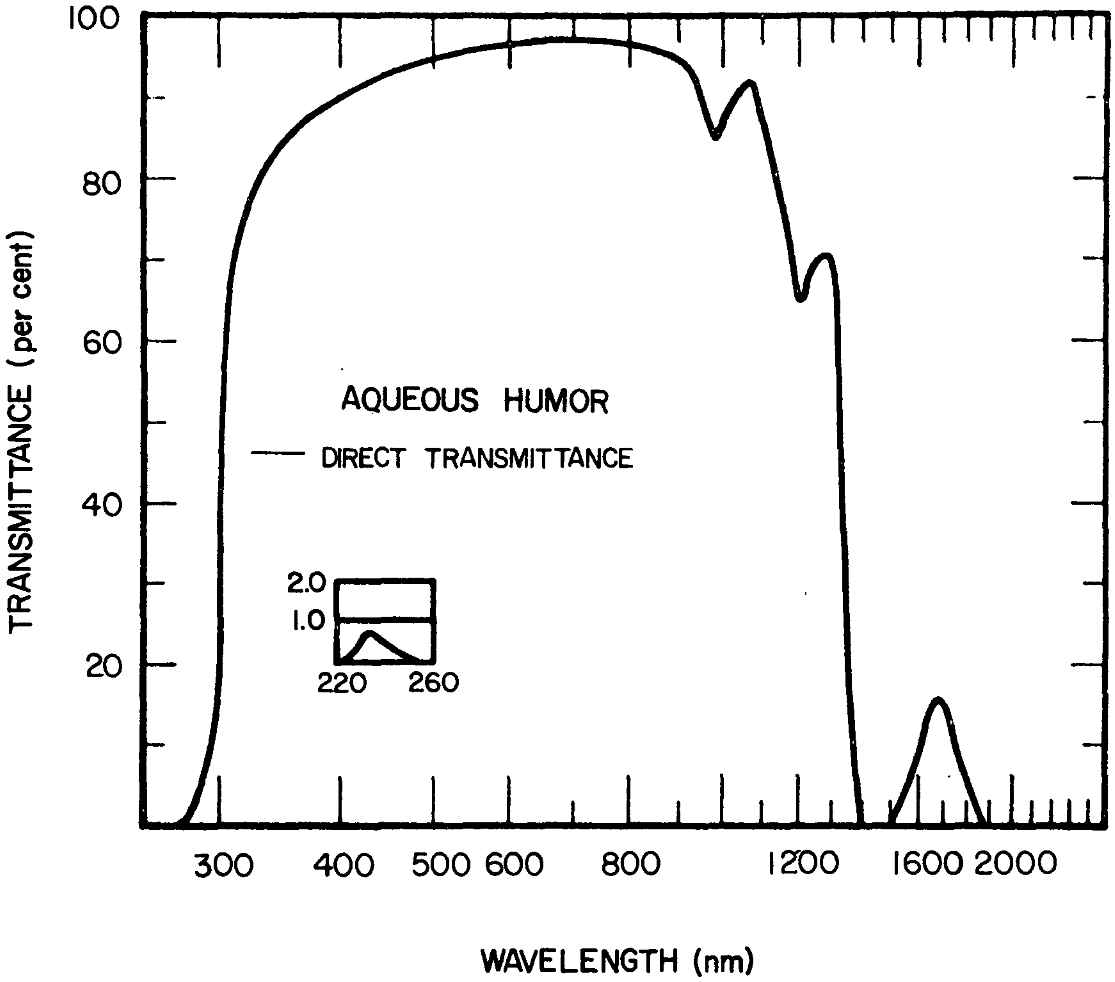
Utilizing the data gathered for separate ocular components, the successive transmission for radiation passing through the whole eye were computed and are shown in Figures 11 and 12. The authors calculated

Figure 7* - Transmittance of the cornea.



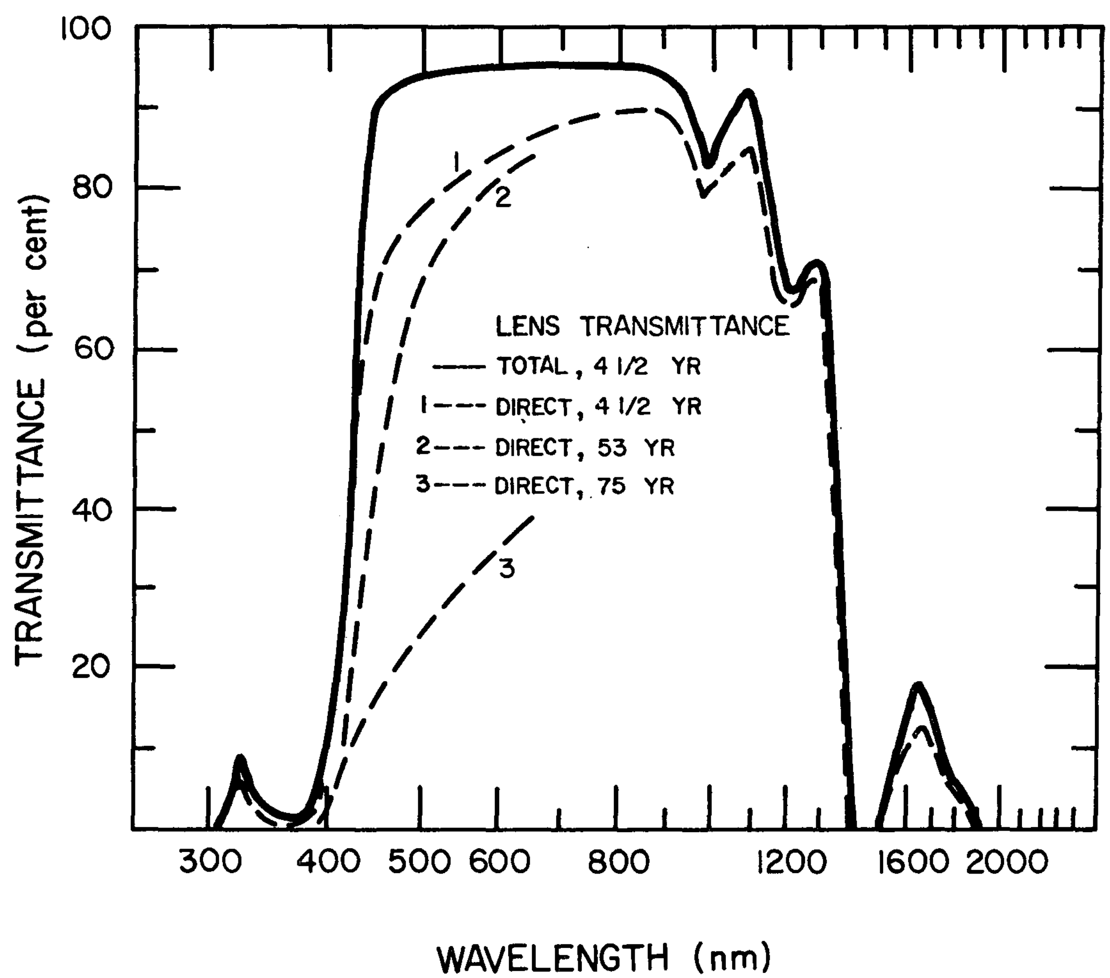
*From Boettner, E.A. and J. R. Wolter, (11).

Figure 8* - Transmittance of the aqueous.



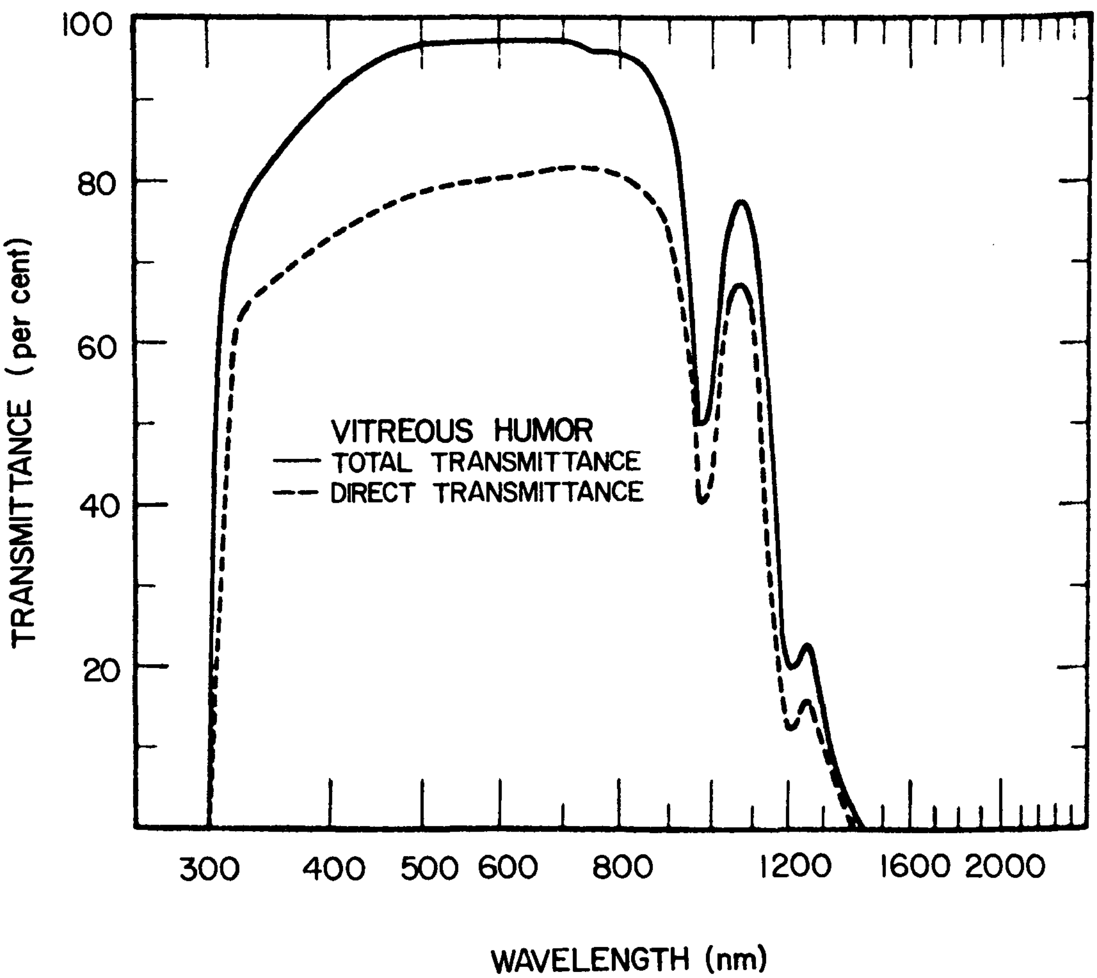
*From Boettner, E.A. and J.R. Wolter, (11).

Figure 9* - Transmittance of the lens.



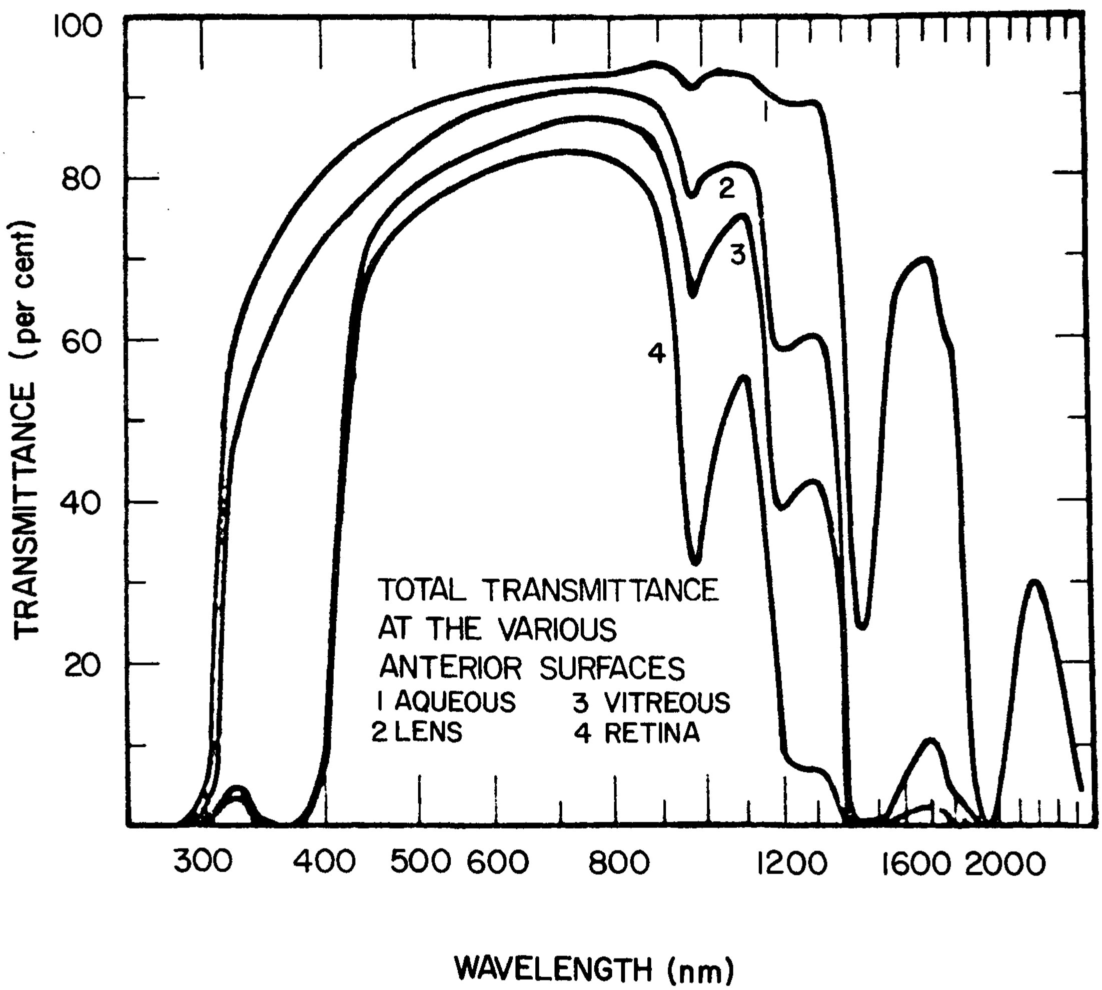
*From Boettner, E.A. and J.R. Wolter, (11).

Figure 10* - Transmittance of the vitreous.



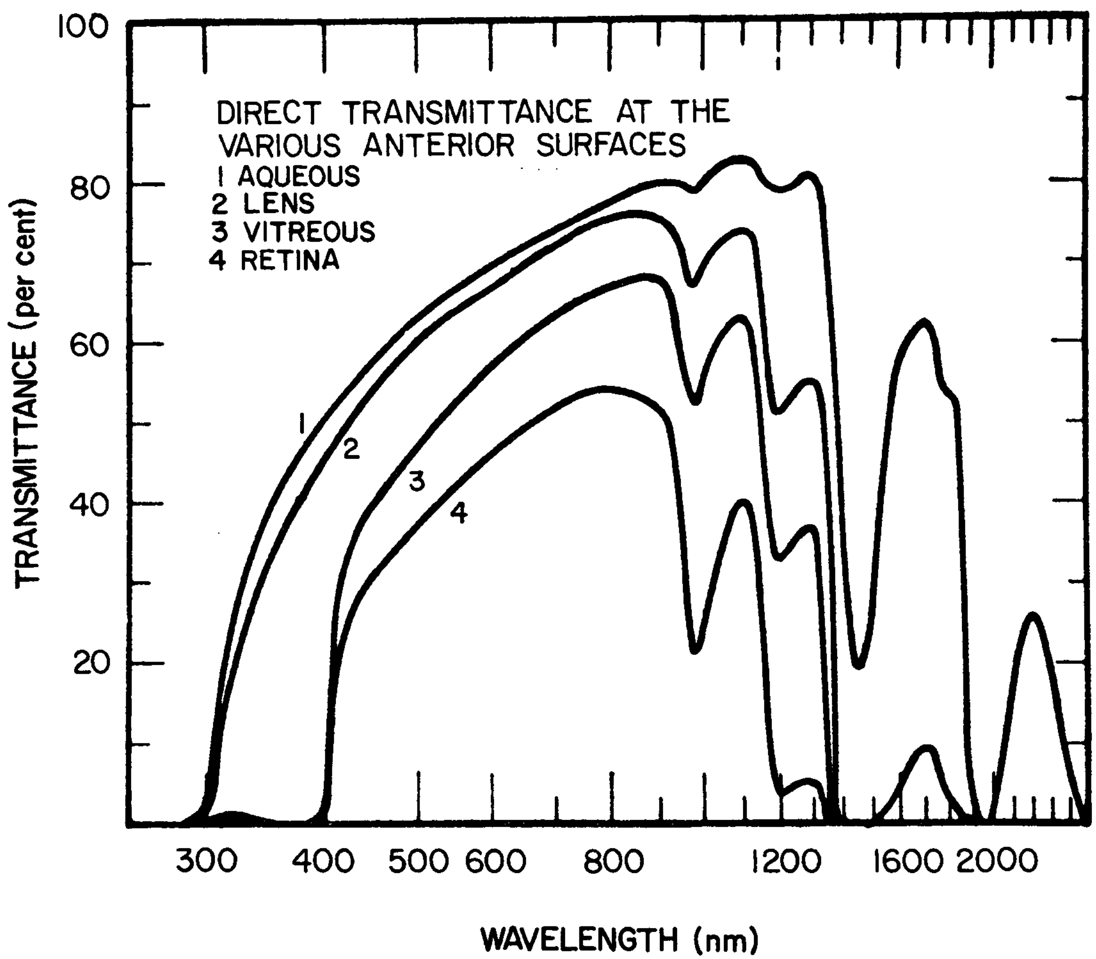
*From Boettner, E.A. and J.R. Wolter, (11).

