A MATHEMATICAL MODEL OF FLASHBLINDNESS

Robert S. Czeh, Arthur W. Casper,
and Ernest C. Segraves, Jr., of
the General Electric Company

October 1965

USAF School of Aerospace Medicine
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas

DISTRIBUTION OF THIS
DOCUMENT IS UNLIMITED

A MATHEMATICAL MODEL OF FLASHBLINDNESS

Robert S. Czeh, Arthur W. Casper,
and Ernest C. Segraves, Jr.

FOREWORD

This study was conducted by the General Electric Company, 4000 N. W. 39th Street, Oklahoma City, Oklahoma under Contract AF 41 (609)-2644, Task 630103, with the USAF School of Aerospace Medicine, Aerospace Medical Division, Brooks Air Force Base, Texas. The Contract Monitor was First Lieutenant D. J. Lehmiller, USAF, Oculo-Thermal Section, Ophthalmology Branch (SMKOR). The study was carried out between 1 Nov. 1964 and 31 Aug. 1965. This report was submitted for publication on 20 Dec. 1965.

Arthur L. Korotkin was principal investigator until 30 April 1965; Robert S. Czeh was principal investigator thereafter.

The authors wish to acknowledge the assistance of Christopher W. Zinn, Laurence Oliver, Joseph Dasbach, and Paul G. Rasmussen.

ABSTRACT

In planning certain military missions it is desirable to know the extent to which vision may be impaired by the flashblindness that can result from the intense light of a nuclear explosion. This report describes an attempt to provide assistance to such planning by constructing a mathematical model of flashblindness. The literature was surveyed to determine whether or not the construction of a model was feasible. Using selected data, two equations were developed for predicting recovery time from flash energy, display luminance, and display visual acuity. The prediction errors made were determined in a few situations and compared with the errors made by other prediction techniques. Limitations of the applicability of the equations were noted.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

1.0 INTRODUCTION

A nuclear detonation creates a fireball of such high temperature and luminance level as to constitute a serious hazard to vision well beyond the distance at which blast, shock, or radiation have any significant effects. Approximately 35 per cent of the energy in a typical air burst, at an altitude below 100,000 feet, is thermal radiation (Glasstone, 18). Therefore, a large burst of say two megatons can produce burns of the rabbit retina at a distance of 370 miles (Brown, 6), and even a small burst of 100 kilotons or so can produce threshold retinal burns at 14 miles (Ham *et al*, 19).

In addition to the threat of permanent eye damage, and beyond distances at which eye damage can result (Parker, 34), there is a second visual hazard from nuclear detonation -- flashblindness. Given that the atomic fireball in its early stages can be as much as 100 times as bright as the sun (Byrnes *et al*, 9), a temporary loss of visual adaptation can result from the sudden, intense increase in ambient illumination that accompanies a burst. Severin, Newton, & Culver (40) point out that the inability to read aircraft instruments for as long as 60 seconds can well jeopardize a bombing mission and Hill & Chisum (22) indicate that flashblindness for as short as 5 seconds can have serious consequences for the interceptor pilot, depending on the particular maneuver being undertaken at the time of onset of flashblindness.

A great deal of research has been devoted in recent years to the study of flashblindness and to the development of methods and devices for protecting against flashblindness. A number of protection methods and devices have been suggested; for example --

- Monocular occlusion (Brown, 6)
- Increase in display luminance (Brown, 7; Metcalf & Horn, 30)
- Pupillary miosis (Minners, 33)
- Specialized filter goggles (Plum & Crillz, 38)
- Optical goggle systems (Sneed, Knight, & Hartouni, 44)
- Explosive-lens goggles (Chisum & Hill, 12; Laxar, 27; Lowry, 29; Thomsen, 46)
- Electromechanically-operated goggles (Wayne-George Corp., 50; USAF, 55)
- Louvred-lens goggles (Timm, 47)
- Explosive optical shutters (Britten, 4; Pisano, 36)
- Photochromic filters (Allinikov, 1; Bowman _et_ _al_, 3; Fox, 15)
- Phototropic filters (Harries, 20; Parkhurst, 35)
- Stressed plate shutter (Hauser _et_ _al_, 21)
- Photoconductive electroluminescent films (Sneed, Sacks, & Knight, 45)

Apparently, no present device or method is entirely satisfactory. The devices may for example, respond too slowly, or remain too transparent, or can be used only once. One of the difficulties may be that the basic studies of flashblindness, upon the results of which protective developments are based, have largely been independent and uncoordinated efforts directed at some problem other than protection. As Parker (34) points out, there is obviously a hazard, but knowledge of it is qualitative rather than quantitative; a mathematical model which integrates much of the existing data would be useful in evaluating existing and proposed devices and in writing specifications for devices that are to be developed. The study reported here was accomplished with a view to providing such a mathematical model.

The study was accomplished in three Phases. Phase I consisted of a literature search to identify those studies which provide experimental data of possible use in developing the model. Phase II was devoted to identifying the relevant independent variables and to converting those variables to common units. Phase III was devoted to the development of the model itself.

2.0 LITERATURE SURVEY

The Statement of Work provided a number of titles as a starting point. In addition, searches were made at the Defense Documentation Center, the Medical Index at the National Library of Medicine, and in the Psychological Abstracts, and current issues of relevant journals, whose articles would not yet have been indexed or abstracted, were also searched; the journals searched were, primarily, the various journals published by the American Psychological Association, the Journal of the Optical Society of America, the Journal of the Human Factors Society, and the Journal of Engineering Psychology. The literature search was supplemented by visits to Ohio State University's School of Optometry and to the U. S. Naval Air Development Center's Vision Laboratory.* The visit to Mrs. Miller's laboratory at Ohio State was especially valuable; she supplied some unpublished results from a very recent study which, as it turned out, supplied most of the data on which the model had to be based.

It is believed that almost all the relevant literature available by the end of 1964 was located. Approximately 200 publications provide quantitative data and a great many others discuss flashblindness in qualitative terms or deal with protective methods or devices. Of the 200, only 23 provided data that might be useful for the model; the remainder fail to provide data in a detailed or complete enough form.

Typical results from these 23 studies are plotted on the following pages. In each case, recovery time (on the ordinate) is plotted against

---

* Our sincere appreciation to G.A. Fry and Norma D. Miller of Ohio State and to J.H. Hill of NADC for their help and suggestions.

total flash energy (on the abscissa), and any other variables (e.g., target or display luminance) are parameters. The units of measurement have been standardized as follows. Recovery time is in log seconds. Target or display luminance is in millilamberts (mL) or log mL. Visual acuity is the reciprocal of the visual angle in minutes subtended by the critical detail of the target. Flash energy is given in log troland-seconds or in lambert-seconds. (It had been hoped originally to express flash energy only in troland-seconds, but this was not possible. Few studies provide the information needed to convert to trolands.*) Most luminance unit conversions were made with the aid of the conversion table given in Chapanis (10). A few studies describe the flash in lux; conversion of the corneal illuminance to source luminance was made by means of Equation (71) in Jenkins & White (26).**

Figure 1, replotted from Miller (32), summarizes the results of Russell (39), Metcalf & Horn (30), and Whiteside (52). With respect to the variables flash energy and target luminance, these studies tell much of the story; recovery time increases with flash energy for a time, and then tends to level off; and recovery time increases as target luminance decreases. At flash energies below Russell's lowest (i.e., below approximately 1 L-sec), recovery time becomes shorter still, and may level off as a minimum time is approached; data from Severin, Newton, & Culver (40, 41) plotted in Figure 2 show this (the abscissa is plotted on log paper to stretch out the scale). Brown (8) suggests that there is a minimum recovery time equal to approximately 0.2 sec. which corresponds to visual reaction time and that the

---

* Pupil size can, of course, be estimated. Indeed, such an estimate had to be made to provide the troland-second model with enough data. This is described later.

** The number of different units used to describe the flash is, unfortunately, quite large, and quantitative comparison of results is virtually impossible without converting to some common unit. Vos and his associates (49) call the situation "really embarrassing."

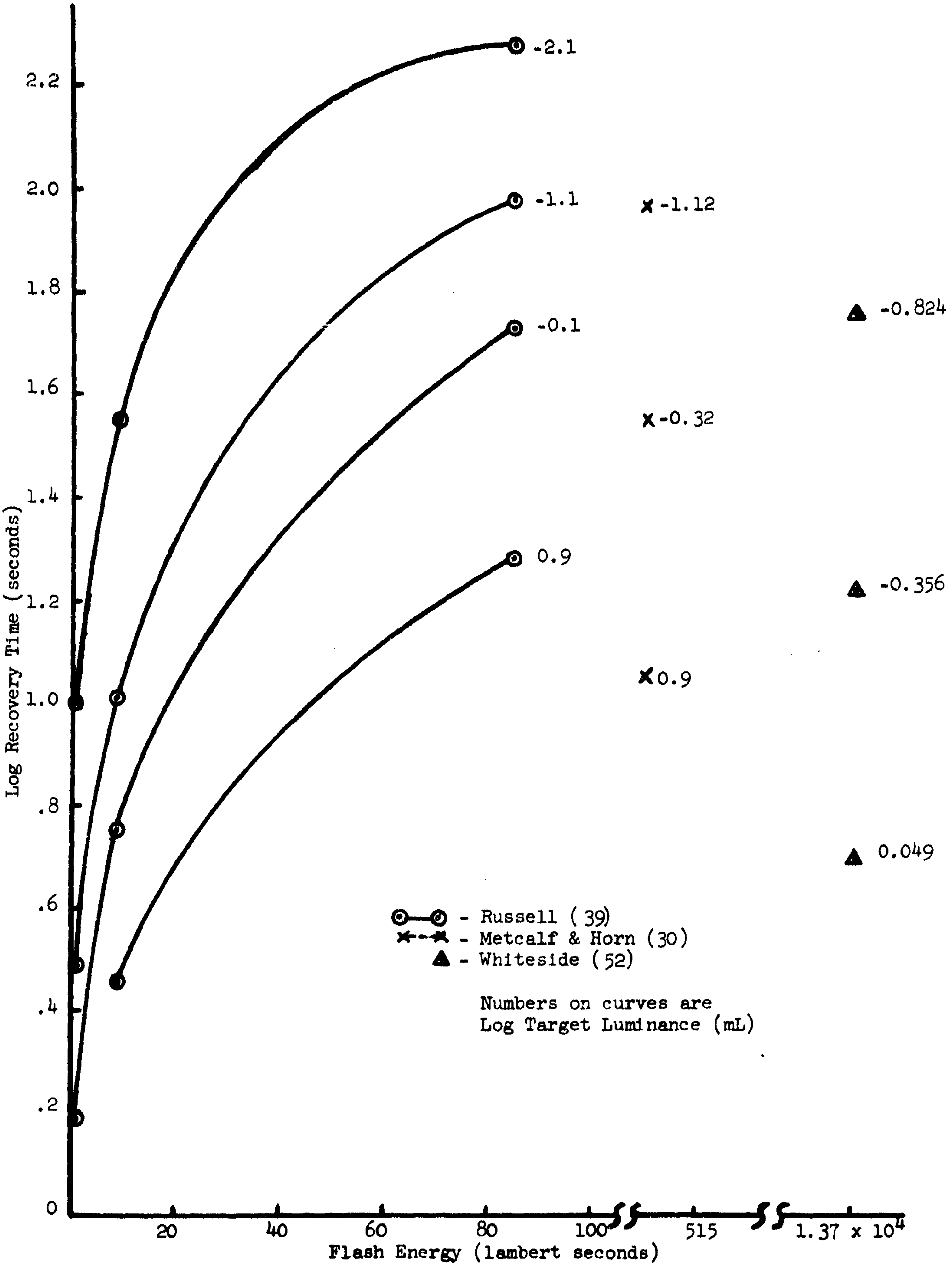

Figure 1. Recovery time as a function of flash energy and target luminance. There is a rapid increase in recovery time followed by a leveling off at high flash energies.