Figure 11* - Total transmittance through entire eye.



*From Boettner, E.A. and J.R. Wolter, (11).

Figure 12* - Direct transmittance through entire eye.



*From Boettner, E.A. and J.R. Wolter, (11).

that the maximum transmittance through an entire eye is 83.5%. They further point out that,

> "It is evident that the amount of scattered radiation through the young whole eye, represented by the difference between curve four in Figure 11 and in Figure 12, decreases with wavelength, from about 55% at 450 mu in the visible to 30% in the infrared. Generally the scattering in the older eye starts at a higher figure (70% or more) in the visible, but proceeds at a more rapid rate of decrease into the infrared" (11).

Boettner and Wolter also looked at the effect of time after enucleation upon the validity of their measurements. While noting that any transmission change occurring within the first 15 minutes after removing the eye would not have been measured by their techniques, since the first readings were made at 15 minutes or more after enucleation, three monkey and two human eyes were studied. With the exception of an alteration in one absorption band in the ultraviolet, no changes in transmission were measured during the testing periods which extended from 15 to 210 minutes after enucleation.

In a study similar to that of Geeraets et al., (38) previously mentioned, Prince reported studies of the measurement of radiation absorption in the retina and choroid of the human eye (79). The experimental design called for absorption measurements of the healthy retina and choroid at intervals of 10 mu in a range from 340 to 1,650 mu. Evaluated as an integral part of the study were the effects of delayed post-mortem enucleation, preservation of an eye in saline, by refrigeration, or variations according to the amount of blood retained within the choroidal-retinal vascular systems.

Prince's studies were initially performed on rabbits to develop the technique necessary for adequately examining human eyes. Based upon the rabbit studies, three pieces of information were gathered which the investigator pointed out as being important considerations when evaluating and interpretating his data on human eyes. These are as follows:

> "1. Leaving the eye in the head after death will probably result in dehydration enough to reduce the absorption curve significantly in most areas. For this reason the absorption will appear to be lower than it should be, and any relating of the results to a real life situation will therefore have to take this into consideration.
>
> "2. Blood drainage from the eye will have a similar effect in lowering the absorption curve.
>
> "3. Transportation of the eye in saline for any period will

increase the water content of the eye, and therefore raise the absorption curve, especially in specific areas. An element of distortion enters into this also by reason of further removal of residual blood by solvency in the saline." (79).

Figure 13 shows the absorption curves obtained from the choroids and retinas in four human eyes, one of which was obtained from the head of a cadaver kept at 39°F. for 72 hours. The distortion of this curve when compared to the other curves of Figure 13 is obvious. The other three absorption curves on this figure are from eyes with different degrees of pigmentation - a light nordic, a dark nordic and a negro. As Prince points out,

> "The outstanding feature of these three curves is the manner in which the pigment, as it increases in density, obscures the characteristics of water and blood which can be discerned in lighter human eyes. In the curve of the blue-grey nordic eye for instance, the high water absorption peak at 1,500 mu is clearly visible, but in that of the darker nordic eye it is only faintly obvious because of the relatively high level of the rest of the curve. In the negro eye there is no trace of it." (79).

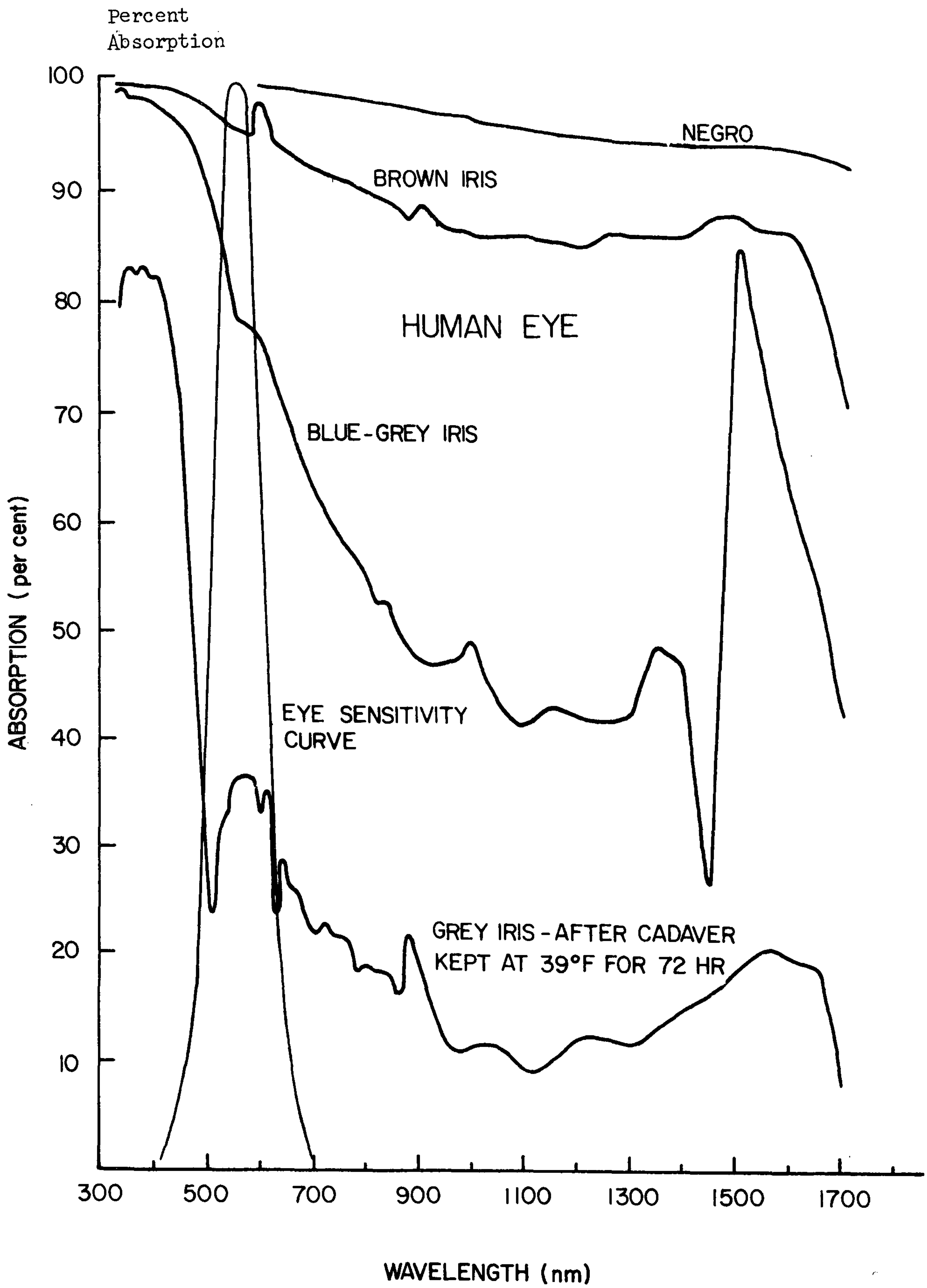
Prince's findings have received concurrence in a more recent paper by Bredemeyer et al. (13).

> "When the retina and choroid alone are measured within the range of 340 to 1,650 mu, the areas of greatest absorption are from 340 to 700 mu and from 1,400 to 1,600 mu in eyes with light colored irides. Eyes with brown irides show greater absorption at all wavelengths, but still with somewhat more at 340 to 700 mu, while negro eyes show absorption of more than 92% at all wavelengths within the range, with virtually 100% absorption up to 700 mu. The data shown for direct measurements of the retina and choroid would be affected ordinarily by the absorption properties of the eye media anterior to these membranes. Such absorption properties are closely similar to those of water." (79).

Figure 14 is a curve which represents the average retinal and choroidal absorption data from a number of eyes without regard to pigmentation. Comparison of this curve and the separate curves in Figure 13 indicates that such an "average" curve bears no close relationship to any of the curves for individual eyes.

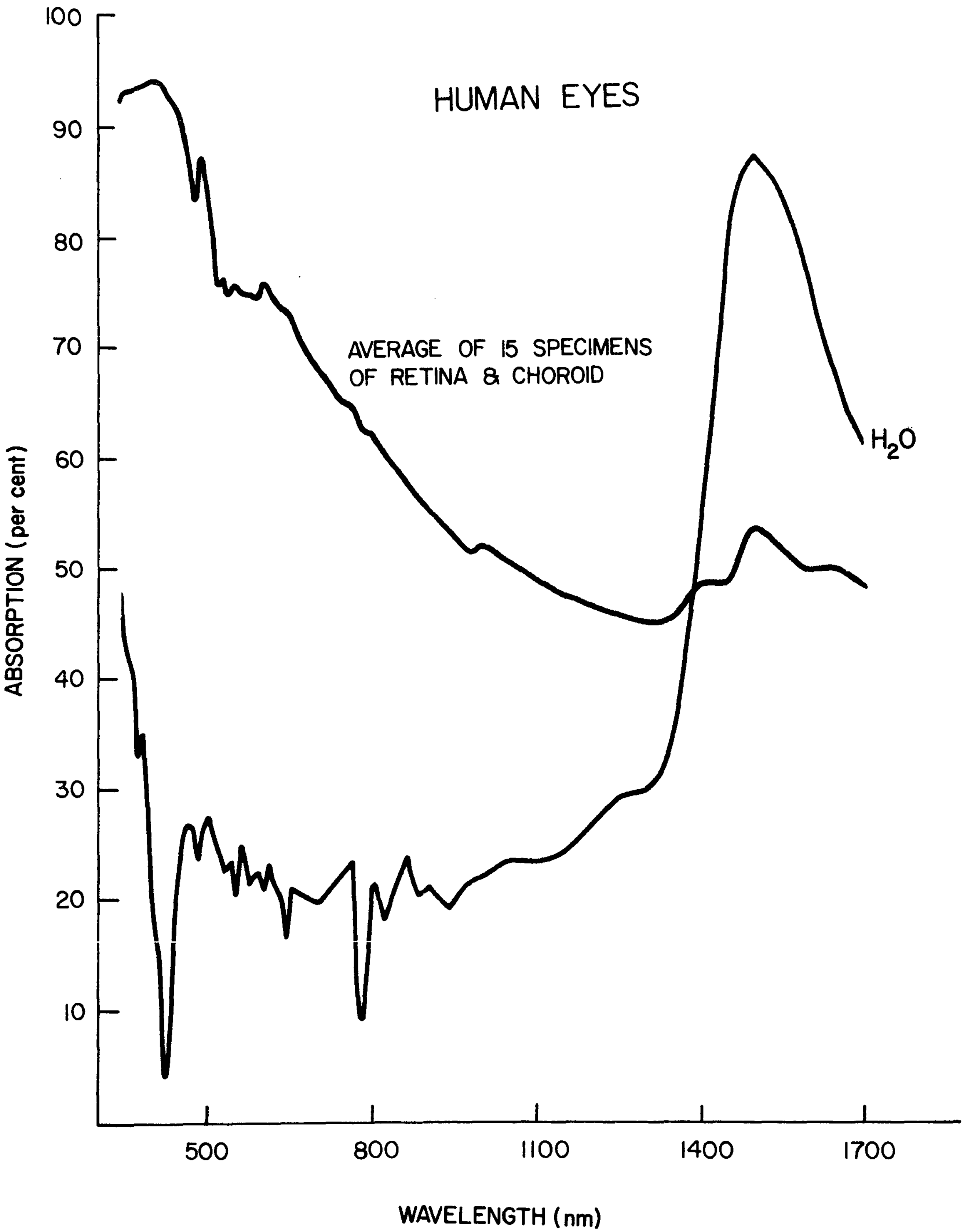
A somewhat different approach to determining the interaction of infrared radiation with the ocular structures is contained in the summary report by Walraven and Leebeek (95). Although the authors do not so state, it appears, from their discussion, that they are reporting

Figure 13*



*From Prince, J. H., (79).

Figure 14*



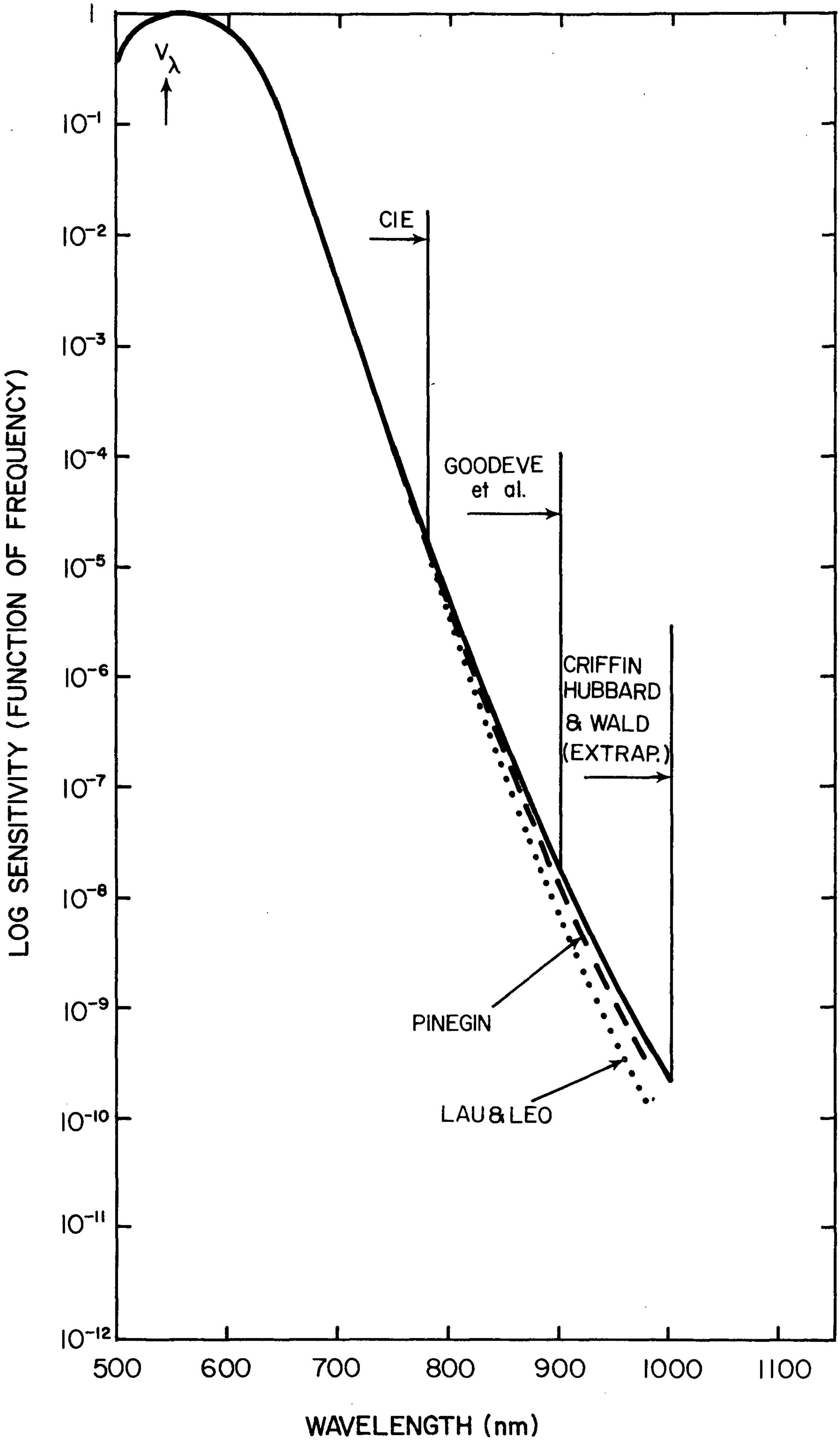
*From Prince, J.H., (79).

the foveal sensitivity of the human eye in the near infrared as measured by dynamic testing. Two figures are presented. The first, Figure 15, represents a compilation of the findings of several investigators. Walraven and Leebeek point out, however, that in these calculations and theoretical considerations, no attention has been paid to ocular structures in front of the fovea. These authors make a calculation allowing for the specific absorption bands of water - pointing out that the transmitting eye media consist of water, primarily. The curve which includes this correction is shown in Figure 16.

Studies relating specifically to corneal transmittance have been recently reported by Dawson (58). The investigations reported has the primary purpose of examining the likelihood of ocular damage by studying the sensitivity of the cornea for warmth using infrared radiation as a stimulus. The study is well done and appropriate sections will be discussed in other parts of this report. In the area of ocular transmission and/or absorption, however, it is worthwhile to call attention to Dawson's studies of measurements of the transmittance of the cornea. These findings are shown in Figure 17. The entire range studied is left on the figure for completeness. It is important to point out the similarity between the figures reported by Dawson and those reported by earlier investigators, previously mentioned in this paper. Attention should be directed, also, to the fact that from about 2,650 mu to 3,100 mu, the cornea is opaque, while a slight rise in transmittance is seen beginning at 3,100 mu. Although his studies do not extend to wavelengths longer than 3,100 mu, Dawson suggests that this gradual rise in transmittance at 3,100 mu may indicate the presence of a "window" at 3,500 mu. No studies have been found which either confirm or deny such a "window." It is obvious that consideration need be given to further evaluating this possibility.

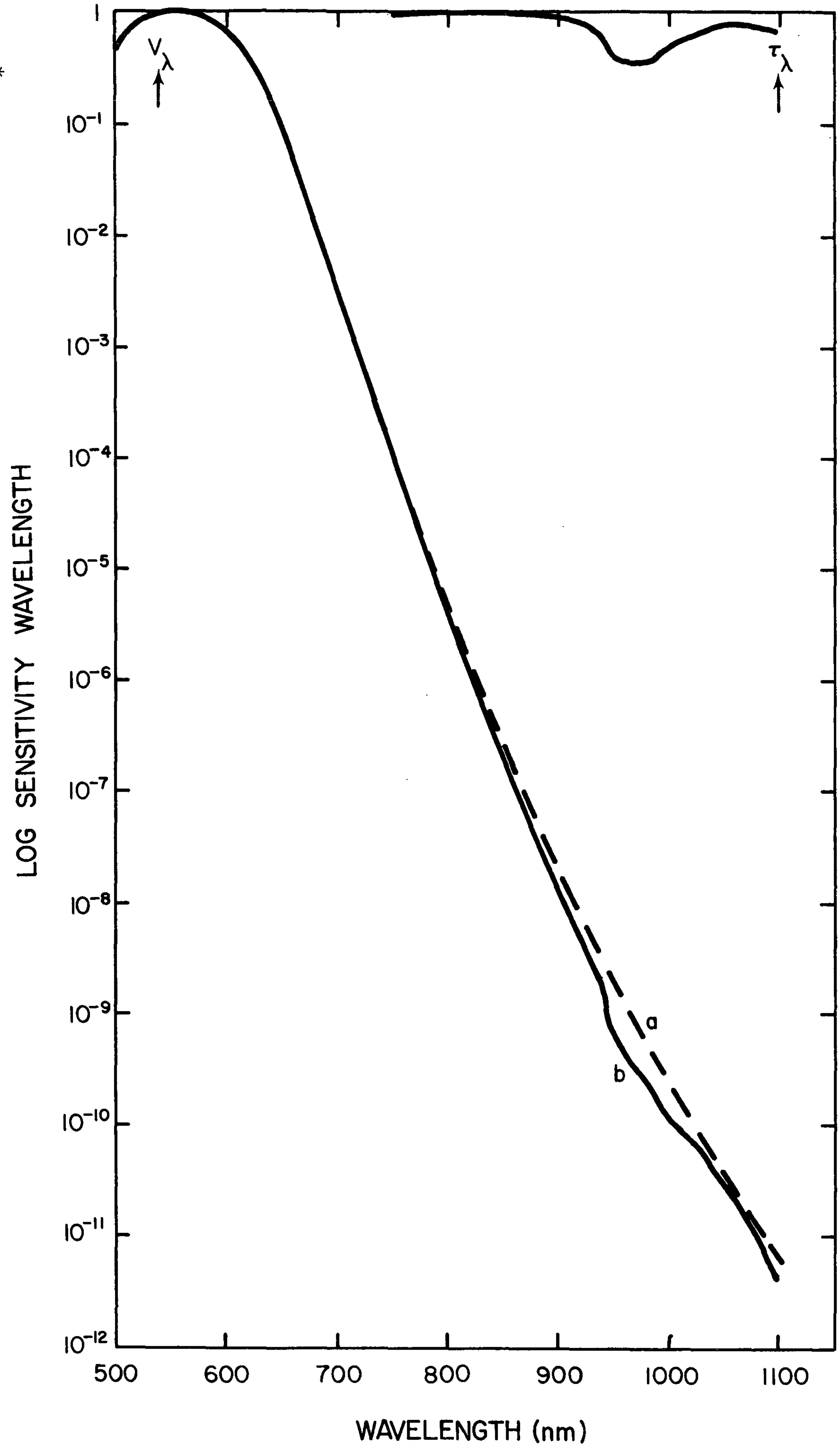
In his studies of the ocular effects from a neodymium laser, it was necessary for Campbell to measure the transmission of electromagnetic energy of various wavelengths by the cornea and lens (15). The results of the measurements on four lenses and three corneas from rabbits were averaged at each wavelength with the results being shown in the curves in Figure 18.

Figure 15*



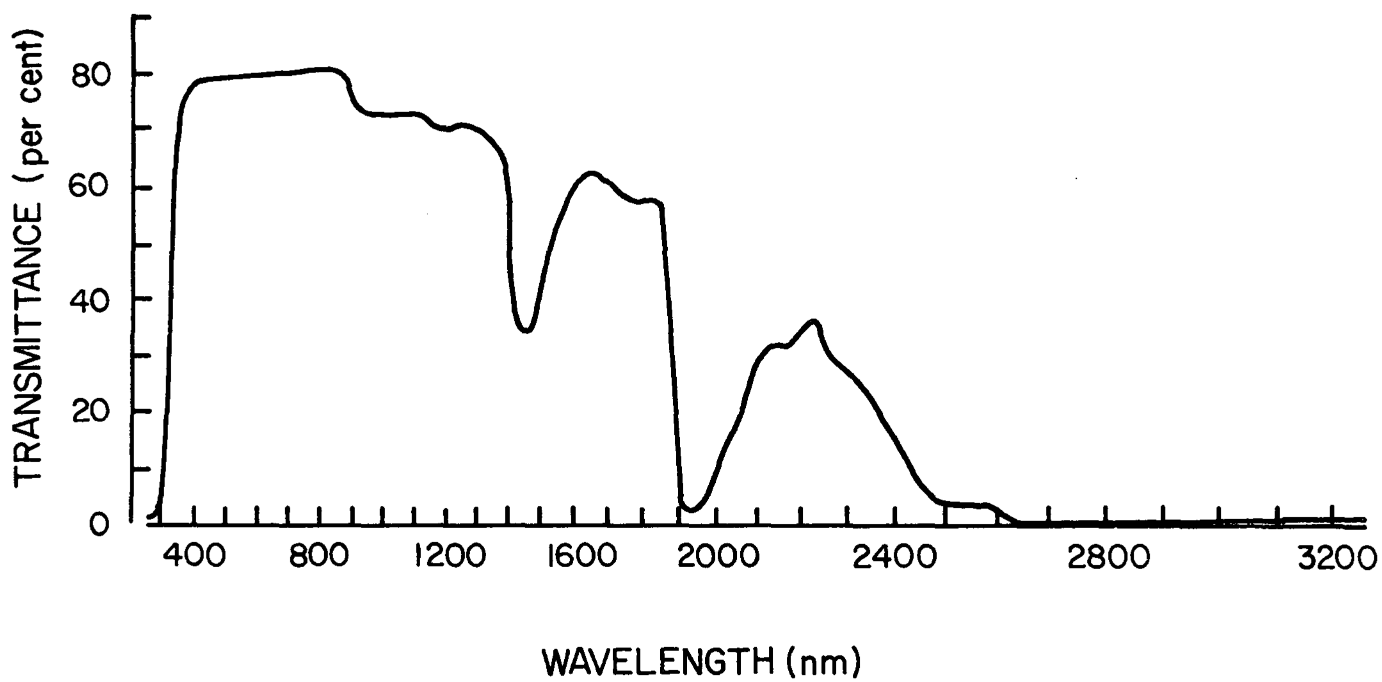
*From Walraven, P.L., and H.J. Leebeek (95).

Figure 16*



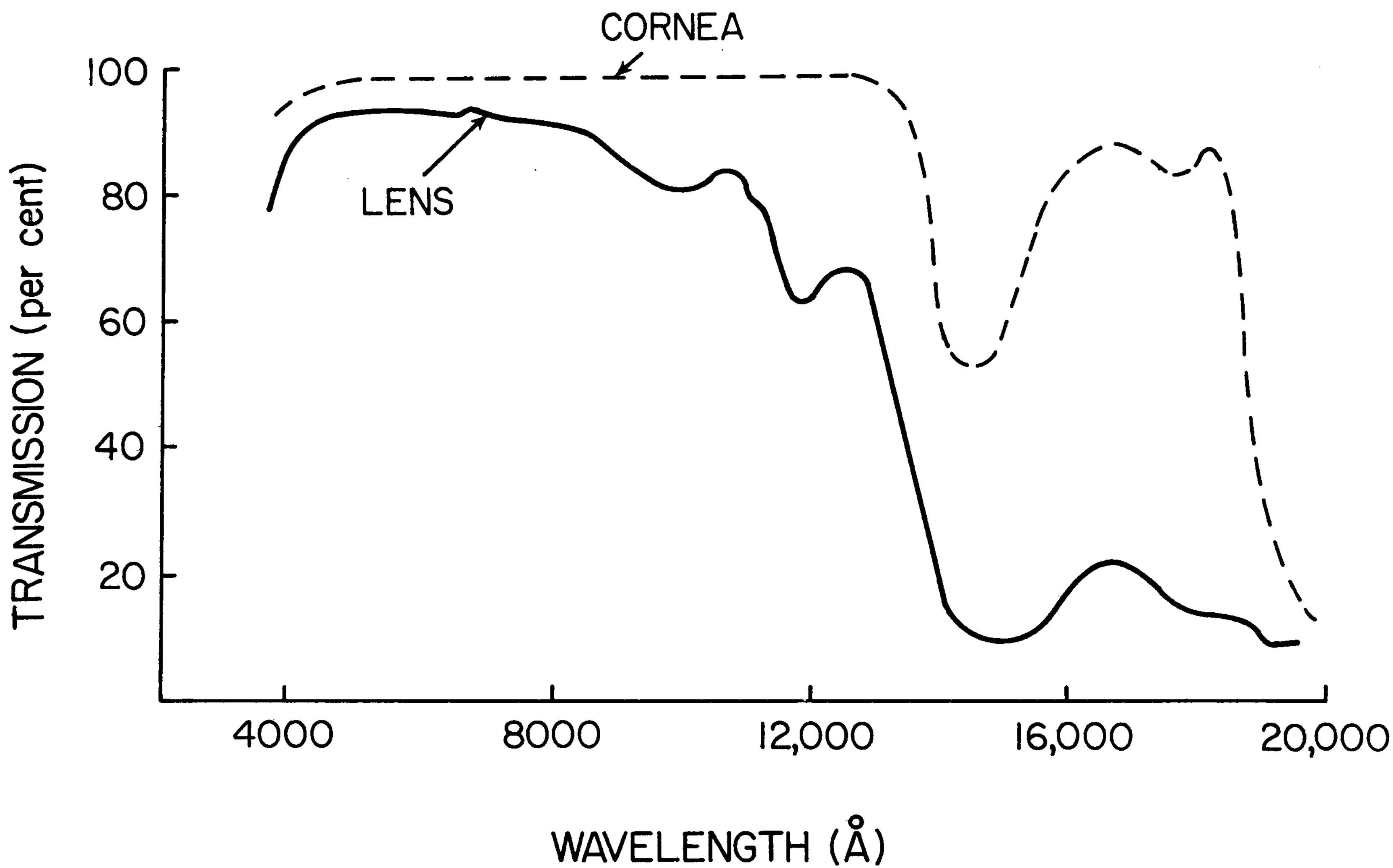
*From Walraven, P.L., and H.J. Leebeek, (95).

Figure 17* - Ultraviolet, visible, and near-infrared difference-transmission spectrum of the cornea of cat.



*From Dawson, W.W. (28)

Figure 18*



*From Campbell, C.J. (15)

PART I: SUMMARY

The multiplicity of approaches and the variables involved with measuring the transmission or absorption of infrared radiation by the eye as a whole or by the individual ocular structures make any concise summary of Part I unrealistic. However, for a reasonably thorough but brief review of the data which seem to be most pertinent, the studies mentioned by Boettner and Wolter on pages 12 through 24, by Prince on pages 24 and 25, and by Geeraets et al., on page 12 cover the problem areas fairly well. The reader with limited time should consult these particular pages.

PART II: THE EFFECTS UPON THE OCULAR STRUCTURES OF THE ABSORPTION OF INFRARED RADIATION

Having presented information relative to how the various ocular structures physically react when exposed to infrared radiation, it is now necessary to examine this information from a more physiological point of view. Specifically, how much infrared radiation of different wavelengths must be absorbed by a tissue for an adverse effect to be produced and, secondly, what are these adverse effects? There would perhaps be some advantage to looking at this problem by beginning at the first tissue in the pathway of the radiation - the cornea - and proceeding along the optical pathway to the retina. Another approach (and the one which we have chosen to follow here) is to deal initially with those structures which have been studied in the greatest detail, proceeding to those tissues which have for one reason or the other received little attention.

The Effects of Infrared Radiation Upon the Lens

From an historical viewpoint, the effects of infrared radiation upon the lens have received much attention. As early as 1739, Heister in his surgical textbook, "Surgical Institutions," suggested a relationship between cataracts and exposure to sunlight (31). This observation was extended by Plenk in 1778, Wathen in 1785 and Wenzel in 1786, the last also noting a relationship between cataracts and those occupations requiring long periods of looking into furnaces (31). Beer in 1799 was perhaps the first to suggest that the cause of cataracts in these laborers was due to heat, rather than light (31). In his 1830 textbook of diseases of the eye, MacKenzie, in discussing the predisposing causes of cataract, says, "Those who are exposed to strong fires, as glass-blowers, forgemen, cooks, laundresses, etc., are supposed to be more frequently than others, the subjects of this disease," (66, p. 710). Meyhofer, finding 42 cases of cataracts among 442 glassworkers under age 40 and 17 among 64 over age 40, was probably the first to study the condition carefully and to discribe the typical posterior cortical opacity which it is now generally acknowledged characterizes the early stages of the cataract (71). These findings received support by Hirschbert who pointed out that cataract formation can occur when the lens is exposed to heat and that the opacity begins in the posterior layer of the lens cortex, this being the most sensitive (52). He further observed that the effect was slow and that cataract development could require months to years.

In the early part of the century, many authors continued to point out the relationship between certain types of cataracts and occupations requiring exposure to heat. Excellent examples of these reports are found in the studies of Robinson (81, 82). In his first report, Robinson made several pertinent observations, noting that both eyes are practically always affected, that the disease begins early in life and progresses slowly and that typically the cataract begins at the posterior pole. Robinson initially believed that the heat and light of furnaces was the etiology of the cataract, although by the time of his second report, he suspected more strongly that heat alone was the responsible agent.

In 1907, Legge confirmed the prevalence of cataracts in glassblowers and it was this report which was most instrumental in establishing the condition legally as an occupational disease (77). (Later studies by Cridland (24), Healy (51), and Roberts (80), pointed out the occurrence of glassblowers' cataracts in workers of other occupations, but who were also exposed to large amounts of heat radiation.) Even by this time, however, there was not universal agreement upon the specific etiological agent causing such cataracts. For example, Schanz and Stockhausen, in 1910, while acknowledging the relationship between the disease and exposure, to furnaces, stated that they believed the specific causal agent to be the ultraviolet radiation from the furnace (87). In reviewing his own work and that of others, Robinson stated unequivocally in 1915 that infrared radiation was the cause of the "heat cataract" (83). Verhoeff and Bell (91) agreed with this concept and went one step further in trying to explain the action of infrared. They pointed out that although the cornea and anterior lens absorbed infrared radiation, the cornea was air cooled and the anterior lens was cooled by the circulating aqueous, such that prolonged heating of either of these surfaces did not occur. However, they noted that the fibrillated structure of the vitreous at the rear of the lens effectively prevented convective currents so that cooling could not easily occur. Nonetheless, Verhoeff and Bell felt that this explanation was not adequate to totally explain heat cataracts and further suggested that the most likely explanation seemed to relate to the possibility that the heat interfered with the normal function of the ciliary body, thereby interfering with the normal "nutrition" of the lens.

Undoubtedly the most detailed studies of the specific mode of action of infrared radiation with the lens came from the controversy between A. Vogt and H. Goldmann. Vogt believed that the cataract was due to the direct absorption of the radiant energy by the lens (93). He considered that the lens absorbed the shorter infrared rays preferentially and that the posterior location of the lesion could be explained by the greater concentration of the radiation at this location because of refraction and reflection from the posterior surface of the lens. Goldmann, on the other hand, presenting many studies during a time period, from about 1930 to 1933, (40, 41, 42, 43, 44, 45), and finally reviewing and summarizing the controversy in 1950 (46), stated that the pathological effect of infrared radiation was not due to direct absorption by the lens. Rather, he believed the effect to be an indirect one, mainly by raising the lens temperature through heat absorbed from the iris. As Duke-Elder points out, perhaps Goldmann's most convincing argument in favor of his view is his demonstration that if a small portion of the iris of a rabbit is irradiated with infrared for 100 hours, but such as never to raise the temperature of the posterior chamber more than 7°C, an opacity in the posterior cortex develops which is limited to that part of the lens corresponding to the irradiated segment of the iris (31). Duke-Elder further states that:

"It would seem reasonable to suppose that the posterior cortical opacity represented products of degeneration in the posterior portions of lenticular fibres, the anterior extremities of which had been damaged by the radiation. This is evidence difficult to confute; and it would seem to exclude any suggestion that the delayed cataract is complicated in nature or is due to an impairment of the oxidative metabolism of the lens or a disturbance of nutrition," (31, p. 6484).