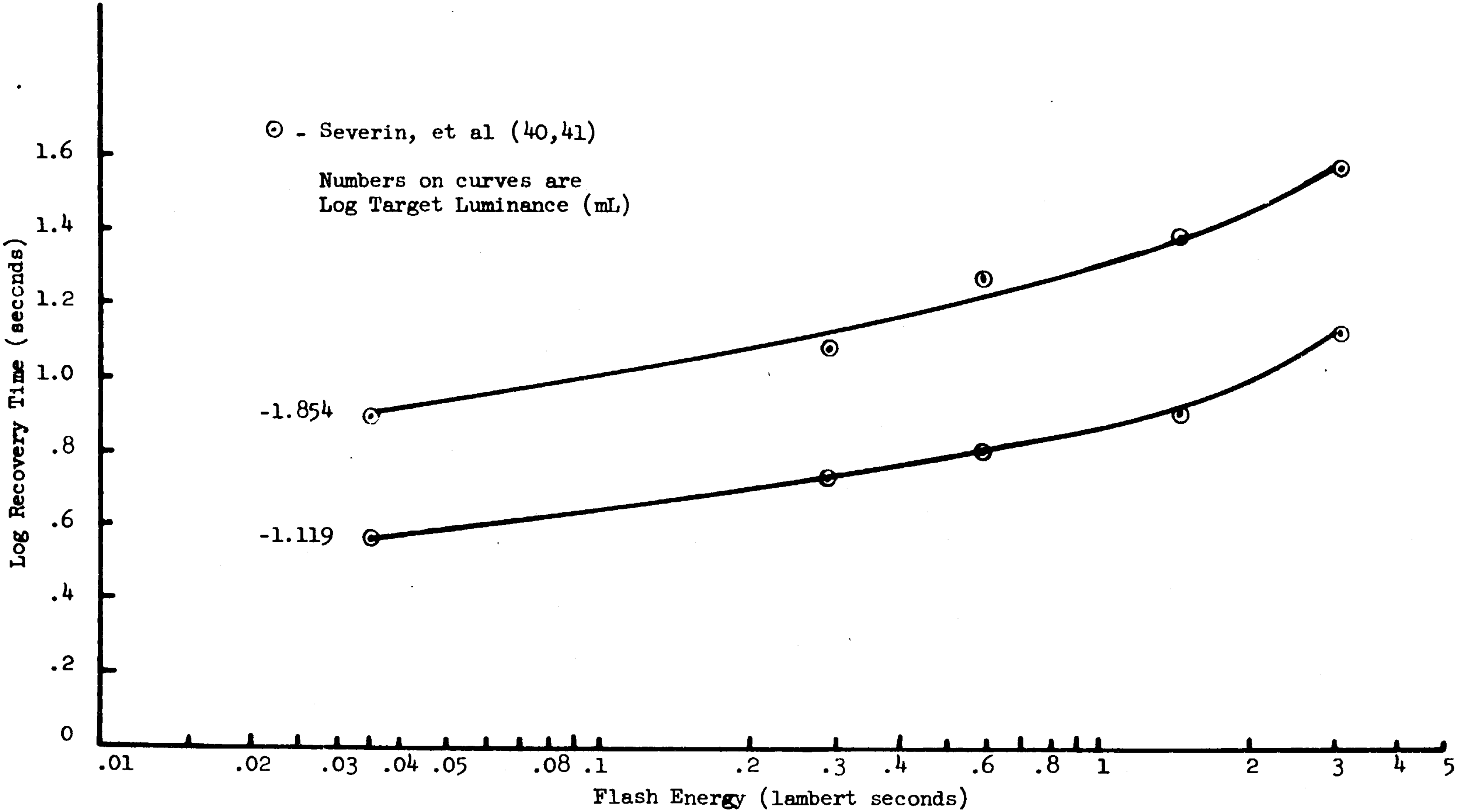

Figure 2. Recovery time as a function of flash energy and target luminance at low levels of flash energy.

tendency for recovery time to level off at the higher energies is due to maximum possible bleaching of the retina's photosensitive substances. Miller (32, and also a more recent unpublished study), using flash energies above 100 L-sec., finds that recovery time increases, but with negative acceleration, as flash energy increases up to approximately 450 L-sec., and then remains essentially constant as flash energy increases further to approximately 1420 L-sec., see Figure 3. Metcalf & Horn (30), Chisum & Hill (11), and Hill & Chisum (23) obtained results that are generally consistent with the foregoing over a range of flash energies from approximately 3 log td-sec to approximately 8 log td-sec; Figures 4 and 5 present these data. As flash energy is increased still further up to 1.57×10^5 L-sec, recovery time may again show positive acceleration; Figure 6 illustrates this with data from Whiteside & Bazarnik (54). Brown (8) suggests that this final positive acceleration reflects real, but reversible, retinal damage; ultimately, irreversible damage and infinite recovery time would result.

It would seem therefore that recovery time varies with flash energy in the following manner. At very low flash energies, recovery time increases with positive acceleration as flash energy increases; the recovery time curve soon inflects and begins a period of negative acceleration and may become quite flat at high energy levels; ultimately, the recovery time curve inflects again and shows a final period of positive acceleration once more, ending presumably in infinite recovery time when irreversible retinal damage occurs. The effect of target luminance is to raise or lower the curve as target luminance decreases or increases since recovery time varies inversely with

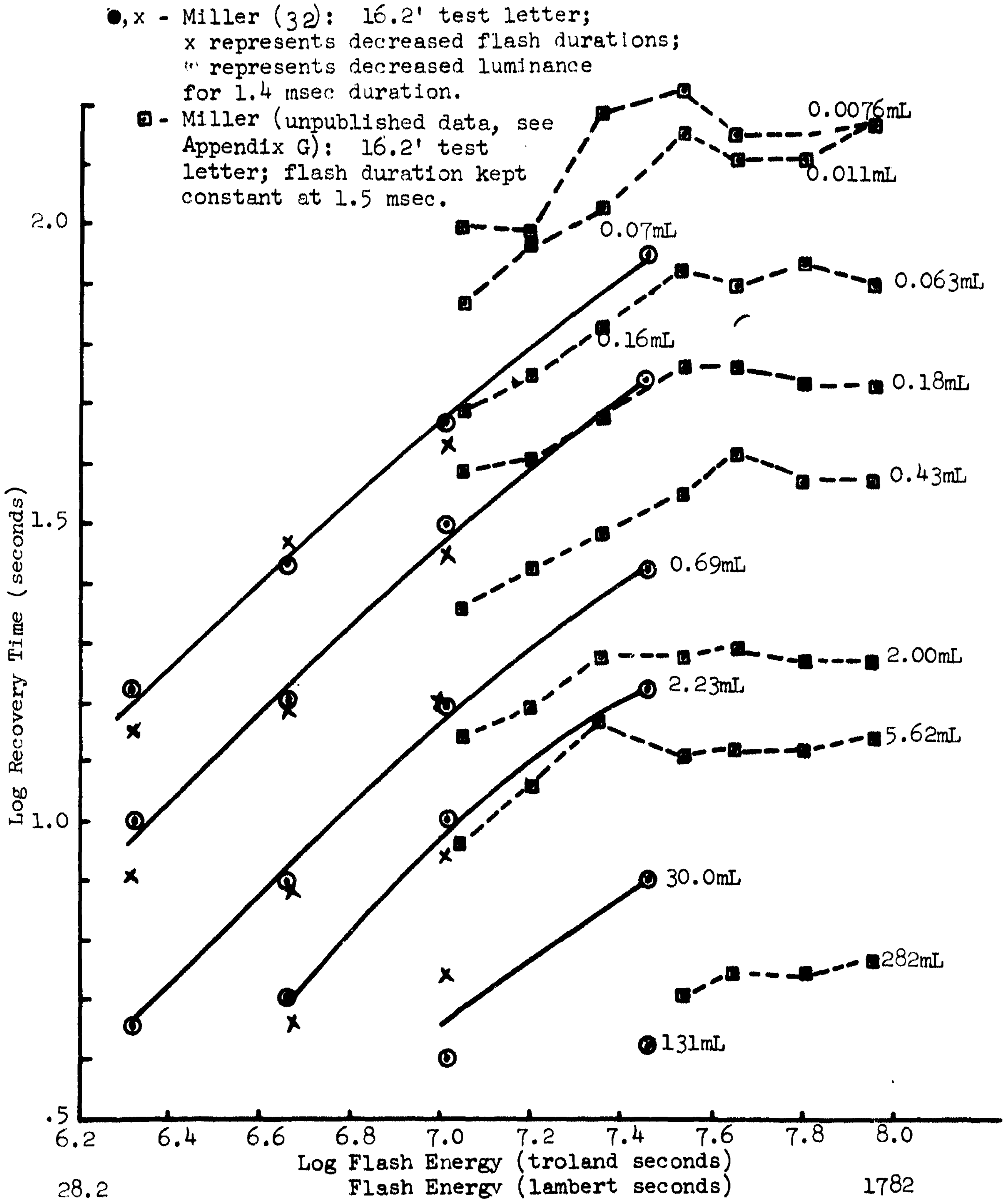

Figure 3. Recovery time as a function of flash energy and target luminance. The flattening out above 7.4 log troland-seconds (450 L-sec.) is clear.

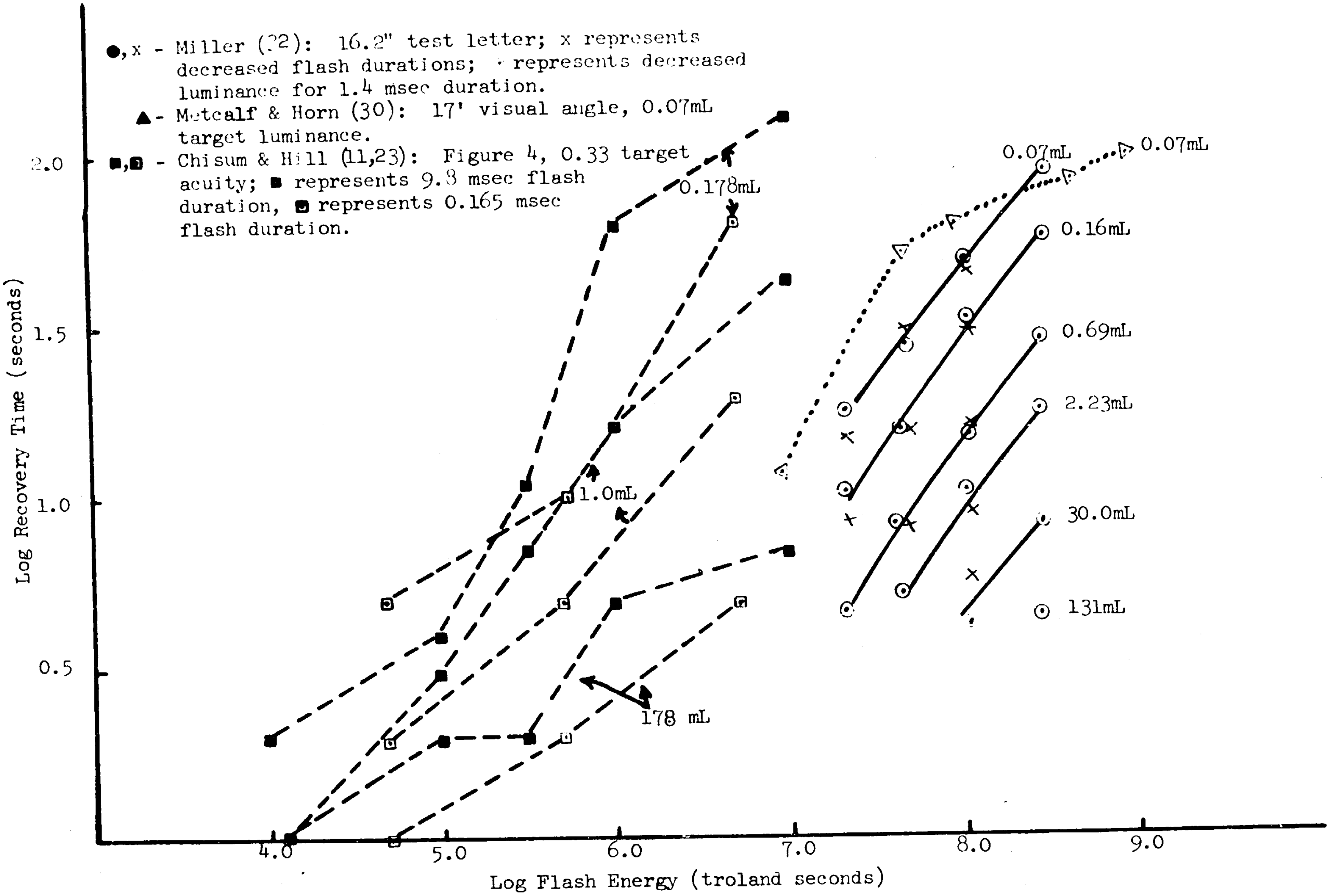

Figure 4. Recovery time as a function of flash energy and target luminance, plotted together with some of the data of Figure 3. The curves for C&H (11,23) are from Part I of their experiment, in which only the display luminance was varied during any given experimental session.