Goldman's work received strong support by the investigations of Bakker who stated, based upon the results of his studies, that no significant specific absorption of infrared radiation by the lens occurred (4), and that the iris is responsible for absorbing heat, only secondarily heating the lens (5).

Despite the excellent studies of Goldmann, Bakker and others, there was by 1950 still not general agreement as to the mechanism of the production of "heat cataracts" as reviewed in the paper by Kutscher in 1946 (58), and in an article by Cogan in 1950 (2). The latter author, however, apparently came later to agree in general with Goldmann's findings and stated in 1959, "the cataracts may be due in part to energy absorbed directly by the lens but [sic] is more probably due to energy absorbed by the pigment of the iris and secondarily transmitted to the lens," (21, p. 294).

Wright suspected that the high incidence of posterior cortical cataracts noted in natives of India might be explained by exposure to excessive solar infrared radiation. He was not, however, able to demonstrate such a cause-effect relationship (97).

In 1950, Dunn made certain investigations of his own into the relationship between exposure to infrared radiation and the development of cataracts (33). His comments were added to by those of Keatinge et al. (55) and briefly reiterated by Barron (6). These studies represent about the only recent reports which seriously question the cause-effect relationship in the production of "heat cataracts" and/or their occurence in certain types of workers. Dunn presents the experiences of one company in which workers have been exposed "to extremely intense infrared radiation for many years... with negative results as regards ocular disturbances," (32, p. 180). He further notes that, "the high incidence of cataract that inspired the early studies of British workers cannot be disregarded; so it is suggested that possibly the fundamental causative agent was not discovered at that time," (32). Dunn carries his comments one step further when stating:

"It is suggested, in view of the experience reported, that it might be advantageous in other trades and exposures to review the earlier works on various occupational diseases, with a view to re-evaluating some of the present-day occupations. While factors of safety are

are most certainly desirable, it does not seem that industrial hygienists can be commended, even when guided by the highest humanitarian urge, for imposing undue financial loads on industry to provide corrective measures for a nonexistent disease or a disease of extremely low incidence," (32, ibid.).

Keatinge et al., reviewing many studies including those of Dunn (just mentioned) and of Coates and Keatinge (19), make several conclusions. They state that opacities in the posterior capsule and even in the posterior cortex of the lens do not seem to be specific to those exposed to a high intensity of infrared radiation. They note further that only a small proportion of workers exposed to the risk of infrared radiation develop radiation cataracts and that the incidence of the condition appears to be falling considerably. The authors report posterior capsular changes as relatively common in young men who "may have not experienced any undue degree of infrared radiation, and it seems plain that posterior capsular changes are not necessarily the result of exposure to high levels of radiation," (55, p. 312). Further, it is pointed out that there is evidence that other types of electromagnetic radiation than infrared radiation can produce posterior cataracts, referring as an example to the reports of Cogan, Donaldson and Reese (22). It should be noted that the workers examined and reported in this study by Keatinge et al., are metal workers - not glassblowers. This latter point may be important in explaining some of the confusion when the comments and findings of Barthelmess and Borneff are considered (7). These authors take note of the greater incidence of lens damage in glassblowers as compared with metal workers. They note also that the "pure" radiation load in the metal industry is greater than in glassworking, measuring the daily dose of radiation of glassblowers working near melting furnaces to be 2,000 to 3,000 watt/sec/cm^2 of which about 10% is infrared radiation of wavelengths smaller than 1,400 mu. (12). The radiation load of metal workers is found to be consistently higher than this exposure level. However, in spite of the greater radiation "load" in the metal industry, the authors believe that there is less effect on the lens since the low temperatures in the metal industries favor the convection away of the absorbed radiation heat.

An excellent study which attempts to clear up some of the differences between the work of Goldmann and Vogt (previously mentioned) is that reported by Langley et al. (59). These investigators summarize their understanding of the points of contention between Vogt and Goldmann as follows:

> "He (Vogt) did transmission studies of the structures in the anterior segment ... for infrared rays ... tested the various wavelengths for their ability to produce cataracts ... noted other changes which occurred in the neighboring tissues. He came to the conclusion that the cataract was due to a rise in temperature of the lens," (59, p. 476).

Vogt, however, felt the temperature rise was due to a specific absorption of certain wavelengths of infrared radiation. As Langley et al., continue, however, Goldmann

> "felt that the transmission of the cornea, the aqueous, and the lens to light and near infrared was moderate and that not enough would be absorbed to account for the changes which took place in the eye. Also, he felt that light striking the iris was almost completely absorbed at its posterior surface, that is at the pigmented epithelium, where it was converted to heat,"

and transmitted to the lens (59, p. 476). Langely et al. designed their investigation to further evaluate this difference of opinion, attempting to produce cataracts in rabbits by one exposure of the iris to heat radiation. The heat source was a 100-watt zirconium arc lamp which was focused to give an image of 6.75 mm^2. The thermal output of the lamp applied at the point of focus equaled 2.2 $Cal/mm^2/minute$ or 220 $Cal/cm^2/minute$. This beam was focused at a single point on the iris of the experimental eye. Based upon their studies, the investigators made several observations. It was found sufficient to irradiate only the iris of a rabbit to produce an opacity in the lens. Also, it was believed to be the local elevation of temperature at the anterior surface of the lens which causes the cataract, rather than the total amount of heat applied to the total eye. The authors state, "Our findings confirm Goldmann's view that the light and infrared rays are absorbed at the pigment epithelium of the lens, and that cataract develops later as a result of this epithelial damage," (59, p. 487). The authors also point out that with their heat source and with all exposures being for 30 seconds, the latent period for the development of a cataract can be considered as being between 60 and 90 days, by which time 70% of their subjects' eyes had cataracts. Langley et al. note, however, that "We see no reason to doubt that with different dosages the latent period would vary, as described by Goldmann," (59, p. 487).

Quite similar studies were more recently performed by Bernat and Hryniewiecki (9), who found results in agreement with those of Langley et al. The former, in addition, observed an increase of the weight of the lens affected with the cataract and a decrease of the total quantity of hydrosoluble protein.

In spite of these fairly recent studies just discussed, it should be noted that all investigators are still not in agreement as to the etiology of the heat cataract. For example, in 1961, Neubauer and Krause suggested that Goldmann had not studied infrared of long enough wavelengths and that their investigations did reveal specific absorption bands of infrared by the lens (7). Accordingly, they felt that additional research was necessary to clarify the relationship between infrared radiation and cataract production.

Nonetheless, preponderance of opinion is strongly in favor of Goldmann's thesis and supportive exposure information still appears, such as reported by Maslenitskaia (67) recently from the Russian experience. Merte also points out the general agreement with Goldman's thesis (69), and how it has been applied in extending compensations obligations to workers other than glassblowers with "heat" cataracts.

One final paper examining the relationship between infrared radiation and the development of cataracts deserves comment. This is the report of the investigation by Dawson (28), in which he examines the incidence of ocular pathology following infrared radiation applied as a stimulus to the cornea for thermal studies. Using cats as subjects, each animal's left eye was exposed to short infrared rays. The radiation source was a tungsten filament lamp with an integral parabolic reflector, focused so that the incident beam size upon the cornea was 5 mm. The rate of energy output of the lamp was 7.04 gcal/sec/cm^2 and exposure times varied from 15 to 365 seconds. At this energy level, the spectral distribution of the lamp approximates that of a 3,250 K blackbody, having a Gaussian function, slightly skewed towards the long wavelengths and having minima at 400 and 2,600 mu.

Dawson's findings concerning the lens can be summarized briefly as follows: At low dose levels (less than 100 gcal/cm^2) no immediate effect was seen. However, by ten days after the exposure, lens opacities had developed in two of the six rabbits, while two additional rabbits developed in two of the six rabbits, while two additional rabbits developed lens opacities between 60 and 70 days post exposure. With intermediate dose levels (100 to 300 gcal/cm^2) at least three of six eyes showed lens opacities, with the latent period seeming generally to be shorter than with lower energy levels. The development of corneal pathology precluded more specific statements. At high energy levels, (greater than 300 gcal/cm^2) all animals were observed to develop lenticular opacities.

Dawson notes that his findings of relatively long latent periods for the development of cataracts are in agreement with the findings of many other investigators and, further, lend credence to the concept of the long latent period for the development of cataracts in humans exposed to infrared radiation over long periods of time.

The Effects of Infrared Radiation Upon the Retina and Choroid

Although much interest has been focused in modern times upon those non-visual effects of electromagnetic radiation upon the retina, such interest is by no means new. This is particularly the case with concern about the effects of infrared radiation upon the retina and choroid. It is imperative, however, to keep in mind the difficulty in this particular area of heat in separating the effects of infrared radiation from those of visible radiation. As Duke-Elder states so well:

> "Since, however, the greater part of the incident energy in the visible and paravisible regions of the spectrum is abosrbed by the pigmentary layer of the retina and the pigment of the choroid and degraded into heat, any lesion due to this portion of the spectrum may be assumed to be thermal in nature. Such lesions are therefore caused indiscriminately by infra-red or visible light, the reaction being unrelated either quantitatively or qualitatively to any particular wave-length but depending merely on the concentration of energy incident in this region. The differentiation of wave-lengths is therefore of academic interest only but, since much of the concentration of energy at the posterior pole of the eye derived from a source such as the sun is represented by the visible parts of the spectrum, these must bear partial responsibility. It will be remembered that all radiations of this type are subject to optical refraction and are therefore brought to a focus, usually on the macula; the density of energy thus falling on a small region of the retina can be very high and a destructive lesion may thus be produced at this site by radiation which is innocuous to the rest of the eye ..." (31, p. 6491, 6492).

Eclipse blindness appears in literature as ancient as Plato's Phaedo and is repeatedly mentioned through classical times as an apparently common phenomenon. Frequent macular lesions have been reported in members of certain religious cults who practice "sun viewing" while praying (85). The concept of a time-dose relationship in the extent of retinal damage was recognized by Verhoeff and Bell (91). Assuming total solar radiation as being about 10^6 ergs/cm^2/sec, these investigators calculated that with a pupillary diameter of 2 mm, approximately 3% of this energy will enter the eye and 30% should be subtracted for absorption and reflection so that the total energy concentrated in the retinal image will be about 20,000 ergs/sec. Taking the retinal area as about 0.15 mm in diameter the concentration of energy in the image is nearly 113×10^6 ergs/cm^2, more than enough to cause destructive effects.

As early as 1882, Deutschman, noting the production of retinal lesions by sunlight, related the similarity of occurrence of retinal burns from heat in factories to those retinal burns seen from sunlight exposure (30).

Eccles and Flynn, in 1944, using rabbits as experimental animals, found that with 30 seconds exposure to sunlight, an intensity at the retina of 40 $cal/cm^2/min$ produced no damage, while at intensities of over 50 $cal/cm^2/min$ a lesion was commonly produced (33). With intensities of 70 $cal/cm^2/min$ an occasional lesion was produced after ten seconds, a mild lesion typically after 30 seconds and a severe lesion invariably after two minutes. A lesion was produced within a few seconds by levels of 100 $cal/cm^2/min$. Some idea of the intensities of these energy levels may be appreciated when comparing these levels with the unfocused energy of the sun at sea level on a clear day with the sun at the zenith - 1.72 $cal/cm^2/min$ (19).

Cogan, in his 1950 review article of the effects of radiation energy upon the eye notes that the far infrared rays probably cause no damage to the retina, since they are absorbed in the anterior portions of the eye, but that the short infrared rays and the visible rays not only reach the retina but are refracted by the ocular media so that the rays form an intense energy focus (78). He further notes that of the energy reaching the earth from the sun, about 39% is in the visible range and 55% in the infrared, and that differentiation as to which part of the spectrum is primarily responsible for the retinal lesion is, at best, academic.

Damage of the retina by infrared radiation from welding arcs has been reported by Minton (72), who states that the retinal burns so produced are largely due to the short infrared radiation from the arc. Minton does not mention that these lesions may be due in part at least to the visible part of the radiation from the welding arc, this accounting for about 26% of the total energy distribution of the arc, of which about 16% reaches the retina.

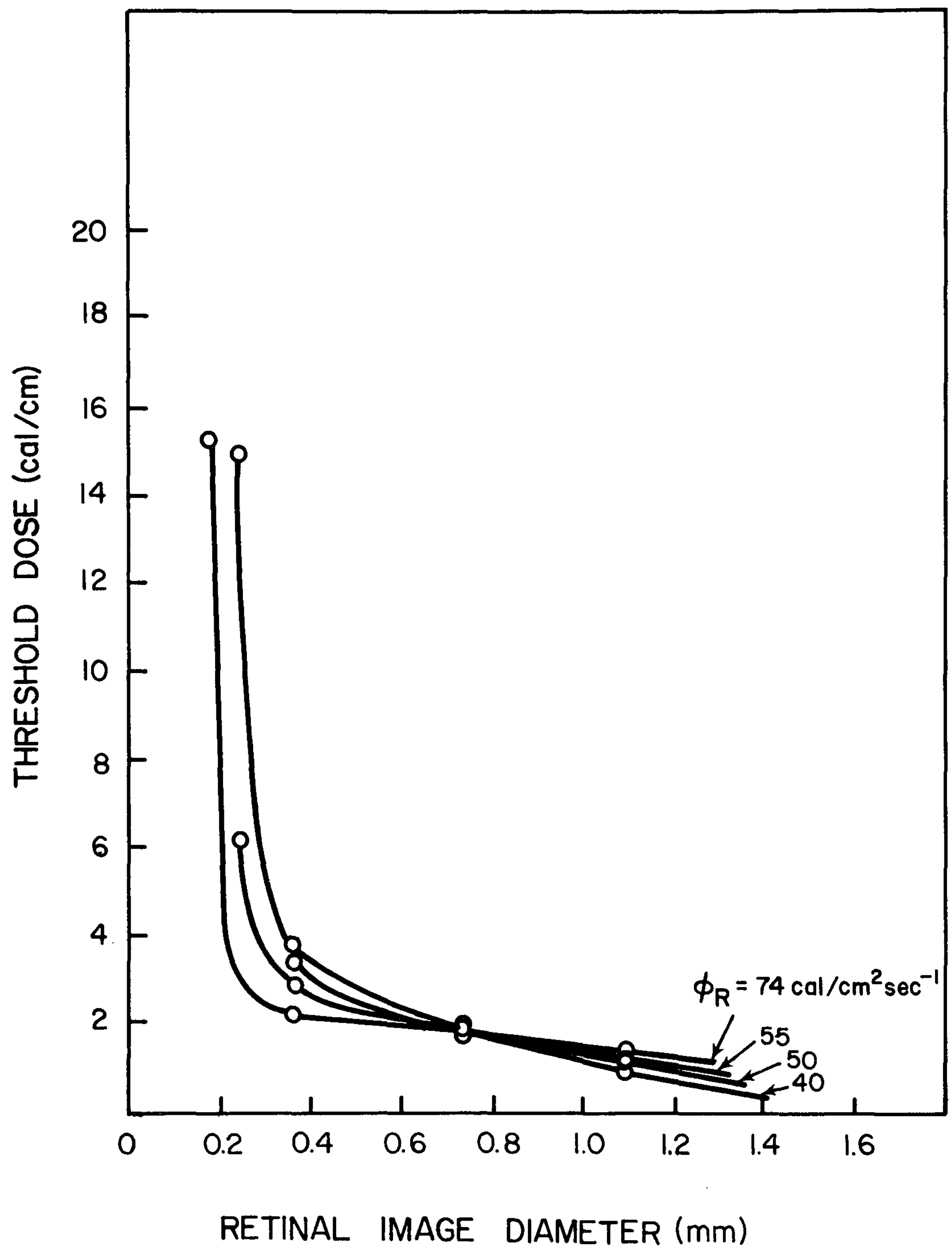
Buettner and Rose pointed out that the greatest ocular danger with exposure to the flash of a nuclear weapon is from the thermal radiation (14). They noted that the image of the fireball, when focused on the retina, has a thermal irradiance which is independent of the "inverse square law" out to distances where the resolution of the eye fails. With an interest in evaluating the retinal hazards from nuclear weaspons, Ham et al. (47), investigated the threshold values of thermal dose required to produce a lesion in the rabbit retina as a function of rate of delivery of thermal energy, pulse shapes and image size. Several important observations resulted from their study. It was determined that the effect of retinal image size is more important than energy pulse shape or rate of energy delivery in producing retinal burns. Further, the size of thermal lesions on the retina was found to depend upon exposure time and it was noted that it is necessary to know the size of the retinal image before thermal dose to the retina can be calculated. Ham et al. also suggested that the dependence of the burn threshold upon image size is a conduction phenomenon which can be best understood in terms of temperature gradients within the retina.

The threshold level was defined as that combination of irradiation rate, exposure time and image size which produced a lesion observable after five minutes observation in 50% of a series of exposures. Using these criteria, the thermal threshold for minimal lesions in the rabbit retina (using Chinchilla gray rabbits with neither extremely light or dark fundi) was found to range from 1 to 15 cal/cm^2, depending upon the image size, the rate of energy delivery and the shape of the energy pulse. However, no major differences in burn threshold were detectable for different pulse shapes within the range of irradiances produced by a high intensity carbon arc, used as the radiant energy source, where the image diameter on the retina was 1.0 mm or greater. Further, Ham et al. note, that their data do indicate that for exposure times of 20 ms or less the burn threshold does not depend upon pulse shape. For small image diameters - e.g., 0.5 mm or less - pulse shape was found to be important for exposure times of 50 ms or more. A failure of reciprocity of time and irradiance levels was noted and investigated at time intervals from 20 to 250 msec and at irradiance levels from 70 cal/cm^2/sec to 12 cal/cm^2/sec respectively. This failure of reciprocity was noted to result, apparently, from the effects of image size upon the retina. This observation is shown, in part, in Figure 19. The investigators report that the effect of spectral quality upon the production of the retinal burns observed was not specifically investigated, but that it seemed likely that the visible spectrum was more effective than the infrared in producing retinal lesions.

The clinical utilization of electromagnetic radiation focused on to the retina at high enough energy levels to produce retinal coagulation has received much attention. Although much of this information is not directly related to this study, some review of certain of these studies are helpful. Meyer-Schwickerath developed a technique for the clinical use of "photocoagulation" as it became called, especially to seal holes in the retina (70). The technique received confirmation by investigators such as McDonald and Light (65), as well as by many others.

DeMott and Davis, in 1959, examined the irradiance thresholds for chorioretinal lesions in several mammals (29). These investigators commented that, "Since the ocular media transmit a relatively narrow spectral band, the source of energy used is not important, as long as its spectral emission covers the range from 0.3 u to 1.3 u," (29, p. 653). The results of their studies are shown graphically in Figure 20. It should be noted that the curve shown is noted as a dual function, with the portion of the curve to the right of 2 cal/cm^2/sec a straight line function with a negative 1 slope, indicating that the radiant exposure necessary to produce a lesion is constant and lies between 0.5 and 1.5 calories per square centimeter. To the left of this value, the curve seems to rapidly approach a vertical asymptote, indicating that a certain minimal level of irradiance is necessary before any exposure time will be effective. The authors thus suggested that apparently an equilibrium is established in slightly more than ten seconds, during which time heat is being removed by the blood supply at the same rate it is being absorbed. Applying these data to humans, the authors suggest that since the human blink reflex occurs with about a

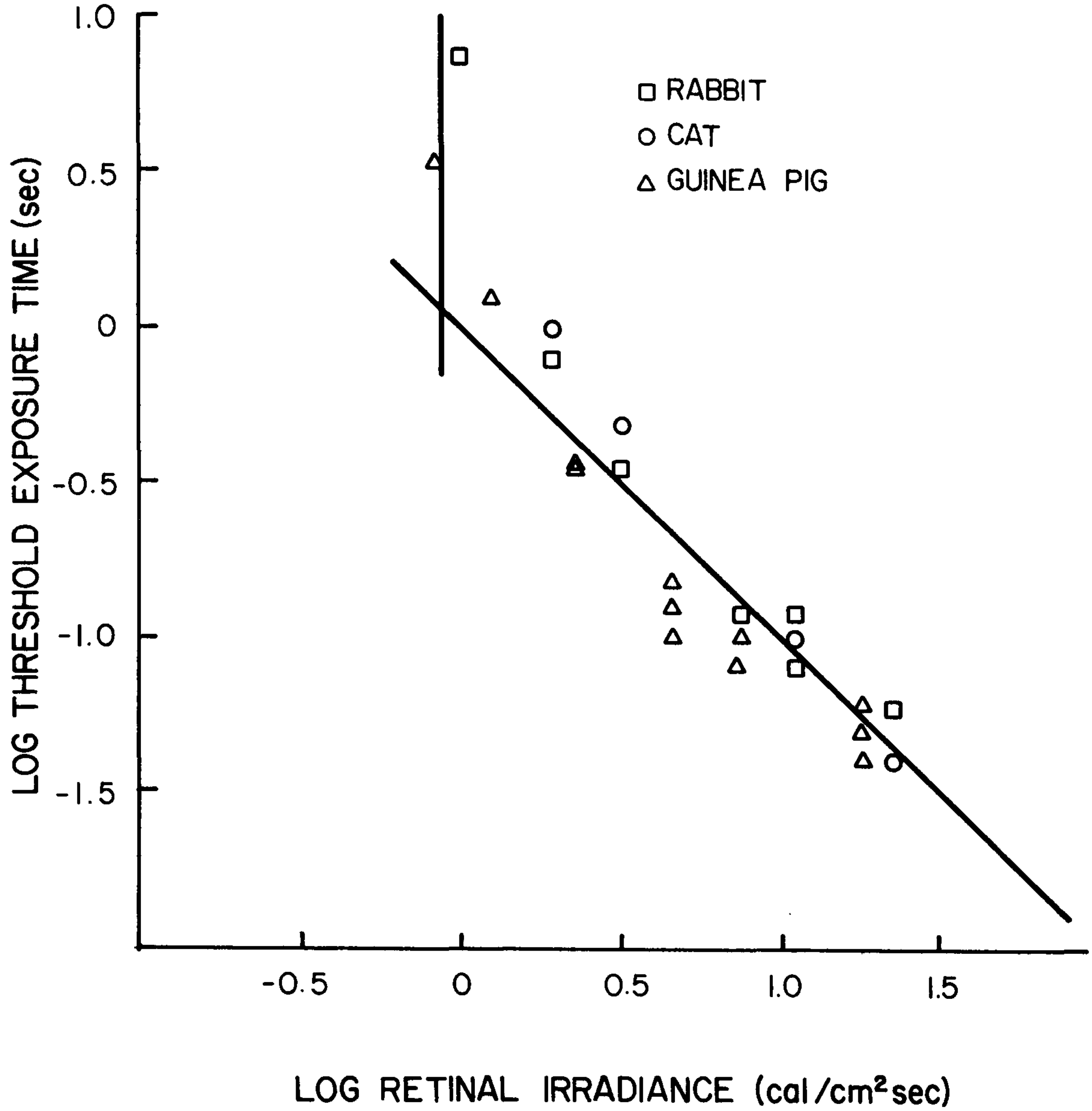
Figure 19* - Threshold dose vs. retinal image size for several retinal irradiances.



*From Ham, W.T., et al, (47).

Figure 20* - Exposure times required to produce a threshold retinal lesion as a function of retinal irradiance. The line of Slope —1 represents a radiant exposure of 1.0 cal. per square centimeter. At irradiance less than 0.7 cal. per square centimeter per second, retinal lesions could not be produced at any exposure time through 10 seconds.

IRRADIANCE THRESHOLDS



*From DeMott, D.W. and T.P. Davis, (29).

0.1" latent period a retinal lesions would probably not occur with a retinal irradiance less than 4 cal/cm^2. Demott and Davis concluded their studies by stating that at irradiance levels greater than 2 cal/cm^2/sec a radiant exposure of 1.0 cal/cm^2 produces a threshold lesion; at irradiance levels less than 0.7 cal/cm^2/sec lesions cannot be produced at any exposure time through 10 seconds. In light of the studies by Ham et al., previously discussed, it should be noted that image sizes were not reported as being precisely controlled in this study.

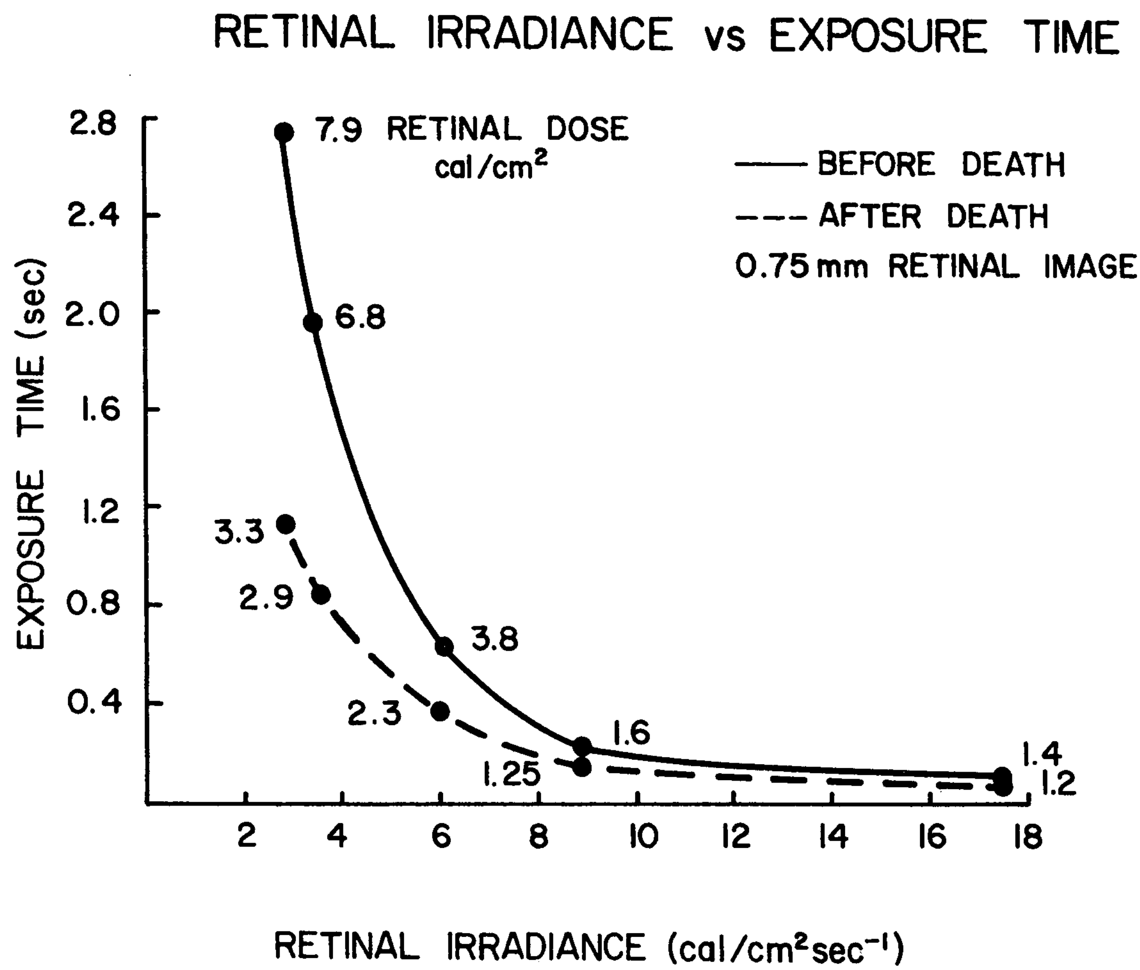
Lieb and Geeraets, reporting in a review article in which no original investigative data are presented, suggest that the energy required to produce retinal damage is about 2 to 4 cal/cm^2, depending upon the pupil diameter, the time of energy application, the pulse shape, etc., (63). They note that, normally, with a glance towards a high radiant energy source such as the sun that the visible light causes a blink reflex so quickly (within 150 msec) that no harm occurs. However, with an eclipse, the visible light may be reduced markedly, the pupil diameter may be large and no blink reflex may occur, thus allowing the persistent infrared radiation to enter the eye at levels as high as 10 cal/cm^2/sec, with a retinal burn resulting.

In a study performed by Jacobson, Cooper and Najac, the retinas of Chinchilla-gray rabbits were exposed to a high intensity light source (53). The ranges of image sizes and exposure times were controlled similarly, but differed from those used by Ham et al. (47). Jacobson's investigations were conducted with image sizes of 0.7, 1.0, 2.0 and 4.0 mm in diameter and exposure periods ranged from about 15 to over 300 ms. Where Jacobson's study overlapped with that of Ham in image size and time exposure, the two experiments are in agreement. However, Jacobson's results from larger image size indicate that the threshold dose increases with increasing retinal image size and it should be recalled that this is the opposite observation of that by Ham for small image sizes (47).

It has been previously suggested in this section that the rate of flow of the blood supply to the retina appears to play some role in determining the threshold for damage. This question was investigated by Geeraets et al. (38), by exposing the eyes of 40 adult rabbits to the energy from a neon light source for periods of approximately 0.1 sec to 3 sec and at various rates of energy application. The retinal image size was kept constant at 0.75 mm in diameter. By exposing rabbits before and after death, it was found that the rate of blood flow significantly increased the lesion threshold. The investigators concluded that, "for exposure times greater than 0.3 seconds, heat loss due to blood flow and tissue conduction increase substantially the amount of energy required to produce a threshold chorioretinal lesion," (38, p. 91). The results of their studies are shown graphically in Figure 21.

To this point, there has been no study presented which examined the relative effectiveness of different spectral frequencies in producing chorioretinal burns. Such a study was performed in 1963 by Bredemeyer

Figure 21* - Influence of rate of blood flow and tissue conductivity on thermal threshold lesions in rabbit fundi. Data before and after death are given for same retinal irradiances at different exposure times, altering the required total retinal dose.



*From Geeraets, W. J., et al, (38).

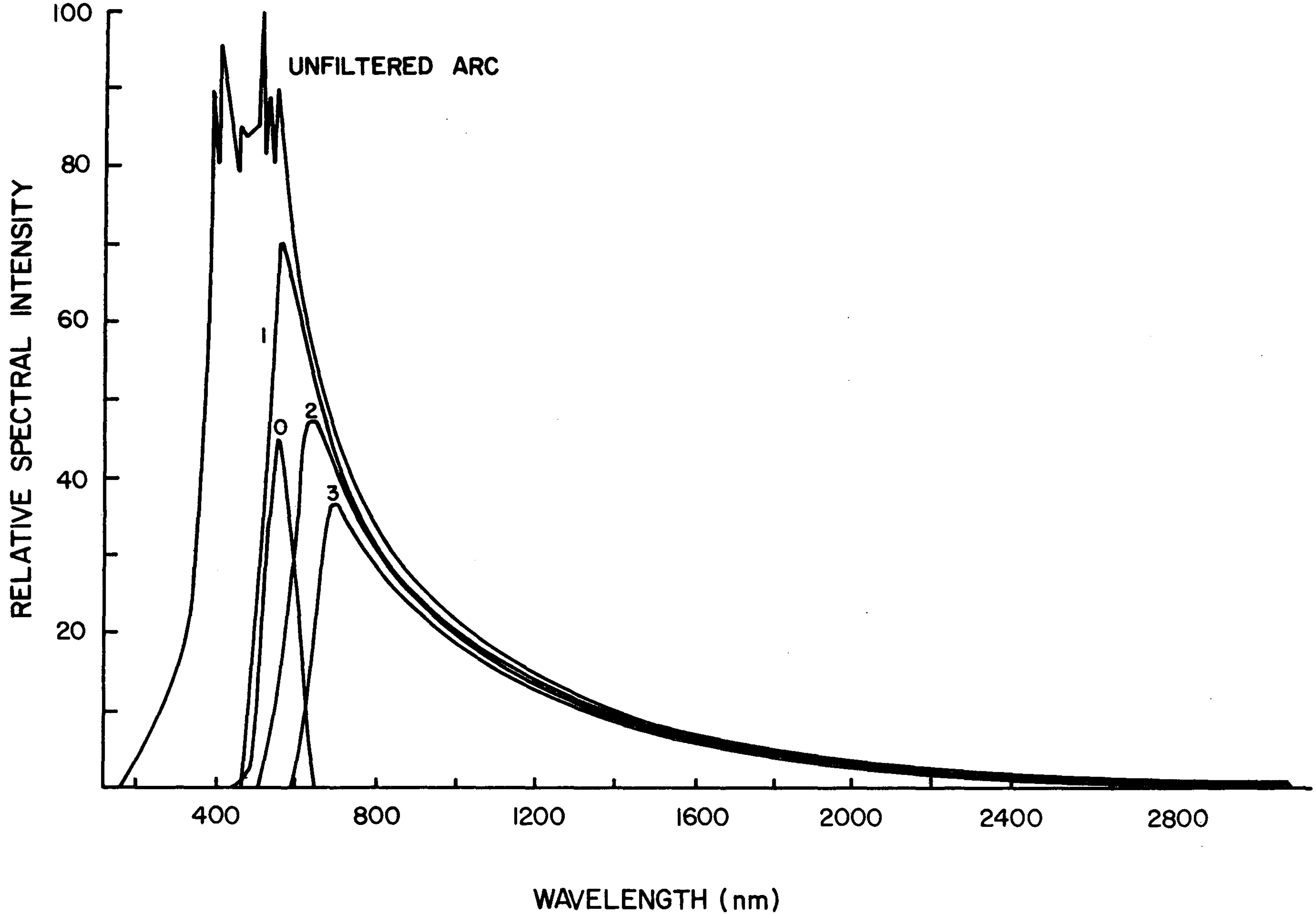
et al. (13), and, having been carefully performed, deserves a close review. The experiment was limited to that part of the spectrum between 200 and 3,000 mu. The investigators point out the difficulty in defining what is a "threshold" burn.