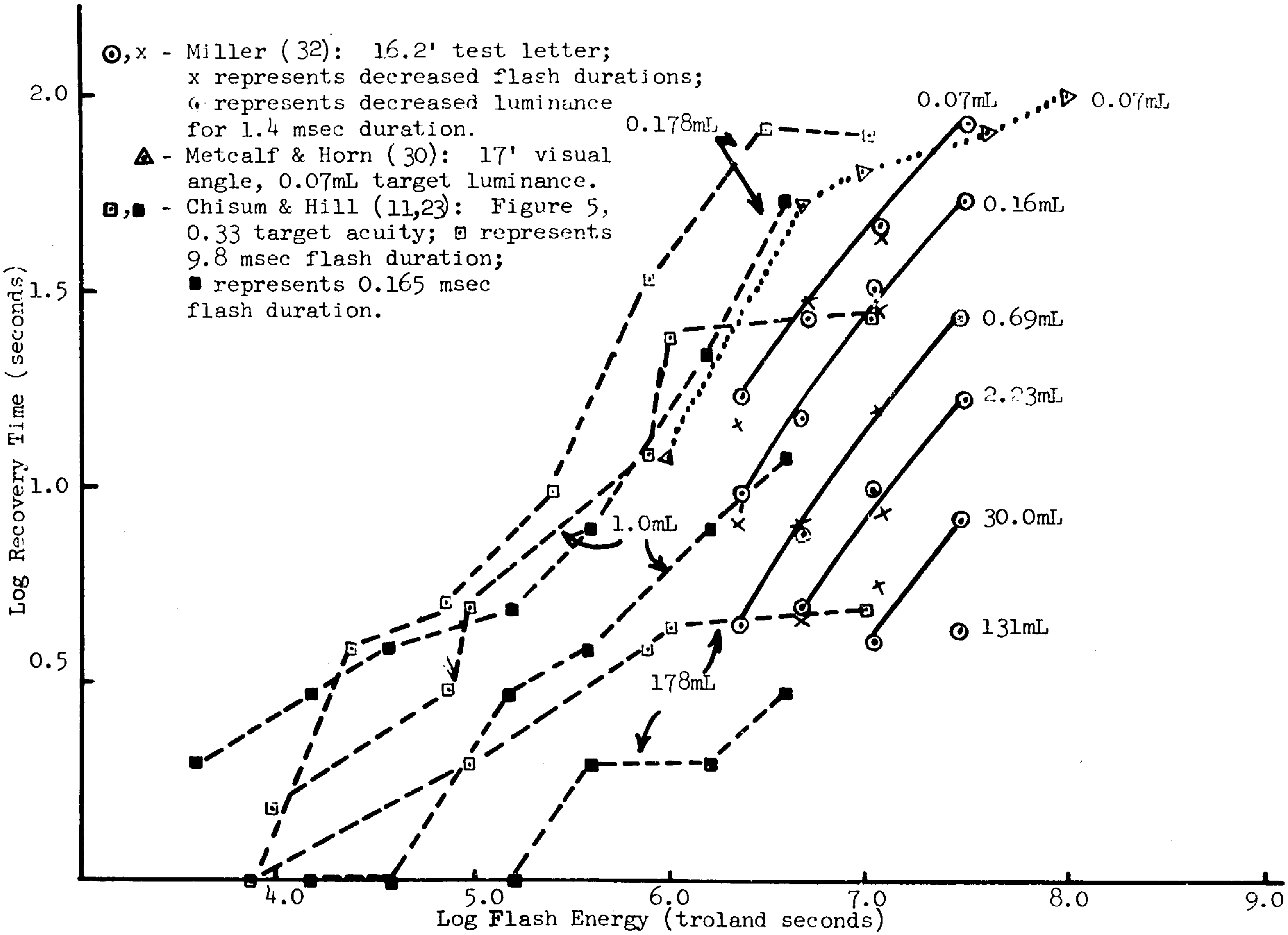

Figure 5. Recovery time as a function of flash energy and target luminance, plotted together with some of the data of Figure 3. The curves for C&H (11,23) are from Part II of their experiment, in which only the adapting flash was varied during any given experimental session.

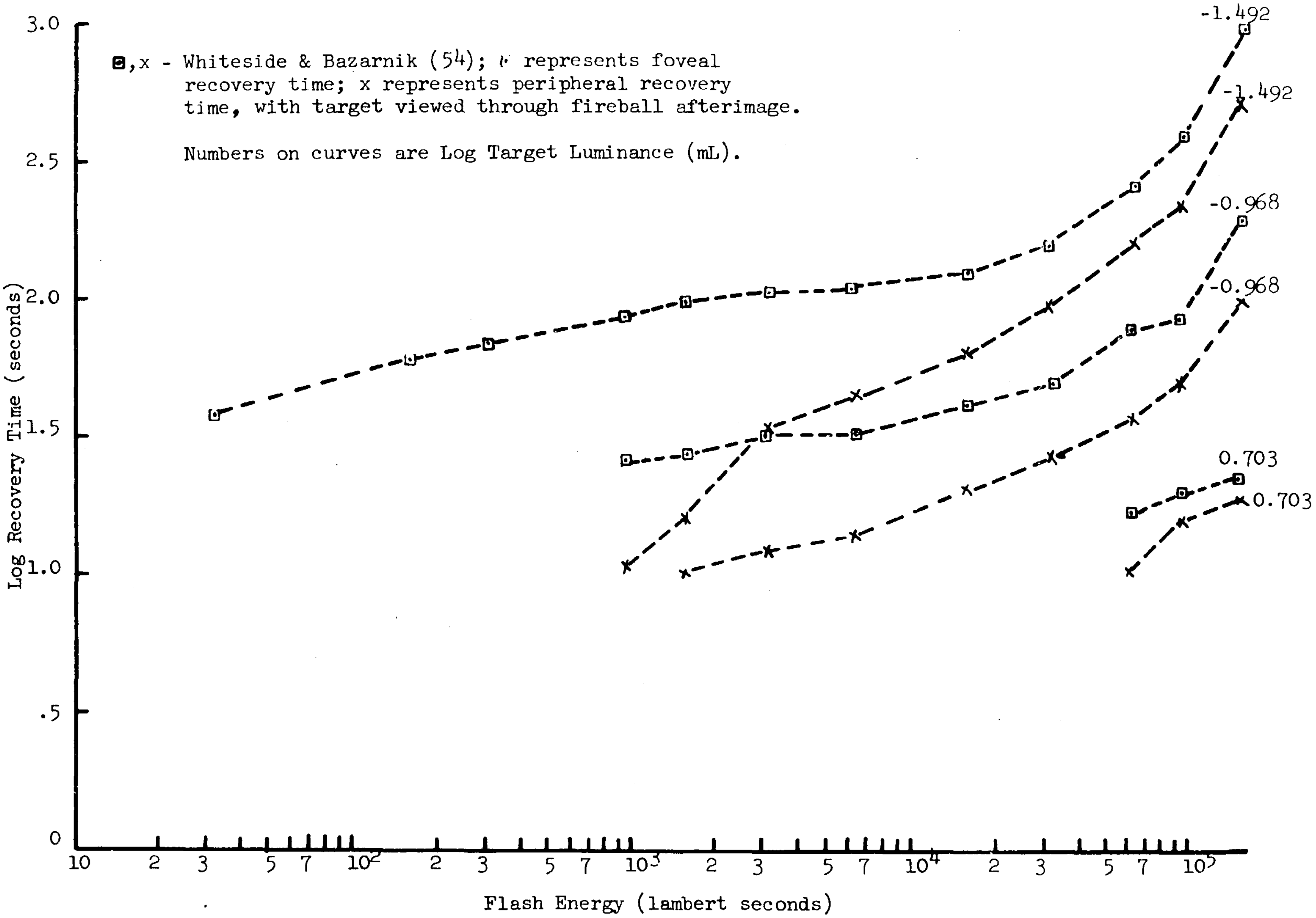

Figure 6. At very high flash energies, recovery time apparently increases very rapidly; but see text. In addition, recovery time depends on whether the target is viewed with the fovea or through

target luminance; the curve is not displaced by target luminance uniformly over its whole extent, however, since there is some anchoring at very low values of flash energy (where recovery time is equal to the reaction time of the visual system) and at very high values of flash energy (where recovery time becomes infinite as a result of retinal damage). Brown's (8) representation of the situation is reproduced here in Figure 7. The conclusions apparently hold over a variety of experimental conditions summarized in Table I.

It should be noted, however, that there is some question concerning at least the location of the upper (high flash energy) end of the curve and possibly concerning the positively accelerated behavior of the curve, even if the intuitive appeal of the positive acceleration is admitted. The data at the high end are from Whiteside and Bazarnik (54). But Whiteside and Bazarnik's light measurements may have been incorrect. Vos, Frederikse, Walraven, & Boogaard (49), drawing on retinal burn data, suggest that the light measurements may indeed have been wrong by a factor of 100 or more. If this is so, the curves of Figure 6 should all be moved at least two log-cycles to the left. Whiteside & Bazarnik's maximum energies would then be approximately 1.57×10^3 L-sec., very nearly equal to Miller's maximum energies. But Miller's recovery time curves are virtually flat at this energy level (cf. Figure 3), while Whiteside and Bazarnik's would be showing positive acceleration.

Several researchers have studied the effect of target visual acuity on recovery time and have found, in general, that recovery time increases as the visual acuity required for the target increases. Figure 8 from Brown (5) shows the results obtained with targets whose visual acuity requirements were 0.33 and 0.13 respectively. Brown's targets were gratings of alternating

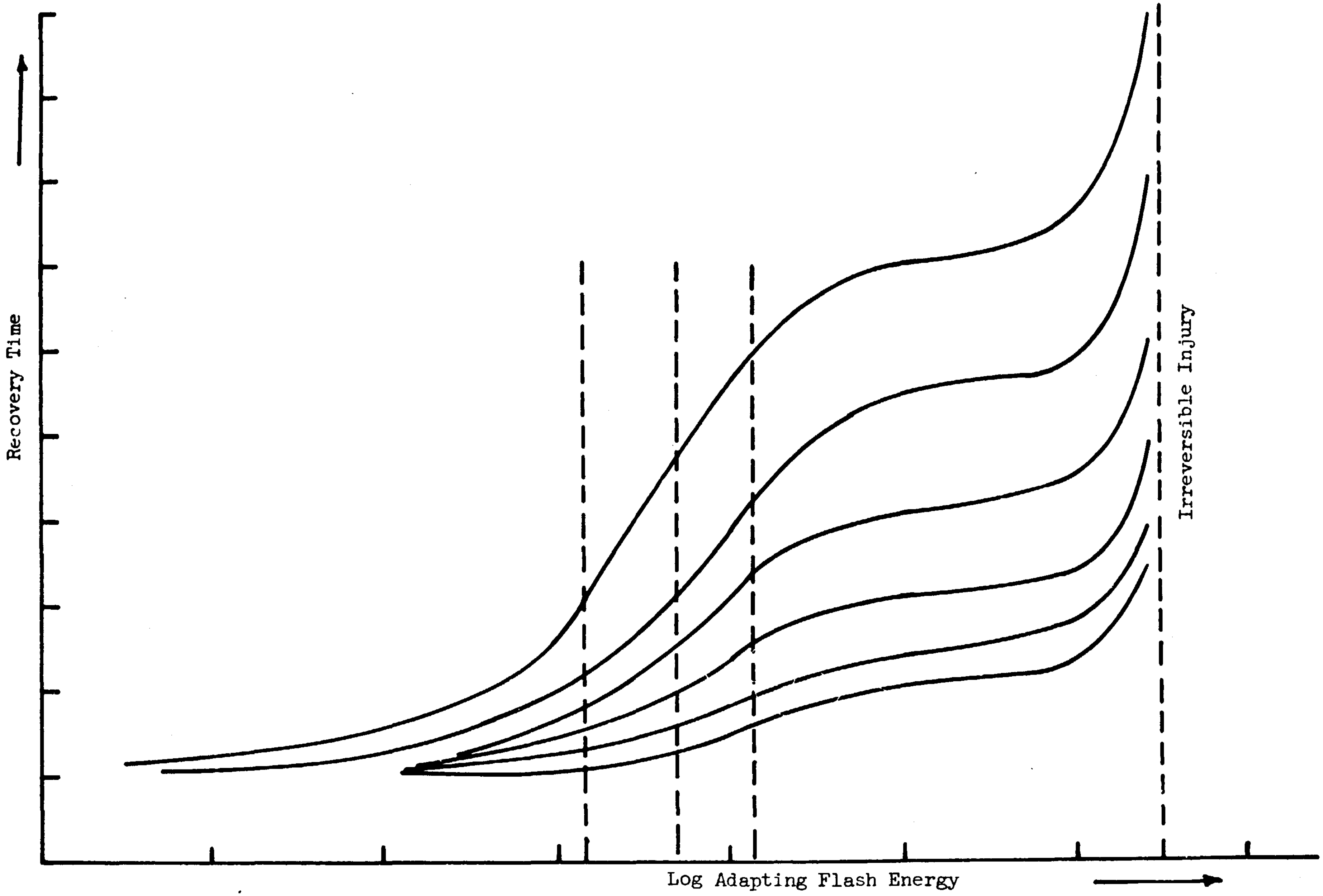

Figure 7. Hypothetical functions showing the manner in which recovery time varies with flash energy and target luminance. Target luminance increases from a low value for the top curve to a high value for the bottom curve. (From Brown, 8.) The effect of target visual acuity is much the same, except that the bottom curve is associated with a low visual acuity requirement and the top curve with a high visual acuity requirement.

TABLE I
A COMPARISON OF EXPERIMENTAL TECHNIQUES

Reference # and author	Pupil Size	Visual Angle	Description of Source and Pre-Test Procedures	Adapting Flash Duration	Description of Target	Size of Critical Detail in Target	Region of the Retina Stimulated
Brown(7)	—	14°	Xenon arc (dark adapted for 20 min.)	0.95 sec	Grating pattern of parallel, opaque lines separated by clear spaces equal in width to the lines. The display area subtended a visual angle of 1°18' at eye of observer. The circular display area was centered in the adapting field area.	Visual acuity of 0.26 and 0.08	A circular area of the retina 1°18' in diameter and centered at a point approx. 39' temporal from the center of the fovea along the horizontal meridian.
Brown (5)	—	15°	Hanovia compact Xenon arc (dark adapted for 15-20 min.)	0.9 sec	Parallel lines and spaces of equal width ruled on glass. The display area subtended a visual angle of 1° at the exit pupil. The center of the test field stop coincided with the center of the 15° adapting field.	Visual acuity of 0.33 and 0.13	—
Whiteside & Bazarnik(54)	—	7.5°	sun (observers were dark adapted)	0.01 - 1 sec	An air speed indicator illuminated by four standard ultraviolet cockpit lamps which were so disposed as to give equal illumination.	—	Flash is centered on the fovea.

(Continued)

(Continued)

Reference # and author	Pupil Size	Visual Angle	Description of Source and Pre-Test Procedures	Adapting Flash Duration	Description of Target	Size of Critical Detail in Target	Region of the Retina Stimulated
Metcalf & Horn (30)	6 mm diameter	3°58'	carbon arc searchlight (pre-adaptation in room of 0.07 ft. candle for 15 min.)	0.1 sec	An adaptometer, i.e., a 25 mm circular opening thru which a light bulb flashes on and off at 1 sec. intervals. The contrast between on and off is regulated by placing filters between the lightbulb and the circular opening. Recovery is defined as recognizing the contrast for two successive on-off cycles.	A 17 min. arc test stimulus	——
Chisum & Hill (11, 23)	5 mm diameter	15°	Xenon-filled helical flash lamp (observer dark adapted for 20 min)	0.03, 0.165, and 9.8m sec	Acuity gratings requiring visual acuity of 0.13 and 0.33 (acuity levels = reciprocal of visual angle in minutes). Observer is to resolve the grating and tell its orientation (vertical or horizontal).		
Russell (39)	——	2°,20°	Filament lamp (No pre-test procedures mentioned.)	0.003 - 10 sec	A black silhouette of a monoplane (seen from dead ahead) of a size corresponding to an airplane of 50 feet span at a distance of 300 yards. This target was pinned on a white board which was illuminated to give various background brightnesses. Target subtended 3.2° at observer's eye. Flash coincided with target. Black ring superimposed on airplane silhouette.		

(Continued)

(Continued)

Reference # and author	Pupil Size	Visual Angle	Description of Source and Pre-Test Procedures	Adapting Flash Duration	Description of Target	Size of Critical Detail in Target	Region of the Retina-Stimulated
Whiteside (53)	4mm diameter (estimated)	about 17°	fireball of nuclear explosion. (The unprotected eye looked 3° to the side of the fireball.) Also modified calibration source.	100 m sec	Adaptometer	1°-2° illuminated square	
Miller (32; unpublished data, appendix G)	4.1 mm x 4.3 mm	2.5° to 10°	Maximum flash field luminances of 5.4×10^{5}L produced by Xenon-filled discharge tube seen by Maxwellian view.	.04 m sec to 1.4 m sec	Sloan-Snellen test letters of four sizes corresponding to from 42 to 14.3 min of arc.		
Severin, et al (40,41,42,43)	Measured for each subject after preparation using miotic or mydriatic agent. Mean pupil diameters were 2.20 mm, and 7.43 mm	63° 20'	Zeiss light coagulator. Eight illuminance levels from 645 lux to 242,100 lux.	150 m sec	Goldman-Weekers adaptometer. Two test patches of .06 and .013 ft.-L and 25 mm in diameter		

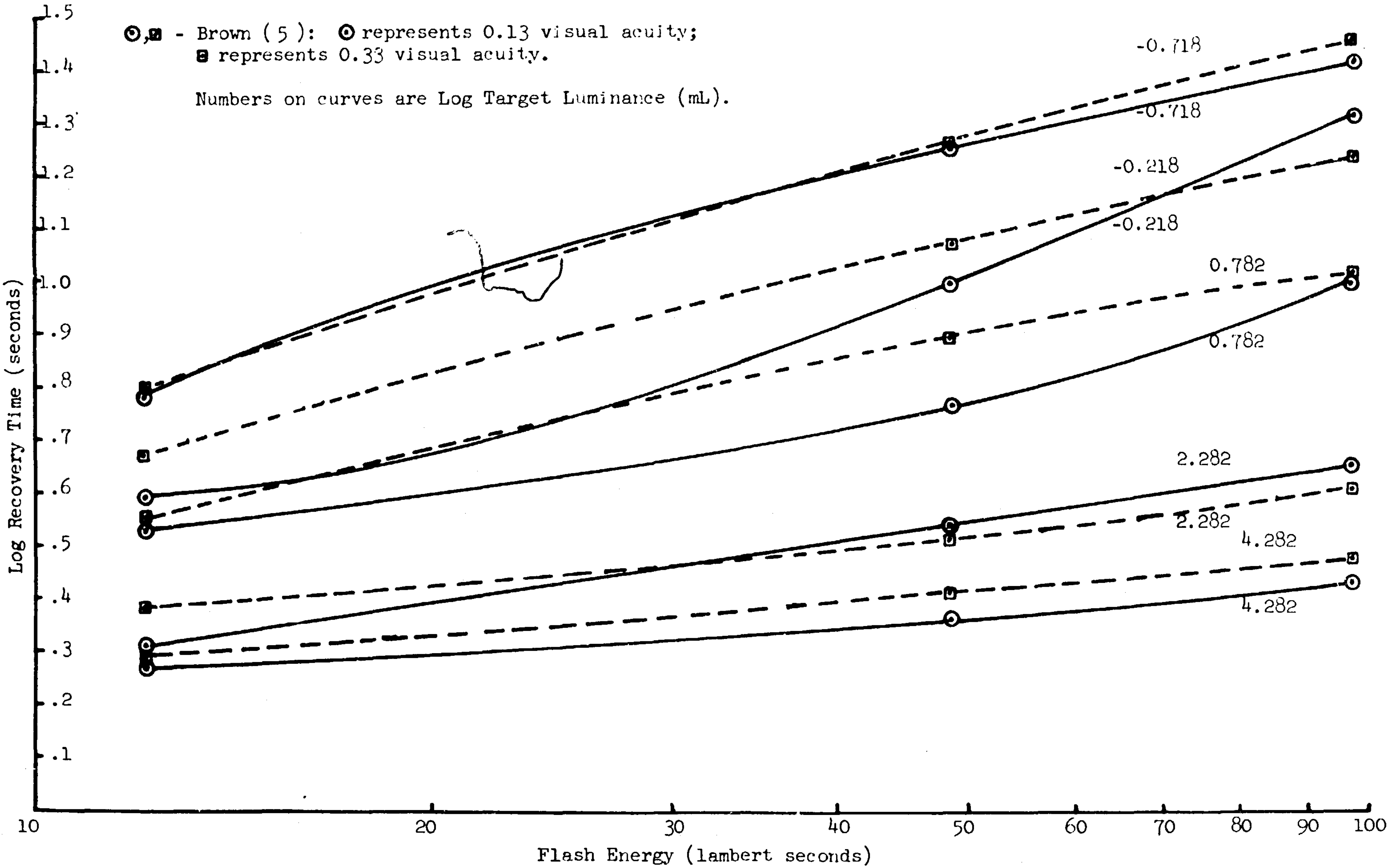

Figure 8. In general, recovery time increases as the target visual acuity increases. The targets are acuity gratings.

black and white bars of equal width; visual acuity is the reciprocal of the visual angle subtended in minutes by any one bar. Miller (32) obtained similar results, as shown in Figure 9. Her targets were individual Snellen letters; visual acuity is therefore given by the reciprocal of one-fifth the visual angle in minutes subtended by the entire letter. Brown (7) has also shown that target visual acuity interacts with target luminance. Figure 10 shows the situation. At low target luminance, recovery time is shorter for targets requiring less visual acuity, while at high target luminance, the effect of visual acuity is virtually nil; obviously, however, the effect of visual acuity cannot be completely nil, at high luminances, since the target must be one that can be perceived under normal conditions. But see Figure 8.

The studies summarized thus far all delivered the flash to the fovea and measured recovery time with the target viewed through the flash's afterimage. Whiteside (53) delivered the flash to the parafovea and measured recovery time with adaptometer targets viewed with the fovea and compared these with recovery times while viewing targets through the afterimage; the data were gathered during an atomic weapon test, with the flash supplied by the burst. Table II summarizes the results. At each target luminance, the recovery time with the target viewed with the fovea is shorter than the recovery time with the target viewed through the afterimage; and, of course, recovery time increases as target luminance decreases.