> "The criterion for the threshold dose causing a chorioretinal burn, therefore, should be the slightest visible change of the tissues. These changes, however, are not easily detected, particularly since at threshold levels the actual lesion may be much smaller than the retinal area which was exposed to the radiation. This is due to a different heat gradient of the marginal portions. Furthermore, the tissue changes following threshold doses occur with some delay in time. While there may be no change whatsoever immediately following exposure to radiation, one can observe a distinct well-limited area of hyperemia after a time interval of the order of minutes. This may be followed by the appearance of an edema, giving the lesion a soft, gray-white appearance. In order to have a rather well defined qualitative criterion for chorio-retinal burns, it was arbitrarily decided to regard every lesion as a positive burn when within half a minute following exposure to radiation, the tissue showed a gray or white discoloration," (13, p. 1 & 2).

Anesthesized rabbits were used as experimental animals and were divided into three groups depending upon their degree of fundus pigmentation. The fundus of the eye was exposed to radiation of the same wave length while varying the intensity of the radiation so that the level of irradiance was determined at which 50% of the exposures resulted in a burn, this level being taken as the threshold. In this manner, five different spectral bands were determined in each eye, this involving between 20 and 40 exposures per eye. These five spectral bands are shown in Figure 22. It should be noted that the image size was kept constant at 1 mm diameter in all cases.

The mean values of burn thresholds with constant exposure of 0. 0.400/sec, corrected for transmission of the ocular media, are shown in Table 6. The notation "t" in the table refers to the calculated ocular transmittance values for the specific spectral distribution. The effect of altering the duration of exposure is shown in Table 7. The investigators then compared their data using the unfiltered arc with that of Ham (previously mentioned, Ref. 47) for a retinal image of approximately the same diameter. Excellent agreement was noted. In comparing their data with that of Jacobson (53), it was noted that differences in spectral distribution in the two studies accounted for large discrepancies in the results of the two investigations. Bredemeyer et al. proceeded to calculate the absorption spectrum underlying chorioretinal burns, so that after correction for the absorbed retinal irradiance, burn thresholds for filtered and unfiltered sources would be in agreement. Although the reader is referred to the original article for full development of the method for calculating the appropriate data, the results of these calculations, using the data of Bredemeyer et al. as well as that

Figure 22* - Relative spectral distribution of filtered and unfiltered Jet-arc radiation.



*From Bredemeyer, H. G., et al, (13).

Table 6. Mean Values of Burn Thresholds*

Corrected for Ocular Media

Values in watts/cm^2 0.400-second exposure

Condition	Unfiltered Arc	Filter 0	Filter 1	Filter 2	Filter 3
τ	0.628	0.915	0.667	0.618	0.569
Light Pigmentation	36.7	35.0	47.4	74.2	
Medium Pigmentation	27.0	27.6	32.3	50.0	68.1
Heavy Pigmentation	26.5	23.5	29.5	36.8	48.4
Grand Mean	30.1	28.7	36.4	53.7	58.2
Log	1.478	1.458	1.561	1.730	1.765

*From Bredemeyer et al[13].

Table 7. Effect of Exposure Duration*

Burn Thresholds Uncorrected for Ocular Media

Values in watts/cm^2 Variable Exposure

	Exposure (seconds)				
Rabbit and Eye	0.100	0.200	0.333	0.400	0.500
J21 OD	91.3	73.1	61.9	61.9	61.9
OS	100.0	60.6			
J22 OD		50.0	33.9		
OS					
Ratios	1.925	1.329	1.000	1.000	1.000
Estimated Burn Thresholds Corrected for Ocular Media (watts/cm^2)	58.0	40.0	30.1	30.1	30.1
Log	1.763	1.601	1.478	1.478	1.478

*From Bredemeyer et al[13].

of Ham and Jacobson, are shown in Figure 23. In Figure 24 the authors have attempted to relate thresholds for combinations of burn size and exposure duration. It should be noted that this latter figure deals only with burns of 1 mm diameter or less. Bredemeyer et al. point out the conflict of these curves with the findings of Jacobson et al. which suggest that the shape of these curves do not apply for lesions of greater than 1 mm diameter. The authors "leave open" the question of the failure of the curves to explain this conflict.

In spite of the data which has been presented to this point, there still appears to be some validity in the question as to what actually constitutes a "threshold" for the effect of electromagnetic radiation upon the retina. In general, the studies reviewed to this point have used some clearly observable anatomical change of the retina which appears in a short period of time as the so-called threshold point. However, as pointed out by Allen and Richey (1) in at least one comparison the production of minimum detectable burns in rabbits may not in fact represent an equivalent end point with the production of human retinal lesions.

This problem has been spoken to by Geeraets et al. (35), who note that:

> "The original definition of a threshold burn was an ophthalmoscopically observalbe lesion barely visible five minutes after exposure. A burn of this type is of course 'threshold' only in the sense that it fits this particular definition, but it is not 'threshold' according to other examination methods. The ultimate in threshold lesions, therefore, is a retinal burn of such degree as to just perceptibly irreversibly impair retinal function."

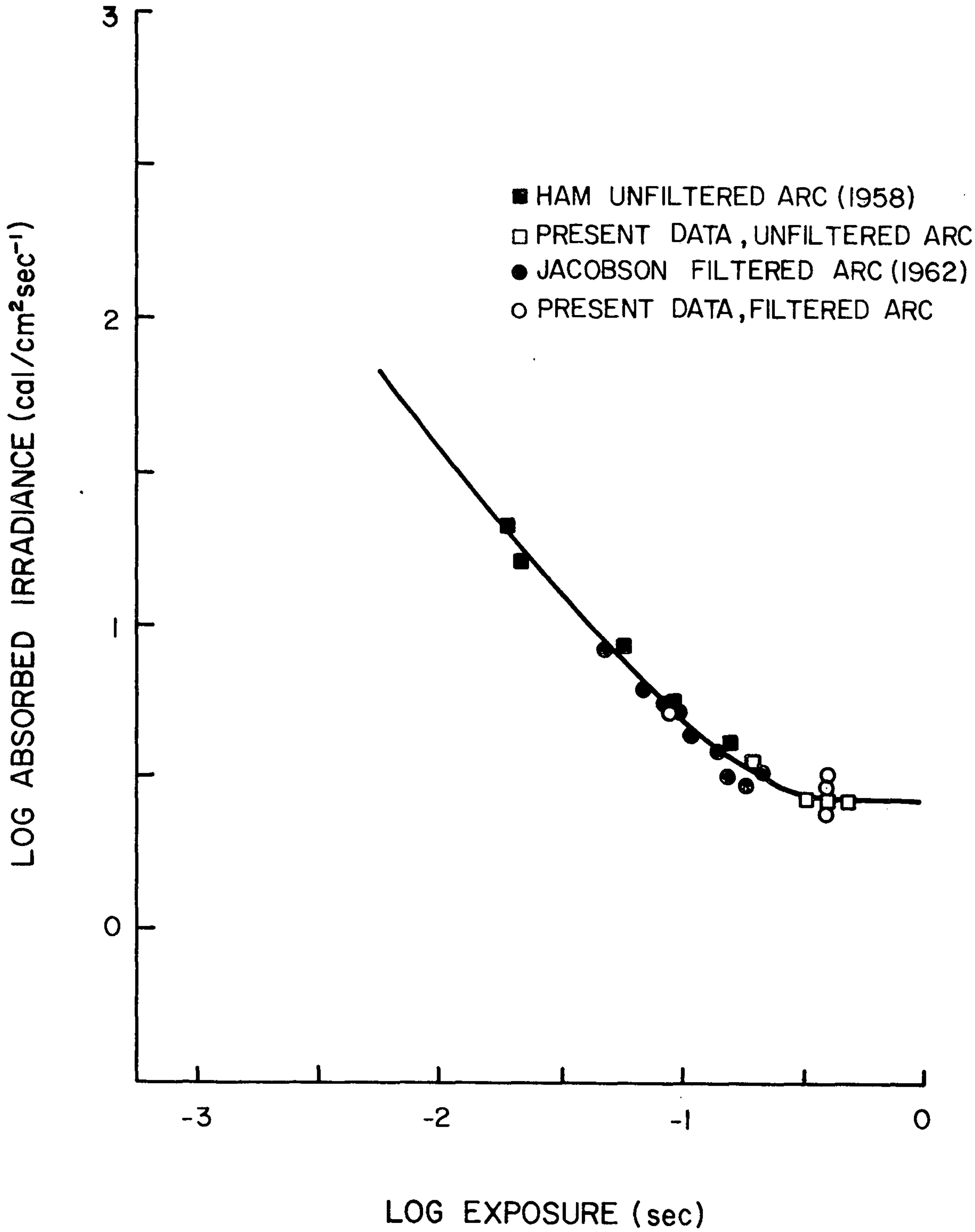
These authors suggest that enzyme inactivation (DPN - diaphorase and succinic dehydrogenase) occurs at lower energies than histological alterations or ophthalmoscopically detectable lesions.

McNeer et al. performed electroretinography on rabbit eyes previously light coagulated with energies below those resulting in clinically visible minimal lesions (68). Reduction of the B wave amplitude was found to be significant at energy levels at one-half of those required for production of minimal visible lesions if a total area of approximately 40 mm^2 had been exposed.

Chan et al. (16) were unable to show any definite threshold effects producing alterations of the soluble retinal proteins other than those related to thermal injury per se.

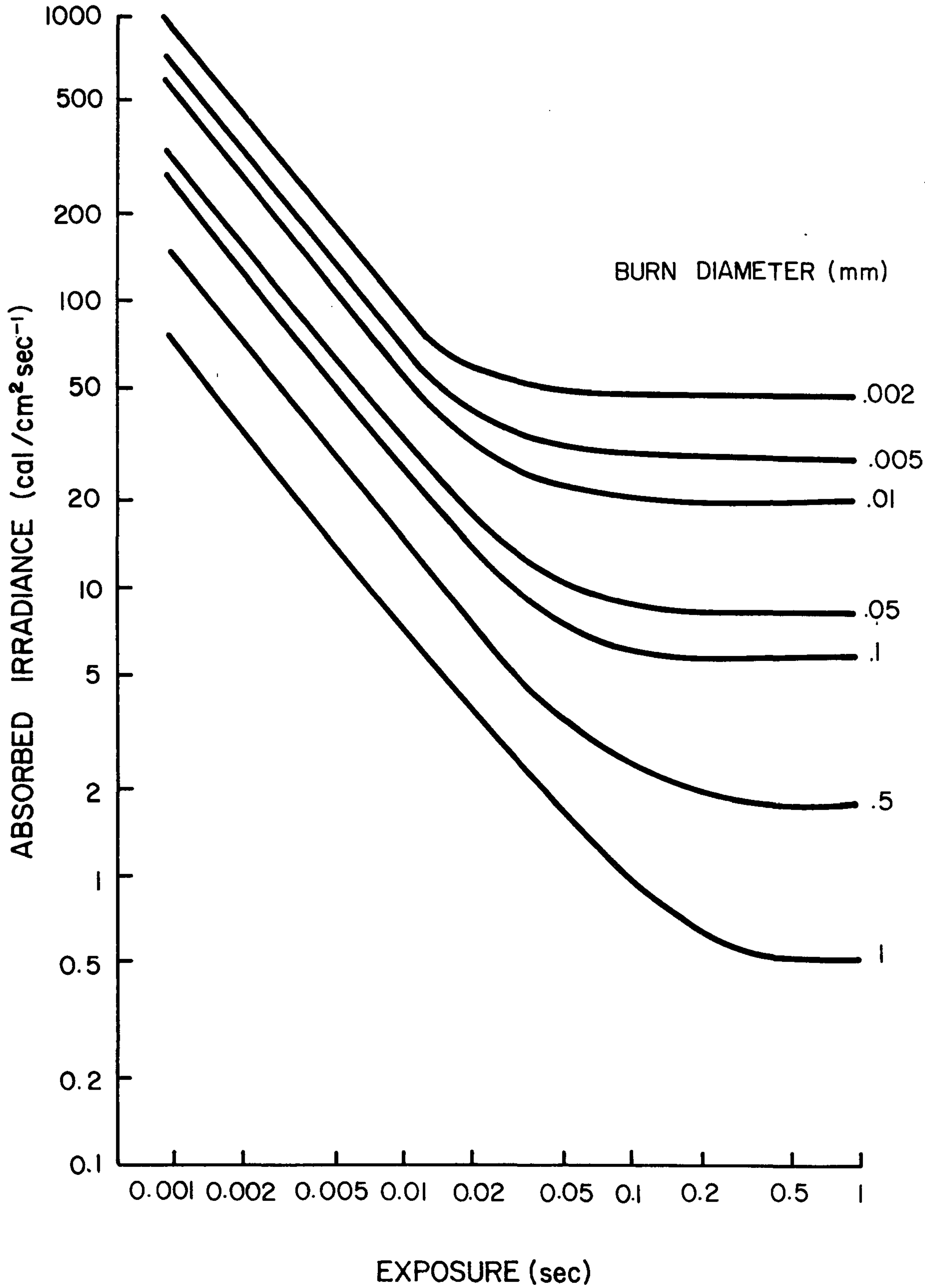
In summarizing a series of investigations (including certain of those just mentioned) Geeraets and Ridgeway conclude that a thermal mechanism can adequately account for the damage produced by high intensity light irradiation (36). Further, they note that such heat

Figure 23* - Experimental burn threshold data.



*From Bredemeyer, H. G., et al, (13).

Figure 24* - Theoretical burn threshold curves.



*From Bredemeyer, H. G., et al (13).

damage is in fact necessary to obtain some of the observed results. Even though these comments appeared in 1963, there does not seem to be any more substantial comment concerning the ultimate cause of retinal damage since that time. Certain difficulties and techniques for actually measuring the temperature changes at the retinal level following retinal irradiance are presented many different articles (26, 27, 23, 48, 49), all from a symposium on research in light coagulation held in 1963.

The question of the retinal threshold for damage by radiant energy received close attention in articles by B.A.J. Clark (17,18). He notes that results derived from many experiments frequently appear to have little similarity in their estimation of retinal thresholds, suggesting that this is the case for several reasons:

" i. type of subject (e.g. human, rabbit) and density of fundus pigmentation;

" ii. exposure time - in individual cases, as exposure time becomes shorter, the threshold intensity increases but the threshold total energy density or dose (cal/cm^2) at the retina is reduced;

" iii. variation in the value for energy transmission of the ocular media used by the various authors in their calculation of retinal energy densities;

" iv. differing spectral distribution of the various light sources, used, e.g., Sun, Xe-lamps, tungsten lamps, ruby lasers;

" v. method of detecting impairment of retinal function, e.g., ophthalmoscopic examination, fundus reflectometry, microscopic examination of retinal sections, visual acuity tests, etc.;

" vi. retinal area exposed - in individual cases, the threshold energy density decreases as the exposed area is made larger;

" vii. accuracy of focus of the source on the retina; and

"viii. variation between subjects, e.g., Cogan cites investigators who found wide variance in the subjective and objective effects of solar retinitis, with an explanation that the more extreme effects may be due to nutritional photosensitization of the retina," (18, p. 92 & 94).

An interesting table of some of the conflicting data has been put together by Clark in Table 8.

Table 8. Summary of Energy Threshold Determinations for Retinal Damage in Rabbits and Humans*

Author	Source and Exposure Time	Subject	Fundus Pigmentation	Ocular Media Energy Transmission T %	Pupil Diam. D mm	Diameter of Irradiated Area d mm	Threshold Intensity cal/cm^2/min at Cornea	Threshold Intensity cal/cm^2/min at Retina	Threshold Energy Density at Retina lac/cm^2
Verhoeff and Bell (1916)	Magnetite arc, 12 min.	Albino rabbit		67		3		6.0	72*
Eccles and Flynn (1944)	Sun, 10X telescope 30 sec.	Grey rabbit		ca.45		1.4	0.75	43	22*
Rosen (1948)	Sun reflected from water, few minutes.	Several humans (maculas)		39(1)	1.6(2)	0.15	0.03*	1.25*	5(3)*
Byrnes et al. (1955)1	Sunlight, approx. 30 msec.	Rabbits		40	5.0	1.0	28.7*	287	0.14
Ham et al. (1957)	Carbon arc, 40-100 msec.	Chinchilla, black and grey rabbits		78	8.0	0.3-1.1		480 or* 1 200	0.8
Flynn (1960)	Sun (partly eclipsed). 2 sec or more.	Several humans		39(1)	1.6(2)	0.15	1.0*	44*	1.5*
Zaret (1963)	Ruby Laser, 0.5 msec.	Grey rabbit	Light	95	8.0	0.15		Between* 770,000 & 77,000	Between 6.45 & 0.65
Weale (1964)	Tungsten lamp with ON 20 filter, 30 sec.	Human, foveal & non-foveal areas		100	0.9	7.5-8.0		284*	142(4)*
Geeraets et al. (1965)	Xe flash lamp, 30 msec.	Chinchilla grey rabbit		ca.85	8.0	0.76		1 900*	1.0*
Geeraets((1966)	Xe lamp, 1 min.	Dutch rabbit	Moderate	ca.85		0.85		96*	96*
Campbell et al. (1966)	Ruby laser, 0.7 msec.	Chinchilla grey rabbit		95	3.2	0.16*		104 500*	0.12*
Campbell et al. (1966)	Ruby laser, 0.7 msec.	Human (macula)	Average Caucasian	95	3.2	0.28*		188 600*	0.22*

1. From data of Boettner and Wolter (1962). 2. From data of Eccles and Flynn (1944). 3. Estimated. 4. Weale States that an 'edema' effect but no lesions were found at this retinal energy density.

*Values indicated by an asterisk have been calculated or converted from published data by the present author.

*From Clark[18]

Basing his calculations largely upon the data of Verhoeff and Bell, who arrive at a level of 3.6 $cal/cm^2/min$ as the retinal threshold, and decreasing this figure by one-half because of the studies and comments of Geeraets and Flyn, Clark suggests that the threshold level should be set at 1.8 $cal/cm^2/min$ (17).

Recently, Bartleson has attempted to develop a method for computing retinal irradiance, (8), pointing out that similar attempts by Blum and Ham, et al. have the disadvantages respectively of not considering the image size upon the retina in the former case and of failing to consider more than an "average" transmittance of ocular media for radiant energy in the latter. Bartleson's comments concerning the problems with heat transfer in the retina are well throught out (8, p. 418 & 419):

"For the most part, the greatest danger to the retina lies with small sources of high energy. The concentrated retinal images of such sources cause large rates of thermal increase in the retina itself. The generated heat tends to be conducted to lower thermal gradient areas in a rather complicated manner.

"In the simplest case of heat transfer by conduction, the instantaneous rate of heat flow ($d\,Q \,/\, d\,\theta$) is equal to the product of three factors: the area (A); the temperature gradient (-dt/dx), which is the rate of change of temperature (t) with respect to path length (x); and the thermal conductivity (k) of the medium:

$$\frac{d\,Q}{d\,\theta O} = -\,kA\,\frac{dt}{dx}$$

"Now, if the same total amount of radiant energy impinges on a larger retinal area, less energy is absorbed per unit area, and consequently the temperature gradient, dt/dx, will be lower in inverse proportion to the magnitude of the increased area, A. As the formula indicates, the total heat transfer, $dQ/d\theta$, will remain constant, but the rate per unit area, $(dQ/d\theta)/A$, will decrease with increasing area. The rate of heat transfer in the retina is greatly complicated by the fact that it occurs in a nonhomogeneous, three -dimensional medium bounded by molecularly dissimilar media and has, itself, a constantly changing supply of blood. Qualitatively, however, the one-dimensional generalization is still applicable; the rate of heat transfer per unit area (for constant total radiation impinging on the retina) decreases with increasing area.

"This fact leads to a reciprocity failure for the production of thermal lesion. That is, the extent of lesion produced is not simply equal to the product of incident irradiation and the duration of its incidence. Rather, the thermal lesion threshold depends on (a) the rate of energy delivery to the retina, (b) the duration of exposure, and (c) the retinal image area involved. There is, then, no single value of radiant exposure that can be named as a threshold."

Thus, recognizing the complex problem of retinal heating, Bartleson has attempted to present a formula for the calculation of retinal irradiance which includes all the pertinent variables. The formula derived is presented as follows:

$$H_r = \left(S_p \int_{\lambda = 350\ \mathrm{nm}}^{\lambda = 1600\ \mathrm{nm}} H_{c\lambda} \cdot \tau \cdot d\lambda\right) / S_r$$

where H = irradiance in calories-$sec^{-1} \cdot cm^{-2}$.
S = area in square centimeters.
τ = transmittance.
r = retina.
c = cornea.
p = pupil.
λ = wavelength in nanometers.

Thus, this equation involves not only the area factor, but also integration with respect to wavelength. From this formula, then, retinal exposure or total dose can be defined as:

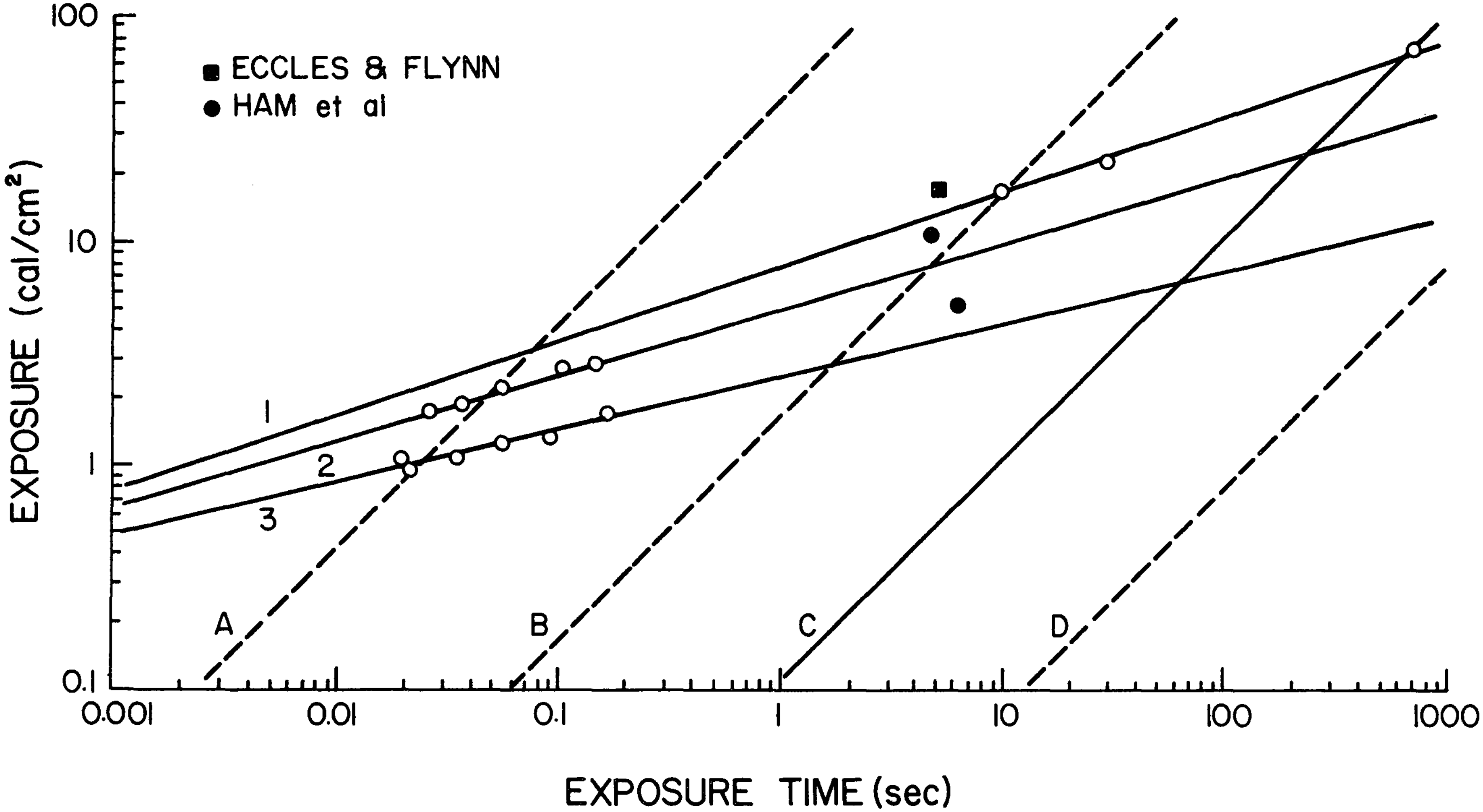
$$E_r = H_r \cdot t\ \mathrm{cal} \cdot \mathrm{cm}^{-2}$$

where t = time in seconds.

The data of Jacobson et al. (53), Eccles and Flynn (33), Ham et al. (47), and Geeraets et al. (38), have been used by Bartleson to construct Figure 25, and Bartleson comments, in part, as follows. Both the threshold and the exposure functions of the figure describe power relations between exposure and time, being linear functions in the log-log corrdinates. The slopes of the lines are equal to the exponents of the power relations, expressed as: $\log E = \alpha \log t + c$ and $E = kt^a$. From Figure 25 it can be seen that α is unity for the exposure functions. Thus, exposure is simply proportional to time. The proportionality constant, k relates to the energy level of the source.

Conversely, the exponents of the threshold functions range from about 0.24 to 0.34, depending upon retinal image size. The power of the threshold functions is lower than that of the exposure functions, according to the data on the figure.

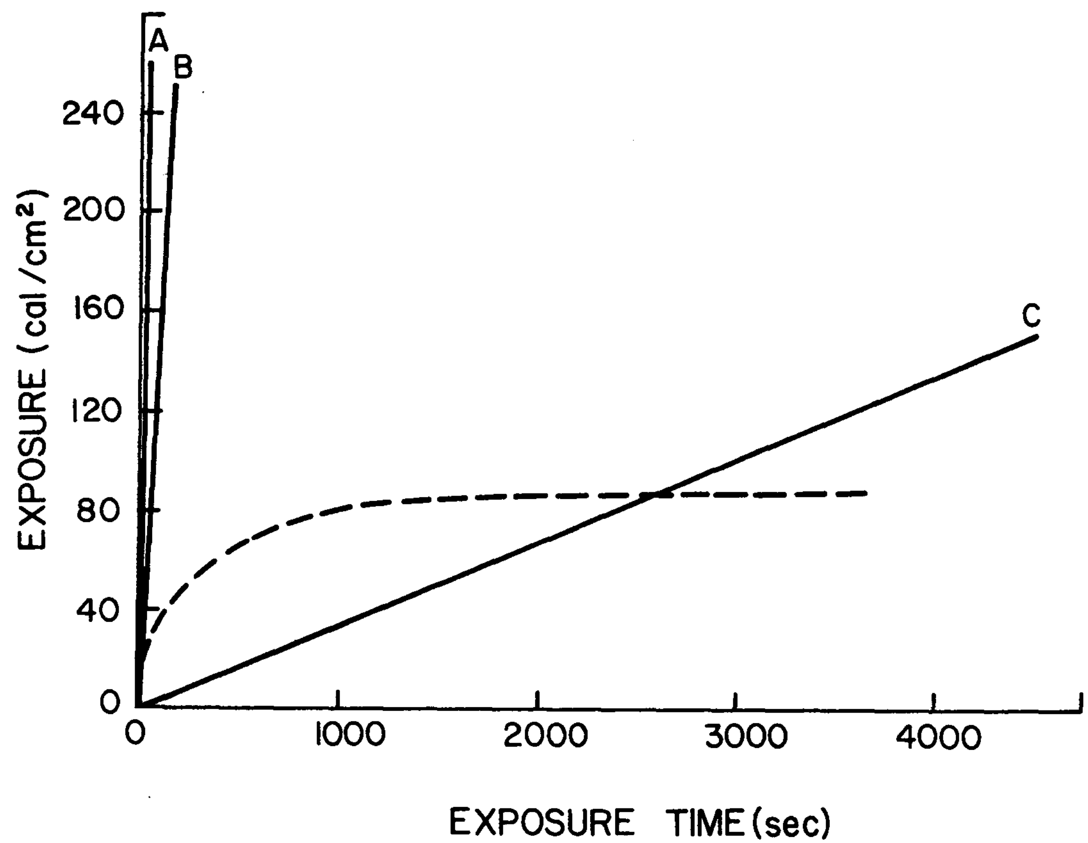
Figure 25* - Exposure required for threshold chorioretinal lesion as a function of exposure time for three retinal image areas: (1) Threshold for 0.016 cm^2 retinal image; (2) threshold for 0.40-cm^2 retinal image; (3) threshold for 0.95-cm^2 retinal image. Curves are constructed principally from the data of Eccles and Flynn and Ham et al. Exposure functions for four light sources at representatative viewing distances and corresponding retinal image areas are also shown for reference: (A) 20 KT nuclear blast at 20 kin (0.03 cm^2); (B) solar energy (0.016 cm^2); (C) Osram XQO-20 KW at 1.0 meter (0.016 cm^2); (D) 4-inch Photo EBR at 1.5 meters (1.08 cm^2).



*From Bartleson, C.J., (8)

Bartleson points out that this latter fact has an interesting implication when extrapolating to long exposure times and weak energy sources. This is shown in Figure 26, where exposure functions for an atomic fireball, the sun and a candle are shown in linear coordinates together with a lesion threshold function for 0.016 cm^2 retinal image. The graph indicates that a threshold retinal lesion would be produced by staring at the candle flame for approximately one hour. It is obvious that there is some point of energy exposure beyond which ocular metabolic processes can compensate for the exposure. It is just as obvious that retinal lesions are produced by looking at the sun. Bartleson states well the problem when observing that between these two extremes are virtually all other significant radiant energy sources and that much more information is necessary if one can make wise judgments as to retinal threshold levels.

Figure 26* - Exposure (plotted arithmetically) as a function of exposure time in seconds. Solid-line functions represent: (A) 20 KT nuclear fireball at 20 km, (B) solar energy, (C) standard candle at 1 foot. Dashed curve represents lesion threshold function for 0.016-cm^2 retinal image.



*From Bartleson, C.J., (8)

The Effects of Infrared Radiation Upon Other Ocular Structures

As was mentioned in the introduction to Section II of this report, this section has been arranged to look first at the effects of infrared radiation upon those ocular structures which have both historically and recently received much attention. This having been accomplished, it now remains for us to consider the effects of infrared radiation upon certain other of the ocular tissues.

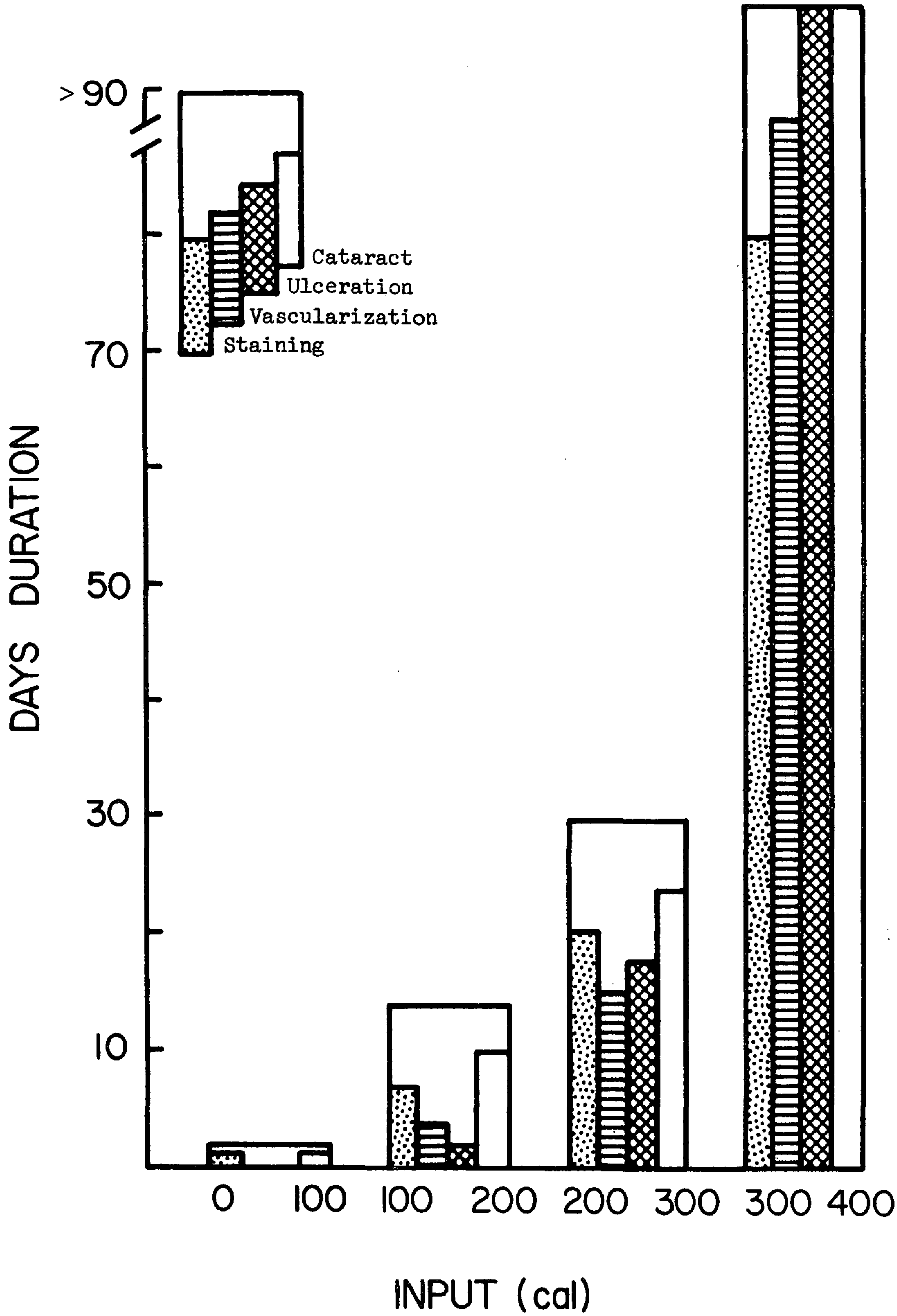
The pathological effects of infrared radiation in large amounts upon the eyelids - or, more specifically, the skin of the lids - are those of an ordinary cutaneous burn (31,20). The lesions then may range from erythma to blistering to necrosis of the tissue. These lesions are to be distinguished from the "sunburn" effect of ultraviolet radiation.