Severin and his associates (42,43) have studied the effect of natural pupil size on recovery time. Since the pupil opening (whether that pupil be natural or artificial) controls the amount of energy delivered to the retina, manipulation of pupil size, given a constant-energy flash, should yield results

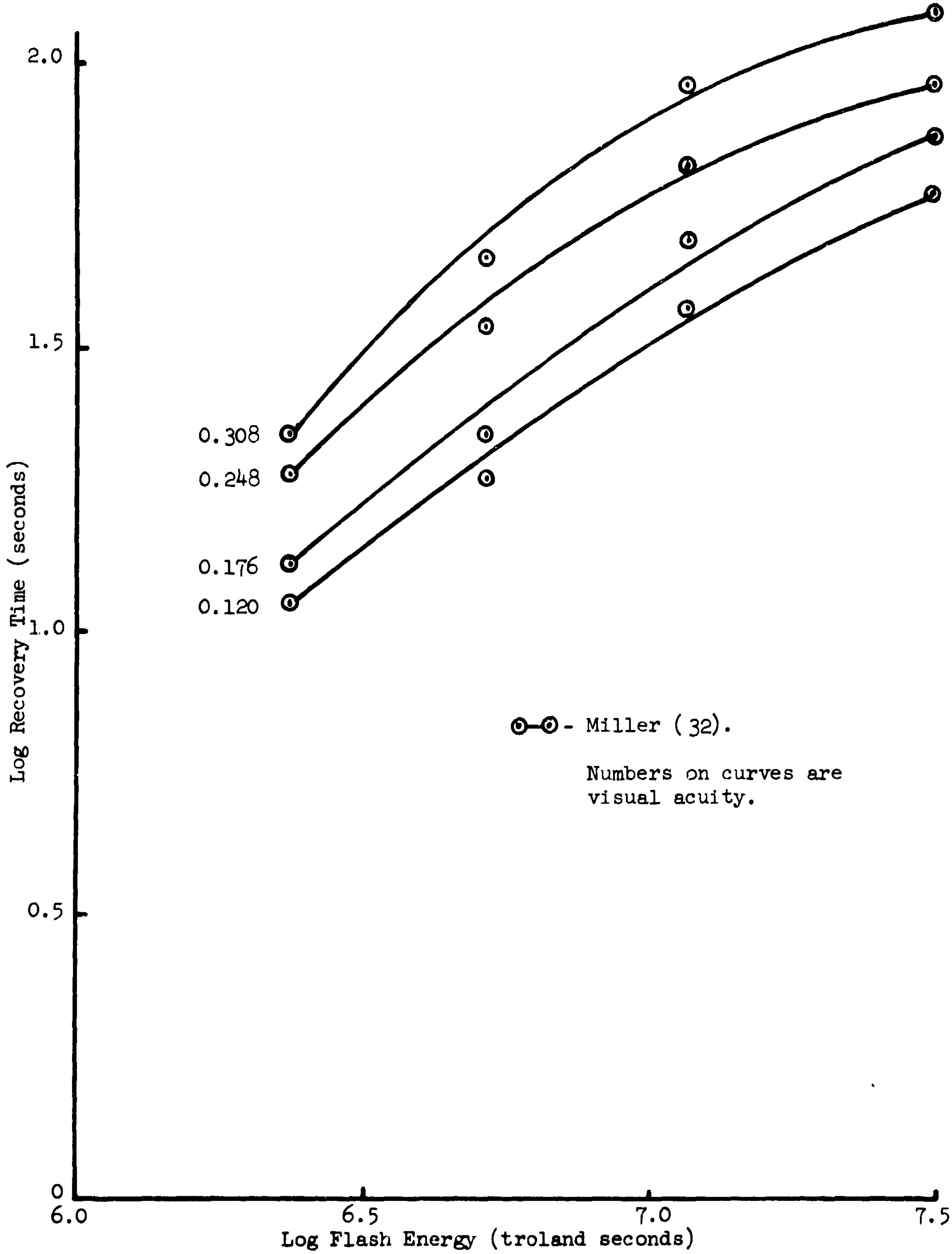

Figure 9. Recovery time as a function of flash energy and target visual acuity. The targets are Snellen letters at 0.07 mL.

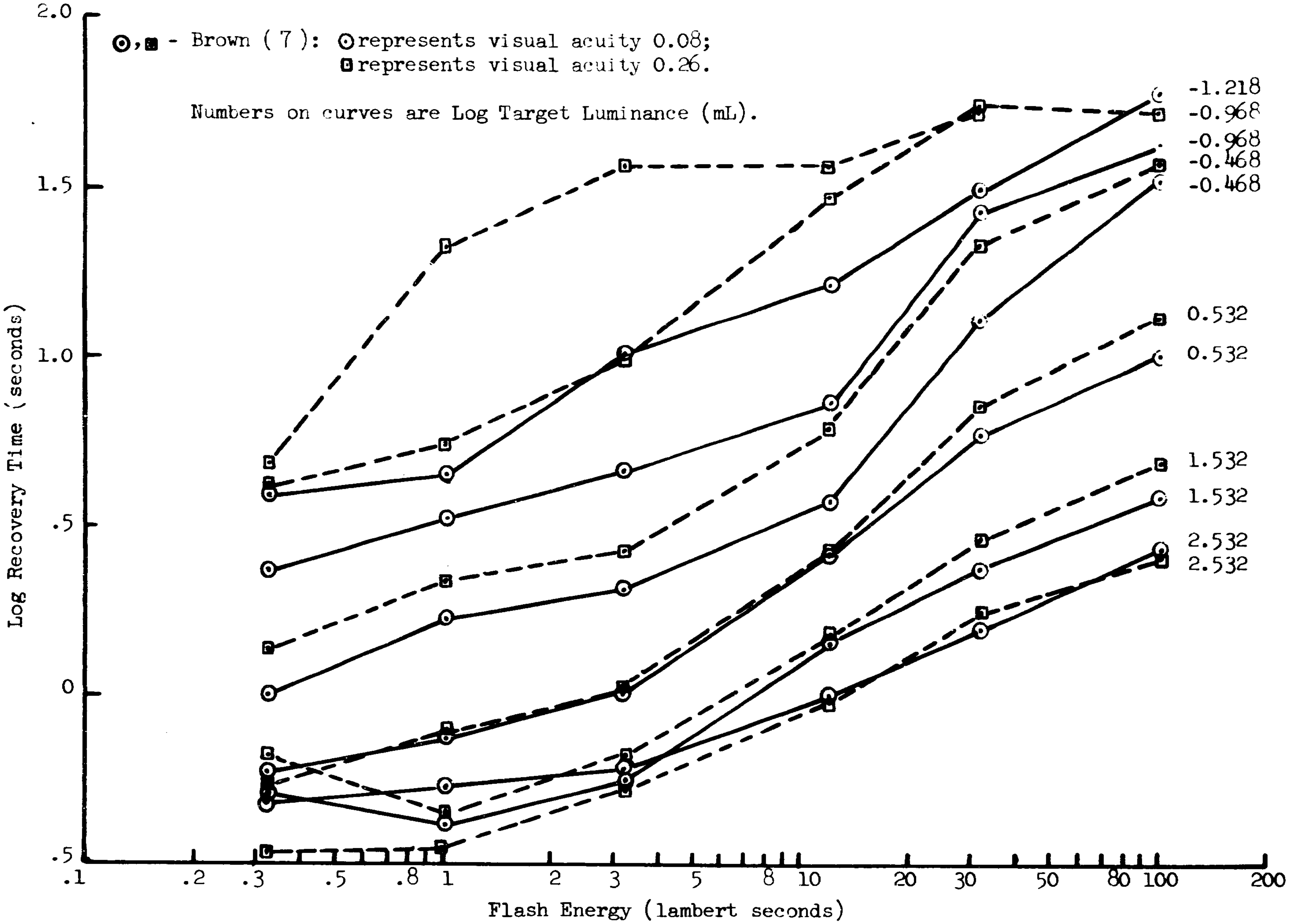

Figure 10. Apparently, the effect of target visual acuity decreases as target luminance increases. But see Figure 8, where the interaction is by no means as clear.

TABLE II

COMPARISON OF FOVEAL VISUAL RECOVERY TIMES AND RECOVERY TIMES FOR A TARGET VIEWED THROUGH THE FIREBALL AFTERIMAGE - WHITESIDE (53)

Adaptometer Luminance			Foveal Recovery Time log sec	Recovery Time thru Fireball Afterimage log sec	Fireball Luminance Integrated to 100 msec	
ft.L	mL	log mL				
1.04	1.12	0.049	0.70	1.45	5.53×10^8 td.sec	1.382×10^4 L.sec
0.41	0.44	-0.356	1.23	1.60		
0.14	0.15	-0.824	1.76	1.95		

similar to those obtained by manipulation of a flash source, given a constant pupil size. Severin et al's results do not coincide with these expectations. Using drugs to dilate or constrict their subjects' pupils, the time required to perceive an adaptometer target after a flash was measured yielding the results shown in Figure 11. Within each pupil size condition, recovery time increases as flash energy increases, and recovery time for brighter targets is less than for dimmer targets, as expected. But the results obtained between pupil size conditions are surprising. For each target luminance, the small pupil curve should be continuous with the large pupil curve. Instead, the curves are not only discontinuous but in addition differ from one another only a very little; indeed, for the more dimly illuminated target, the average recovery time associated with the small and large pupil curves do not differ significantly.

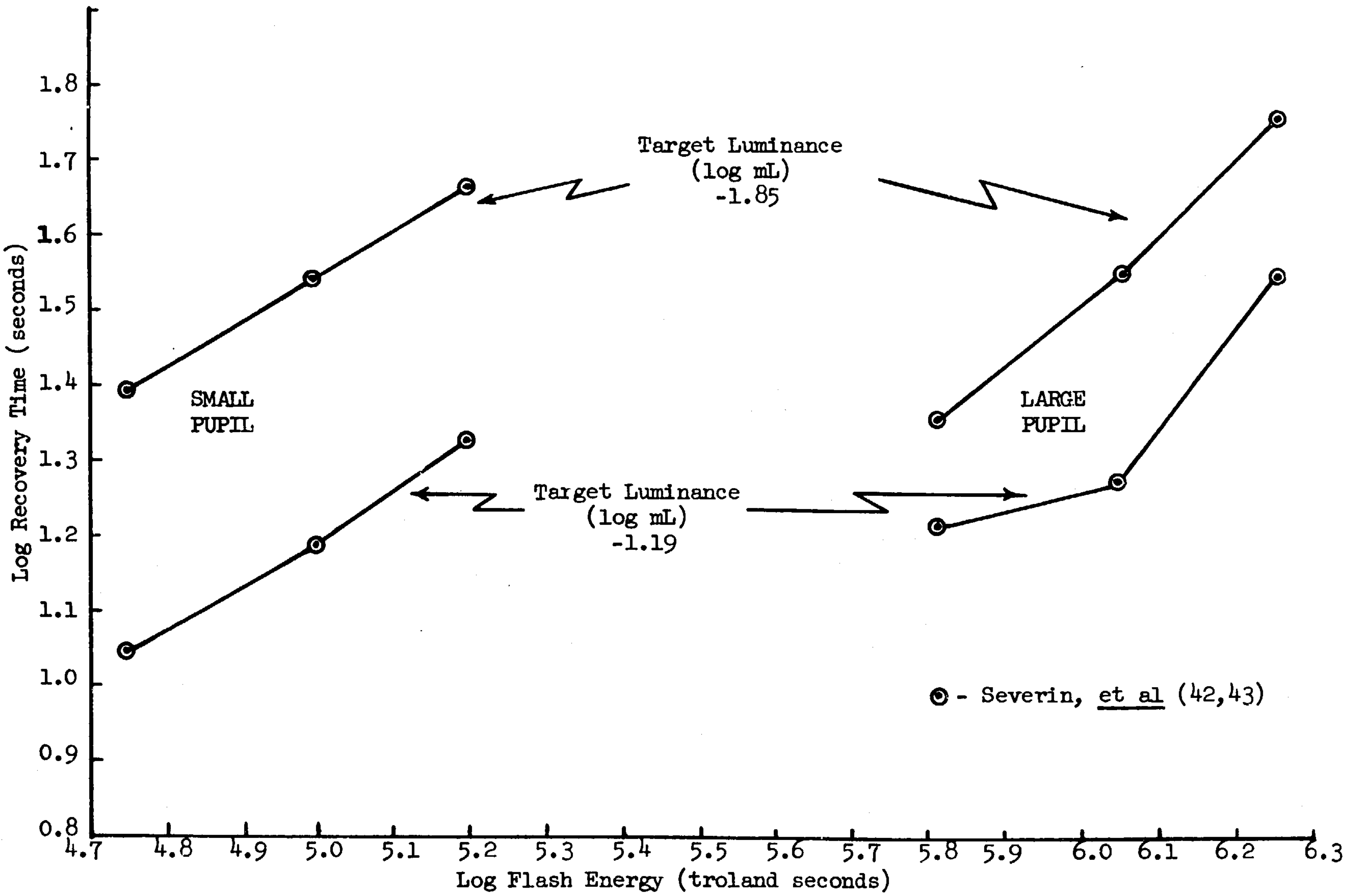

Figure 11. Recovery time as a function of the size of the natural pupil.

3.0 CONCLUSIONS BASED ON THE LITERATURE SURVEY

3.1 The most effective determiners of recovery time appear to be flash energy, target luminance, and target visual acuity. Recovery time increases as flash energy and target visual acuity increase, and decreases as target luminance increases. Visual acuity and target luminance may interact such that the effect of acuity lessens as target luminance increases.

3.2 Given that the eye is not damaged, recovery time changes but little at flash energies between 1400 L-sec. (and perhaps less) and 1.37×10^4 L-sec. for the targets, target luminances, and target visual acuities used in these studies. At still higher flash energies, recovery time probably increases again (and possibly very rapidly), but this may be due to actual, though reversible, retinal damage; caution is necessary here, though, since objections can be raised concerning the study on which this conclusion is based.

3.3 As would be expected because of the wide variety of flash sources, targets, subjects, experimental procedures, etc., used in these studies, the various findings differ from one another in specific details. But in all but one case, the detailed findings are consistent with the main conclusions stated above. There is, indeed, enough consistency to warrant an attempt at generating a mathematical model to predict recovery time from flash energy, target luminance, and target visual acuity.

4.0 SELECTION OF DATA FOR AND SUMMARY OF THE MODELING EFFORT

The modeling effort was defined as one of determining an equation which can be used to predict recovery time from virtually any arbitrary set of flash energy, target luminance, and target visual acuity conditions. Multiple regression techniques were chosen to fit a mathematical function to the data.

This pair of decisions eliminated certain studies from the modeling effort immediately. Whiteside & Bazarnik (54) and Whiteside (53) cannot be used since they provide no exact data concerning the visual acuities of their targets. Chisum & Hill (11), Hill & Chisum (23), Metcalf & Horn (30) and Russell (39) are eliminated since their data are presented only in graphs which cannot be read at all accurately.

It was also decided to eliminate data which were inconsistent with the general trend of the findings or about which there can be some valid question raised as to procedure, calibration, etc. Whiteside & Bazarnik (54) is therefore omitted because of Vos *et al*'s (49) objections to source calibration. Severin *et al* (42) obtained results (cf. Figure 11) very much different than expected; just what mechanism is involved in producing their deviant results is not known, but it almost certainly has to do with the drug-induced pupil constriction or dilation. The study certainly deserves replication and extension to determine whether or not manipulation of the natural pupil does in fact have effects beyond those expected from increasing and decreasing retinal illuminance by manipulation of the flash source, but for the present the study has been eliminated from the model-building effort to avoid perturbing the model unduly. The same researchers also used drugs to dilate the pupil in an earlier study (Severin *et al*, 40,41), and this study also was therefore eliminated.

Miller's latest data were used as the basis for the modeling effort.* Figure 3 is typical of the data used. To provide a great enough range of flash energies, data from Brown (5,7) were also included.

Two power series function equations have been developed, one using lambert-seconds as the main independent variable, the other using troland-seconds as the main independent variable. For the first, Miller's troland-seconds were transformed to lambert-seconds using an exact conversion. Brown's flash energies, given in foot-lambert-seconds, were converted to lambert-seconds and to troland-seconds. Since Brown does not present data concerning his subjects' pupils an exact conversion to troland-seconds was not possible. However, estimates of the pre-flash pupil size, and of the change in pupil size during the flash, were made in order to convert to troland-seconds.

An attempt was also made to fit Miller's data with a Gompertz function (Lewis, 28), an equation suggested by Brown (8) was examined, and an approach to recovery time prediction suggested by Miller** was studied. There was also a brief examination of the influence of intersubject differences. These various efforts are described in the following sections.

---

* These data are unpublished, but were supplied to us by Mrs. Miller, for which we are grateful. The data are displayed in Appendix G.

** Personal communication.

5.0 MATHEMATICAL MODEL DEVELOPMENT

The problem is that of finding a function relating flash blindness recovery time to the three variables, source energy, recovery target luminance, and target visual acuity. Multiple linear regression (m.l.r.) programs were used to fit a mathematical function to 1306 data points. The accuracy with which the function fits the data is determined by calculating the standard error and the coefficient of determination. Variation between subjects was taken to be random and the Bunsen-Roscoe Law was assumed to hold.

The source energy is expressed in two different units (lambert-seconds and troland-seconds); an equation was developed for each.

The data used are in Appendix G, Tables G.1 through G.4 (1049 data points from Miller), Appendix B, Table B.1, and Appendix C, Table C.1 (257 data points from Brown). The Multiple Linear Regression programs used (G.E. No. CD 225D3.001) were coded by the General Electric Company Computer Department. Version II of this program uses the stepwise procedure outlined by Efroymson (14) and described briefly in Appendix M.

Brown's adapting flash energies in ft-lamberts were converted to lambert-seconds and to troland-seconds. Miller expresses the adapting flash energy in troland-seconds. The following equation was used for converting between lambert-seconds and troland-seconds:

$$\int_0^T I_T \, dt = \int_0^T (3.183 \times 10^3) \; I_L \, A(t) \, dt \qquad (1)$$

A (t) is pupil area as a function of time
I_T is the retinal illuminance in trolands

I_L is the source intensity in lamberts.

If the Busen-Roscoe Law holds, then Equation (1) can be written in the following form:

$$I_T = 3.183 \times 10^3 \, I_L \int_o^T \frac{A(t)\, dt}{T} \tag{2}$$

For the duration of the flash, Miller restricted the pupil size with an optical stop; hence, the pupil area A(t) was constant and equal to the area of the optical stop, 17.63 mm^2. In this case Equation (2) may be written as follows:

$$I_T T = 3.183 \times 10^3 \, I_L \, A(t) \, T$$

and

$$E_T = 3.183 \times 10^3 \, A(t) \, E_L$$

where

$$E_T = I_T T = td - sec$$

$$E_L = I_L T = L - sec$$

given that A (t) = 17.63,

$$E_T = 56.116 \times 10^3 \, E_L$$

and $\text{Log } E_T = 4.74909 + \text{Log } E_L$

Rearranging terms,

$$\text{Log } E_L = \text{Log } E_T - 4.74909 \tag{3}$$

Equation (3) may also be derived as follows:

$$\text{Trolands} = (\text{candles}/m^2)\,(A\,(t))$$

But:

$$\text{Candle}/m^2 = (3.183 \times 10^3) \text{ Lamberts}$$

and therefore

$$\text{Trolands} - (3.183 \times 10^3) \text{ Lamberts } (A(t))$$

and

$$E_T = (3.183 \times 10^3)\, E_L \,(A(t))$$

rearranging terms,

$$E_L = \frac{E_T}{(3.183 \times 10^3)(A(t))}$$

Substituting $A(t) = 17.63$ mm^2 and taking logarithms

$$\text{Log } E_L = \text{Log } E_T - 4.74909$$

Equation 3 was used to convert Miller's data to log E_L (lambert-seconds).

The procedure for transforming Brown's data to troland-seconds was as follows. For the duration of the flash Brown permitted the natural pupil to act as a stop. However, Brown's subjects were exposed to the flash for intervals of 0.90 seconds (5) and for 0.95 seconds (7), and therefore the stop (pupil) area A(t) decreased with time. Since his subjects were dark adapted for about 15 or 20 minutes, it was assumed that the pupil was at its maximum of about 50 mm^2 initially. The upper curve in Figure 12 (taken from Bartley, 2, Figure 65) represents the change in pupil area as a function of time for exposure to light of 100 millilamberts. For light of a higher intensity, a more rapid pupil response would be expected, as is shown in the lower curve of Figure 12. This lower curve was derived in the following manner. The first point is defined by the dark-adapted pupil. The last point comes from Figure 13, which is extrapolated from Bartley's Figure 64. (That the eye will not tolerate 100 Lamberts for six seconds is immaterial; a theoretical end-point is all that is needed here.) Given the first and last points, the lower curve in Figure 12 was simply sketched in "parallel" to the upper curve.* The mean value of pupil area was found by integrating

---

* There are certainly some errors here. For example, the pupil response latency (possibly as short as 120-140 msec., according to studies now underway in Miller's laboratory) has been ignored. In addition, the rate of response shown in the lower curve of Figure 12 may be too low. Some of Miller's Ss give a maximum constriction in 1 sec. or so.

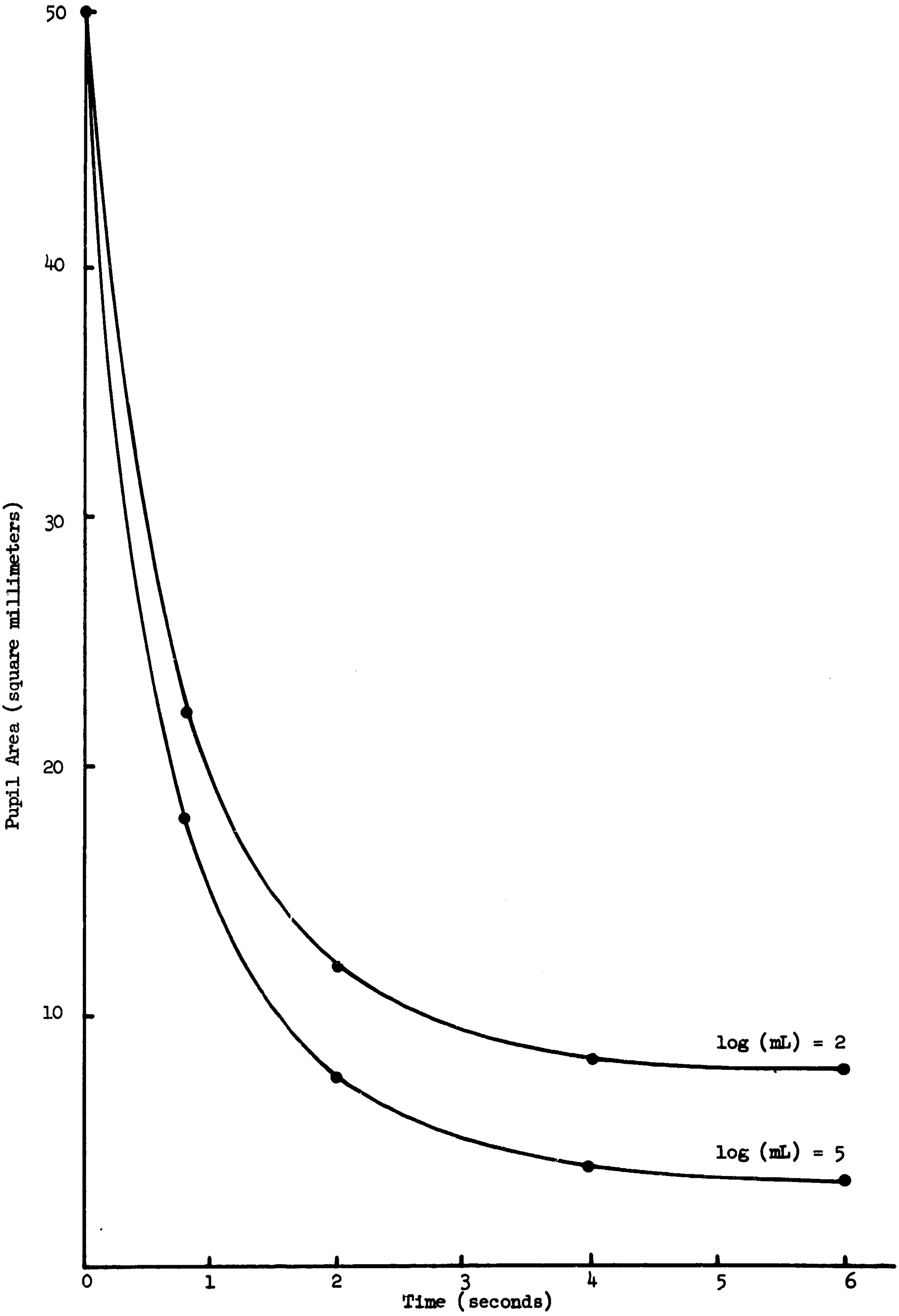

Figure 12. Relation between pupil area and duration of exposure to light.