In the cornea, a similar burn may occur. Destruction of the superficial corneal epithelium and coagulation of the proteinaceous s stroma occur, with resulting corneal opacification. Commonly, as Verhoeff and Bell pointed out, (91), the posterior corneal surface may shown more damage than the anterior, since the surface tends to be cooled by the air and the film of lacrimal fluid. Kutscher notes that since exposure to large amounts of infrared radiation produces corneal pain which is immediate and severe, the eyes are reflexly shut and the head averted; therefore, such lesions are not commonly seen (58). Lele and Weddell have suggested that not only pain, but a specific thermal sensa tion can be produced by the application of infrared radiation to the cornea (62).

Krivobok suggested that in 1941 his studies indicated that infrared radiation exerted some irritative effect upon the corneal nerve endings or produced some degradation product so that certain pathological changes were produced in organs and tissues remote from the eye (57). These included such problems as vascular congestion in the spleen and kidneys. None of the findings reported by the investigator have received confirmation either before or since his report.

In the study by Dawson (previously mentioned), (28), using a tungsten filament lamp as an energy source (and thereby exposing the cornea to a spectral distribution from 400 to 2,6000 mu), total dose levels of less than 100 gcal/cm^2 produced no immediate effect. Within 24 hours, a generalized erythema could be detected and a mild leukoma with spots which accepted a fluorescein stain could be seen. Within 24 to 72 hours all these signs had cleared. At intermediate levels (from 100 to 300 gcal/cm^2) corneal opacities with vascular invasions were noted. Also, penetrating ulcers developed. At levels of exposure greater than 300 gcal/cm^2, all experimental animals developed deep penetrating corneal ulcers. The results of different exposure levels in the study are shown graphically by Dawson as adapted in Figure 27.

Figure 27* - Duration of corneal opacities produced by various doses of infrared irradiation. Subdivisions of the major histograms represent the per cent of animals for that dose level which exhibited a specific anomaly at any time during the experiment. Abscissa values are total gcal/cm^2 dose.



*From Dawson, W.W., (28)

Campbell has recently performed a study to evaluate the effects of a high energy laser on the cornea and lens (15). The laser chosen for the investigation had an emission at a wavelength in the infrared (neodymium doped glass with a monochromatic spectral emission at 1,060 mu). Gray Chinchilla rabbits were used as animal subjects. Table 9 provides a summary of the number of coagulations produced and the total number of corneas treated with the laser. Also indicated are the coagulations detected at each examination after treatment as well as the energy values for each application. Table 10 shows the energy necessary to produce coagulations in each of the four intensity categories. In general, no coagulations were produced by energy levels of less than 1.5 joules and severe burns were always produced by 6 to 8 joules.

Duke-Elder has pointed out that the iris is very susceptible to radiant heat because of heavy absorption by its pigment. "Even moderate doses result in miosis, hyperemia and the formation of an aqueous flare. More severe exposures lead to the development of an extreme irritative miosis which may overcome atropine and may eventually be replaced by a paralytic mydriasis; these changes are associated with an intense congestion with hemorrhages and thromboses and a violent inflammatory reaction in the stroma ... resulting in necrosis of the tissues and, after a few days, in the formation of permanently bleached and atrophic areas," (31, p. 6,480).

A detailed study by Muller offers additional information concerning the question of sphincter paralysis (74). Although specific information is not available concerning the type of energy source used, Muller noted that after short exposures of less than four minutes, a transient sphincter irritation with miosis was at first produced, and with the longer exposures of four minutes, a temporary sphincter paralysis with a dilated pupil was seen. With exposures of five to ten minutes, a permanent sphincter paralysis was produced. Commonly, permanent depigmentation of the edge of the iris was seen within two to four days after exposures lasting five minutes; the depigmentation was always seen after ten minute exposures.

Fry and Miller investigated the possibility that infrared radiation might have an influence upon visual recovery following exposure to a flash radiation. They found that the only portion of a flash radiation that influenced the recovery times for foveal performance was in the visible region. Infrared had no effect on prolonging the recovery times following the flashes, even when it accounted for more than 50% of the total flash energy (34).

A study to investigate the influence of infrared radiation upon intraocular pressure was performed by Sano and Obata (86). They concluded that infrared radiation has considerable effect on intraocular pressure. Immediately after irradiation there was a considerable increase in the pressure; however, this was soon followed by a drop in pressure. Using filters, the most marked effects on intraocular pressure were found when a red filter was used, although similar but shorter lived

Table 9. Total Corneal Treatments at Various Energy Values and Number of Coagulations Detected at Specified Examination Dates*

	Energy of neodymium laser' (joules)								
	0.7-1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5-5.5	6.0-8.0
Number of firings	19	15	17	12	7	7	9	6	6
Number of eyes treated	7	5	5	4	5	4	5	3	4
Number of eyes showing burns	None	3	3	2	3	2	4	2	4
Number of burns detected									
Immediately	None	5	8	3	4	3	5	4	6
1-2 days	None	None	5	3	4	3	5	4	6
5-7 days	None	None	None	3	4	3	5	4	6
14 days	None	None	None	1	4	3	5	4	6
21 days	None	None	None	1	4	3	5	4	6

*From Campbell[15]

Table 10. Classification of Intensity of Corneal Coagulations Produced at Various Energy Values*

	0.7-1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5-5.5	6.0-8.0
Total number of burns produced	None	5	8	3	4	3	5	4	6
Number of faint burns detected									
Immediately	None	5	8	3	2	None	None	None	None
1-2 days	None	None	5	3	2	None	None	None	None
5-7 days	None	None	None	3	2	None	None	None	None
14 days	None	None	None	1	2	None	None	None	None
21 days	None	None	None	1	2	None	None	None	None
Number of mild burns detected									
Immediately	None	None	None	None	2	2	None	None	None
1-2 days	None	None	None	None	2	2	None	None	None
5-7 days	None	None	None	None	2	2	None	None	None
14 days	None	None	None	None	2	2	None	None	None
21 days	None	None	None	None	2	2	None	None	None
Number of moderate burns detected									
Immediately	None	None	None	None	None	1	5	4	None
1-2 days	None	None	None	None	None	1	5	4	None
5-7 days	None	None	None	None	None	1	5	4	None
14 days	None	None	None	None	None	1	5	4	None
21 days	None	None	None	None	None	1	5	4	None
Number of severe burns detected									
Immediately	None	None	None	None	None	None	None	None	6
1-2 days	None	None	None	None	None	None	None	None	6
5-7 days	None	None	None	None	None	None	None	None	6
14 days	None	None	None	None	None	None	None	None	6
21 days	None	None	None	None	None	None	None	None	6

*From Campbell[15]

effects were found with brown filters. The effects of the radiation were found to produce a much greater effect on intraocular pressure than the application of hot air.

Spectral sensitivity curves of the corneo-retinal potential are reported but until a study by Anderson and Kolder no information was available as to whether infrared radiation might contribute to the oscillations of the corneo-retinal potential (2). Their study was designed to test for a difference between the response of the indirectly measured corneo-retinal potential to visible radiant energy including infrared radiation and to visible radiant energy essentially free from infrared radiation. It was concluded that infrared radiant energy does not contribute significantly as a stimulus to evoke oscillations in the corneo-retinal potential of man, when used either as a sole source for radiant energy or together with polychromatic light.

Part II: Summary

The evidence presented in this section leaves little doubt that there are indeed very specific effects of infrared radiation upon the eye.

The direct relationship between chronic exposure to infrared radiation and the development of posterior cortical lenticular opacities seems indeed valid. It would appear that, however, the primary causual effect is indirect; i.e., the important factor is not absorption of radiation by the lens; rather, as suggested by Goldmann, the energy absorbed by the iris and secondarily transmitted to the lens likely accounts for the problem. It is not possible to give threshold figures for the development of these cataracts, other than to say that a time-dose relationship must be considered and that with typical exposures such as seen in industry, the latent period is indeed rather long.

The literature indicates that, as might be expected, the primary effect of infrared radiation upon the retina and choroid is that of a heating effect. Again, the concept of a time-dose relationship must be considered and two points are important. First, if the application of the radiation to the retina is of sufficiently low intensity, the retinal-choroidal blood flow may be adequate to dissapate the heat. Second, the focusing effect of the anterior ocular structures must be considered, with the realization that a "relatively small" amount of radiation striking the anterior corneal surface may be focused to an extremely intense energy density per unit area.

The effects of infrared radiation upon other ocular structures have not received as intensive an investigation as those just mentioned. The effects upon the lid and cornea may be considered as essentially ordinary cutaneous burns.

PART III: PROTECTION OF THE OCULAR STRUCTURES AGAINST EXPOSURE TO INFRARED RADIATION

To this point we have examined the various interactions of infrared radiation with the various tissues of the eye. There can be no doubt that under certain conditions of adequate time-dose relationships, infrared radiation can indeed produce deleterious effects upon ocular structures.

An excellent and most appropriate discussion of just such an example is given by Strughold and Ritter (89), in discussing the problem of eye hazards and protection in space. They point out the peculiar vulnerability for a solar retinal lesion of an astronaut in space without the protection of a light absorbing and light scattering medium such as the earth's atmosphere. This vulnerability may be explained by two mechanisms. First, because of the dark sky of space, the pupils are widely dilated so that when the eye is turned towards the sun it is caught by a "blitz-like" surprise out of the darkness. Second, the intensity of solar radiation because of the lack of an atmosphere in space is greater than on earth - 2.0 cal/cm^2/min versus 1.4 cal/cm^2/min (previous references referred to in this paper have used 1.72 cal/cm^2/min as the solar radiation striking the earth's surface). With travel towards the sun, the solar irradiance in the space near Venus amounts to 3.8 cal/cm^2/min and thus the critical time of ocular exposure would be expected to be much less than even in near-earth missions.

It is thus necessary to examine closely various ways in which the eyes can be protected against such radiation when exposure is necessary or likely, as in the example just cited.

Robinson suggested in 1903, in discussing the prevention of heat cataracts, "The disease can be prevented by workmen wearing dark pure-blue spectacles..... for glass has the property of allowing only 30% of the heat rays to pass through it; and, if the glass is dark coloured, many of the light rays would also be cut off." (81). In his later reports, as well as in the report of Hartridge and Hill (50) and in the report of Verhoeff and Bell (91), the studies of one Sir William Crookes are cited as the authority for the use of protective glasses.

Sir William began his studies in 1909, in an effort to discover the best kind of glass to protect the eyes of glassworkers (25). Numerous metallic oxides were mixed in different proportions, so that 300 different glass samples were made. The most effective for absorbing infrared rays was found to be formula 217, which consists of 96.80% fused soda flux, 2.85% ferrosoferric oxide and 0.35% carbon. The glass is of a pale blue-green color, cuts off 96% of the heat radiation and all ultra-violet rays shorter than 355 mu, while transmitting 40 to 50% of visible radiation (25). Crookes also developed the so-called "Crookes' glasses A and B," which were for persons wishing to avoid glare. The glass eliminates about one-third of the infrared radiation and essentially all the ultraviolet rays (83,31). An idea of the credence of Crookes' work can be gained once it is noted that Duke-Elder, in his 1954 textbook, still noted that "Effective protection (against thermal radiation) can be given by goggles with heat-absorbing glass, particularly those containing ferrous oxide, such as the sage-green glass of Crookes." (31, p. 6, 489).

Von Someren and Rollason studied the spectral distribution and energy of a welding arc for specifying the infrared transmission limits for welding filters. They demonstrated that the radiation at approximately 12 inches (31.6 cm.) from a 280 ampere arc is comparable with that of direct sunlight at the earth's surface and the total amounts of radiant energy that could be absorbed by the eye from such an arc and from direct sunlight were also comparable, although the radiation from the arc was relatively richer in infrared. To specify safe limits for the heating effect of radiant energy upon the cornea they assumed that the diffuse reflection factor of soil, plants, etc. is 5%. They then concluded that since the eye is adapted to the heating effect of the diffusely reflected radiation and since this heating effect is largely due to infrared radiation there should be no risk of cataract due to heat absorbed by the anterior parts if the welding filter has an infrared transmission of 5% or less (90).

Using Von Someren and Rollason's study as background, Clark recommended a so-called shade 11 filter for working with a 280 A arc which has the characteristics of a luminous transmission factor of 0.005%, and in infrared transmission factor of 0.06% thus allowing a safety factor of approximately 100 when compared with the suggestions of Von Someren and Rollason (17).

Duke-Elder has pointed out that an alternative to Crookes' glass, which is heat absorbing, is a heat-reflecting glass, incorporating transparently thin sheets of metal such as gold. An example of this type of alternative is "Pfund's glass," which is made of a very thin layer of gold placed between a layer of ordinary crown glass and one of Crookes' A. The crown glass acts as a mechanical protection agent, the layer of gold reflects 98% of the infrared while allowing passage of 75% of the visible radiation and the Crookes' glass absorbs the ultraviolet and a part of the remaining infrared radiation (31).

Prior to the gold-coated, low-transmission visor being adopted for military use (primarily with the thought in mind to avoid temperary or permanent blindness in pilots exposed to the radiation from an atomic exposure) extensive evaluation programs were carried out by the Armed Forces. Typical is the program instituted by the Navy, as reported by Parker and Boser, (76), in which four basic questions were designed to assess the adequacy of the equipment. The first concern dealt with the sufficiency of the protection against flash blindness. The authors note as follows: "....the first portion of the evaluation involved a theoretical analysis of the protection which would be afforded by visors having one percent or three percent photometric transmission. A report by Lappin presents curves showing retinal irradiance in 150 milliseconds for both low- and high-yield weapons. In computing these irradiances, Lappin assumed an aircraft canopy transmission of 88% an atmospheric transmission factor of 1.0, and 80% transmission of energy through the ocular media, and a normal daylight pupil of 4 mm. ...If we use the 'standard' burn threshold of 0.5 cal/cm^2 described by Bredemeyer, Wiegmann, Bredemeyer and Blackwell as a criterion, it can be seen that a one percent filter will be effective under all conditions with the possible exception of very high-yield weapons. However, inasmuch as Lappin used a transmission co-efficient of 1.0 and thus did not account for energy lost as a function of transmission through the atmosphere, protection agains high-yield weapons must be done at a distance at which the effects of atmospheric attenuation will be significant." (76, p. 146.)

Two points are specifically worth noting about these comments. First, the concern is with total energy reaching the retina; thus, not only visible radiation, but infrared radiation must be considered, as it undoubtedly was in the development of the Navy visor, although not mentioned here. Secondly, the atmospheric attenuation principle is obviously of no value in consideration for space missions.

To this point in this section, we have examined several comments and approaches towards protecting the eye from being adversely affected by an excessive absorption of infrared radiation. If one wishes to develop more specific information about the transmission and absorption characteristics of a specific optic material, certain problems must be considered. The first of these is the choice of the specific optic material or combinations of optic materials as we saw with Pfund's glass. It is obvious that certain other characteristics than the ability of the material(s) to absorb or transmit electromagnetic radiation may well be important. An example of this might be the choice of a glass for its ability to withstand high differential pressures, such as might be encountered in a spacecraft window.

Presently used optic materials are either optical glass or "optical" plastic. Optical glass can be obtained in literally thousands of different types. In general, most optical glass transmits well from 400 mu to 2,000 mu (88). The heavy flints tend to absorb more at the short wavelengths and transmit more at the long wavelengths. The rare earth glasses also absorb in the blue region. "Since the transmission of a glass is affected greatly by minute impurities, the exact characteristics of any given glass will vary somewhat from batch to batch, even when made by the same manufacturer." (88, p. 153.)

Plastics are rarely used for precision optical instruments, since their surfaces are soft and tend to be easily scratched. Shields or lenses are difficult to fabricate except by molding and most plastics will change dimensionally as a result of water absorption (88). The most widely used plastics are polystyrene, polychlorohexyl methacrylate and polymethyl methacrylate.

It is not possible and not appropriate in a report such as this to go into a specific discussion of different combinations of substances which will give either transmission or absorption of different wavelengths of infrared radiation. It would seem likely that one only need to specify the infrared absorption characteristics desired and an appropriate glass or, at the least, an appropriate filter can be devised. As an example, glass is available which, being "heat absorbing glass" as it is called, is designed to transmit visible radiation with a high efficiency while absorbing practically all infrared radiation. Such a glass could be Corning's 1-59 extra light Aklo, PPG's #2043 phosphate 2 mm., or Corning's 1-59 dark shade Aklo (88).

For an overview of the transmission characteristics of the glass products or plastic products one can consult general references such as just quoted, "Modern Optical Engineering," by Warren J. Smith (88), G.W. Morey's, "The Properties of Glass" (73), or a recent revision of the lighting handbook of the Illuminating Engineering Society (54). If specific information is necessary or specific problem areas exist, it would seem most advisable to consult with one of the manufacturers of optical materials so that a material with the desired transmission characteristics might be utilized, or, if necessary, a new material developed.

Part III: Summary

As stated, presently used optical materials are either plastic or glass. It is not possible and not appropriate in a report such as this to enter a specific discussion of the different combinations of materials which can either reflect or absorb not only infrared radiation, but other divisions of the electromagnetic spectrum as well. Rather, it appears that with the many different possibilities of combinations of glass types and well as the many different types of glass which can be manufactured with specific absorption or transmission characteristics that an appropriate glass manufacturer(s) might well be able to meet design requirements.

Further, it seems to this reviewer that although the question is largely of an engineering nature, that present technology is at such a state that no new developments are necessary to satisfactorily formulate and develop an appropriate helmet visor which will, by and large, meet necessary physiological, physical and safety requirements. Discussions on these latter points should be developed with appropriate manufacturers of optical materials.

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