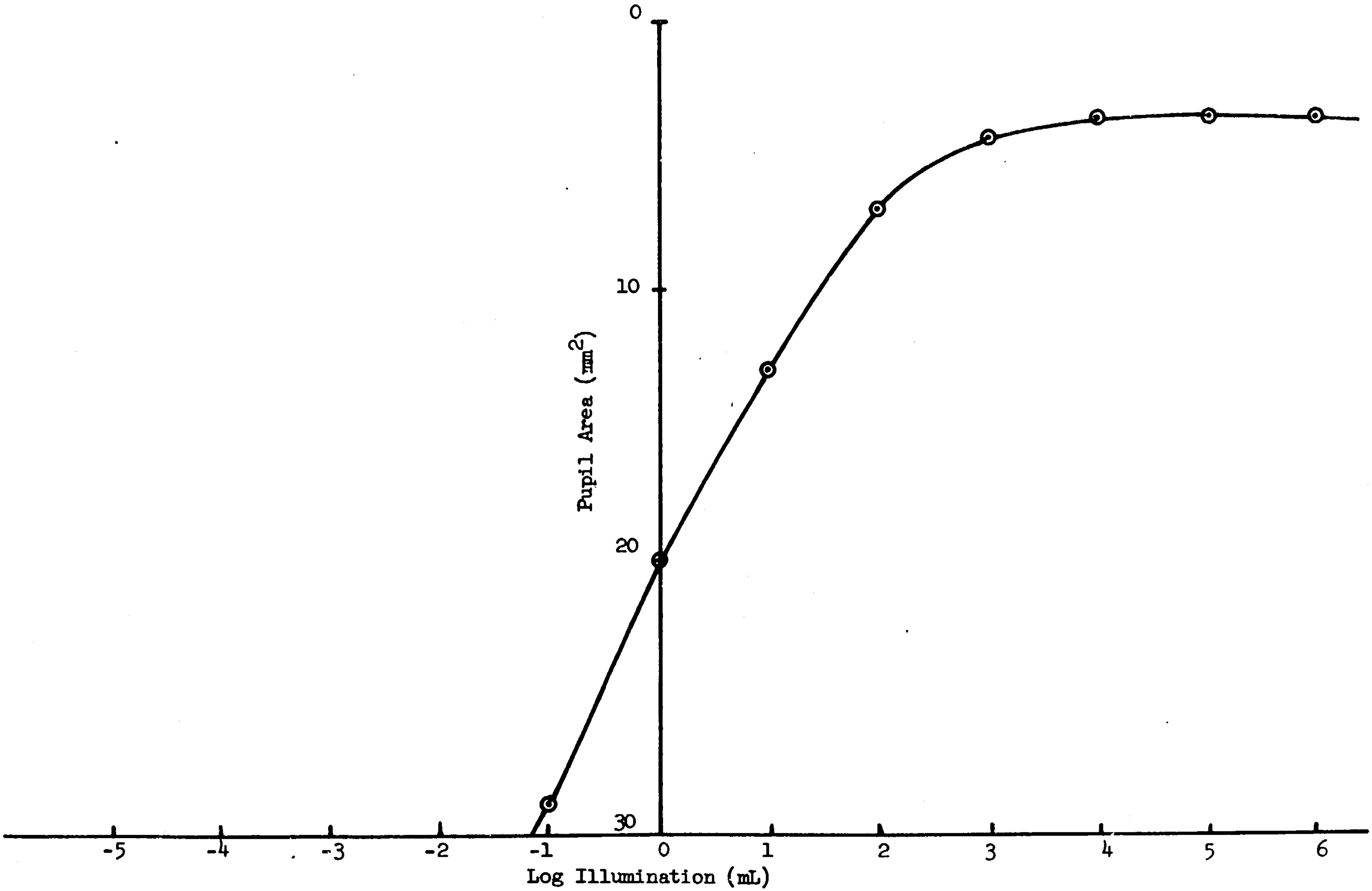

Figure 13. Relation between pupil size and level of general illumination.

under the curves in Figure 12 for the flash intervals to which Brown's subjects were exposed and then dividing by the time interval as indicated by the following expression:

$$\text{average pupil area} = \frac{\int_0^T A(t)\,dt}{T}$$

The trapezoidal rule was used to evaluate the integral. Table III lists the values obtained.

TABLE III

ESTIMATES OF AVERAGE PUPIL AREA FOR BROWN (5,7)

Intensity (log mL)	Time Interval (seconds)	Average Area (mm^2)
2	0.95	30.7763
5	0.95	28.4079
2	0.90	32.7111
5	0.90	29.0556

The time intervals selected were those employed by Brown. Average pupil areas were obtained for the various intensities used by Brown by linear interpolation in Table III. The following function was used to convert the source energy values in Brown's data to troland-seconds.

$$E_T = 3.183 \times 10^3 \quad E_L \frac{\int_0^T A(t)\,dt}{T}$$

The converted values of source energy are listed in Table IV.

TABLE IV

ESTIMATES OF SOURCE ENERGY IN TROLAND-SECONDS FOR BROWN (5,7)

E_L (L-sec.)	Log E_T (E_T troland-sec.)
T = 0.95 sec.	
102.3	6.96615
32.3	6.48876
10.23	5.99734
3.23	5.49915
1.023	5.00061
0.323	4.50018
T = 0.90 sec.	
96.8	6.95194
48.4	6.67548
12.1	6.09377

Brown's and Miller's data combined gave 1306 data points.

The variables used in the regression analysis are functions of the recovery time, source energy, recovery target luminance and visual acuity. The actual function used in the regression analysis can be described as follows:

$$Y = b_o + b_1 X_1 + b_2 X_2 + \dots + b_n X_n \qquad (5)$$

The non-linear equation used in the analysis is made equivalent to the linear equation above by the following transformation:

$Y = \log T$, T is recovery time in seconds.

$X_1 = \log L$, L is recovery target luminance in millilamberts

$X_2 = (\log L)^2$

$X_3 = (\log L)^3$

$X_4 = A$, the visual acuity required for the target

$X_5 = A^2$

$X_6 = A^3$

$X_7 = \text{Log } E_T$, where E_T is the source energy in troland-seconds.

$X_8 = (\log E_T)^2$

$X_9 = (\log E_T)^3$

The source energy was also expressed in lambert-seconds which alters the last three variables as follows:

$X_7 = \log E_L$, where E_L is the source energy in lambert-seconds.

$X_8 = (\log E_L)^2$

$X_9 = (\log E_L)^3$

In the stepwise procedure (14 and Appendix M), intermediate regression equations are obtained. The results for each step are listed for the two cases considered in Table V and Table VI. The standard error of the regression equation and the coefficient of determination are used as a measure of the accuracy with which the equation fits the data. The deviations of measured values from values obtained by the regression equation are measured by the standard error, σy. The fit is good if σy is small and R^2 is approximately one. Values of these measures are listed in Table V and Table VI for each step in the regression analysis. After the first few steps the standard error decreases slowly and R^2 approaches 1.00.

The dependent variable in Equation (5) is the logarithm of the recovery time. From this function of the recovery time, it is possible to determine in a convenient way the fractional or percentage standard deviation in the recovery time itself. The output of the multiple linear regression program includes the standard deviation of the logarithm of the recovery time. The following derivation relates the standard deviation of the logarithm of the recovery time and the percentage standard deviation in recovery time.

$$Y_i = \log_{10} T_i$$

$$dY_i = \log_{10} e \; \frac{dT_i}{T_i}$$

where $dY_i = Y_i - \hat{Y}_i$ and where Y_i are measured values of $\log T_i$ and $\hat{Y}_i$ are regression equation values of $\log \hat{T}_i$

$$\frac{1}{\log_{10} e} \; dY_i = \frac{dT_i}{T_i}$$

$$\left(\frac{1}{\log_{10} e}\right)^2 dY_i^2 = \left(\frac{dT_i}{T_i}\right)^2$$

$$\left(\frac{1}{\log_{10} e}\right)^2 \frac{1}{(n-1)} \sum_{i=1}^{n} dY_i^{\,2} = \frac{1}{(n-1)} \sum_{i=1}^{n} \left(\frac{dT_i}{T_i}\right)^2$$

$$\left(\frac{1}{\log_{10} e}\right)^2 \sigma_y^{\,2} = \sigma_{\frac{dT}{T}}^{\,2}$$

$$\sigma_{\frac{dT}{T}}^{2} = 5.301898 \, \sigma_y^{\,2}$$ variance

$$\sigma_{\frac{dT}{T}} = 2.302585 \, \sigma_y$$ standard deviation

The percentage standard deviation in the recovery time has been determined at each step in the regression programs and is listed in the last column of Table V and Table VI.

The matrix inversion was a source of some difficulty. In an effort to obtain as good a fit as possible, power series of the fifth degree were used, initially, in the regression analysis. The practical problem of maintaining accuracy in the matrix inversion became the critical limiting factor. With 13 terms in Equation 5, the matrix inversion was not sufficiently accurate. (The accuracy of the matrix inversion was checked by multiplying

TABLE V

REGRESSION COEFFICIENTS

ASSOCIATED STANDARD ERROR (σ) AND COEFFICIENT OF DETERMINATION (R^2)

E_T (TROLAND-SECONDS)

STEP	b_0	b_1	b_2	b_3	b_4	b_5	b_6
1	1.1574097	-.31935096					
2	-1.7538926	-.29241164					
3	-1.7982497	-.36234524		.012803591			
4	-1.8097675	-.36262954		.012730228	.38414269		
5	-1.8307634	-.36074734		.012653400	.72683299		-.087066982
6	-3.0360518	-.35832086		.012247334	.69872586		-.083232198
7	6.1851892	-.35684329		.012393744	.66951129		-.080477837
8	6.8678200	-.35722664		.012278942	-1.0915523	4.4583272	-1.4766188
9	7.0009220	-.34826531	.0086512441	.0099458175	-1.1146726	4.5215008	-1.4977985

TABLE V (cont.)

STEP	b_7	b_8	b_9	σ_Y	R^2	$\sigma \frac{dt}{t}$
1				.35139796	.61673516	0.809 = 80.9%
2	.41557043			.18632179	.89233002	0.429 = 42.9%
3	.41850411			.17045672	.90995447	0.392 = 39.2%
4	.40743978			.16597115	.91469678	0.382 = 38.2%
5	.39958345			.16209374	.91869847	0.373 = 37.3%
6	.68674735		-.0022538860	.15859210	.92223303	0.365 = 36.5%
7	-3.7875370	.70961635	-.039142332	.15614741	.92467014	0.360 = 36.0%
8	-4.0653174	.75584073	-.041582256	.15530069	.92554229	0.358 = 35.8%
9	-4.1308911	.76585211	-.042097964	.15449675	.92636799	0.356 = 35.6%

TABLE VI

REGRESSION COEFFICIENTS

ASSOCIATED STANDARD ERROR (σ) AND COEFFICIENT OF DETERMINATION (R^2)

E_L (LAMBERT-SECONDS)

STEP	b_0	b_1	b_2	b_3	b_4	b_5	b_6
1	1.1574097	-.31935096					
2	.33300023	-.28642029					
3	.29925133	-.35949023		.013405875			
4	.19973922	-.35978659		.013301235	.52794498		
5	.13836082	-.35682862		.012891060	.51971671		
6	.12934320	-.34871170	.0078752098	.010764346	.51393208		
7	.11190759	-.34792796	.0081531668	.010662265	.63762841		-.030794247
8	.28590400	-.34829785	.0082577572	.010502476	-1.4831037	5.3652755	-1.7094203
9	.29860996	-.34750866	.0084365343	.010592209	-1.6884846	5.8457139	-1.8571620

TABLE VI (cont.)

STEP	b_7	b_8	b_9	σ_Y	R^2	$\sigma_{\frac{dt}{t}}$
1				.35139796	.61673516	0.809 = 80.9%
2	.37439440			.19115513	.88667147	0.440 = 44.0%
3	.37840169			.17418057	.90597717	0.401 = 40.1%
4	.36802996			.16558188	.91509646	0.381 = 38.1%
5	.45153595		-.0084008539	.16180755	.91898530	0.373 = 37.3%
6	.45019082		-.0084151484	.16118327	.91967106	0.371 = 37.1%
7	.44420971		-.0081951225	.16076030	.92015362	0.370 = 37.0%
8	.45679745		-.0084060241	.15955399	.92140802	0.367 = 36.7%
9	.37525493	.073137494	-.023532257	.15907844	.92193604	0.366 = 36.6%

the initial matrix and its inverse and comparing with the unit matrix.) With only 10 terms, however, the inversion was satisfactory, and it is this 10 term analysis which yielded the coefficients listed in Tables V and VI.

The elements of the product matrix associated with Table V are listed in Table VII. (The first subscript refers to the row and the second subscript refers to the column in the matrix with elements C (i, j) where $A A^{-1} = C$.) Table VIII lists the elements of the product matrix associated with Table VI. The product matrices differ very little from the unit matrix and therefore the matrix inversion is sufficiently accurate in both cases.

Figure 14 is a typical plot of the function with source energy expressed in troland-seconds. The 1σ bounds are indicated by the dotted lines. The distribution of applicable data points from Brown's data and Miller's data about the function is shown on the graph. The controlling influence of Miller's data on the regression equation is evident and is clearly due to the unequal amount of input data from the two experiments. Brown's data has a steeper slope than the regression function in this case. (Indeed, the percentage standard deviation for predicting Brown's data alone is on the order of 50%.) Figure 15 is a similar plot for the source energy expressed in lambert-seconds.

It should be noted that the validity of the regression function in predicting recovery time is questionable outside the bounds of the experimental data. These bounds are listed in Table IX.

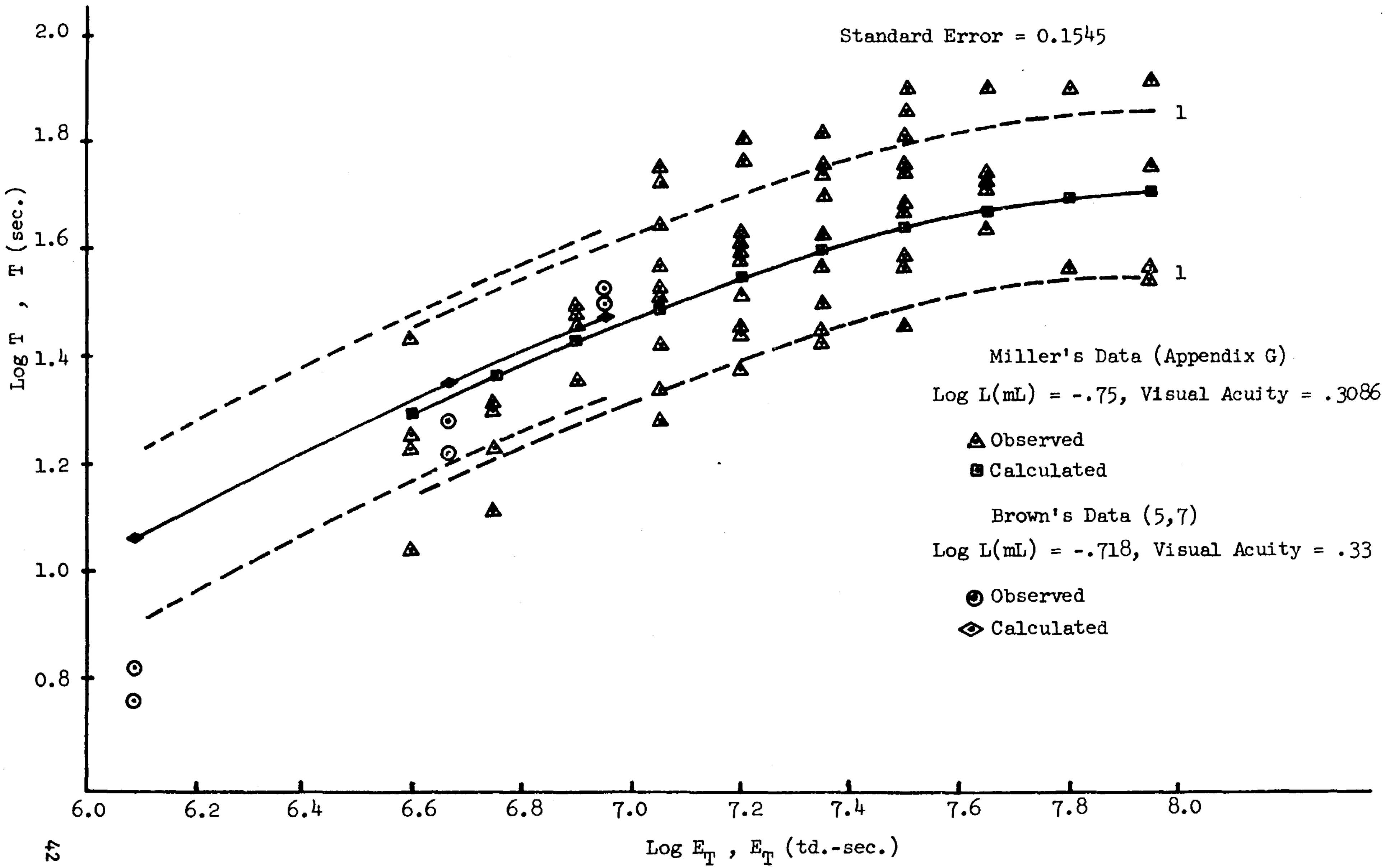

Figure 14. Regression function (troland-seconds).

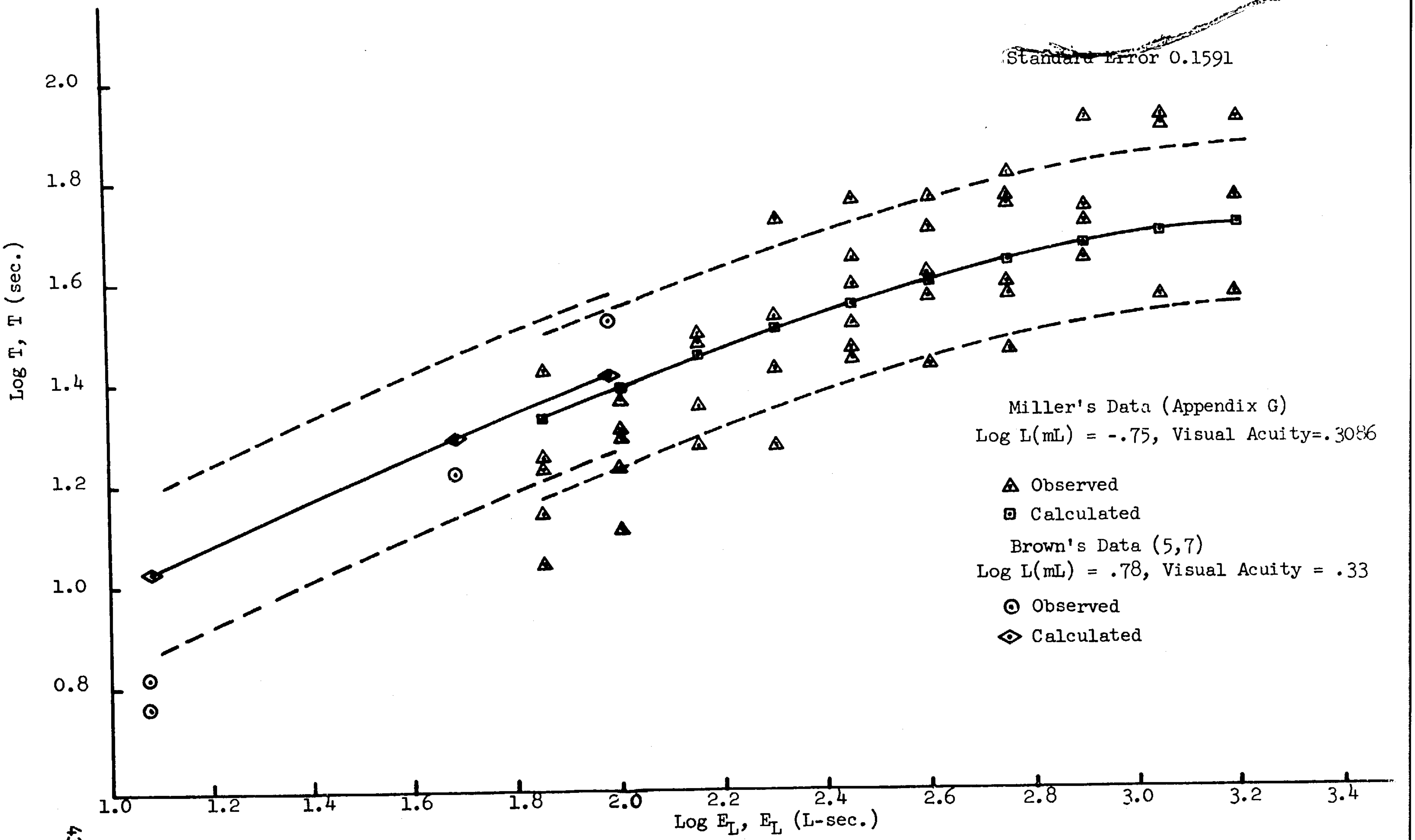

Figure 15. Regression function (lambert-seconds).

TABLE VII

PRODUCT MATRIX $A \cdot A^{-1} = C$

E_I (TROLAND-SECONDS)

```
C(1, 1) 0.10000000E+01
C(1, 2)-0.22351742E-07
C(1, 3) 0.15785918E-06
C(1, 4) 0.10156073E-05
C(1, 5) 0.40803570E-05
C(1, 6) 0.25220215E-05
C(1, 7)-0.72792172E-05
C(1, 8)-0.70445240E-05
C(1, 9) 0.48428774E-07
C(2, 1)-0.93132257E-08
C(2, 2) 0.99999998E+00
C(2, 3) 0.17525163E-05
C(2, 4)-0.60759485E-05
C(2, 5) 0.10849908E-04
C(2, 6) 0.18804520E-03
C(2, 7)-0.29626489E-03
C(2, 8) 0.23755431E-03
C(2, 9)-0.15273690E-06
C(3, 1) 0.24287147E-07
C(3, 2) 0.11863449E-07
C(3, 3) 0.10000042E+01
C(3, 4) 0.14460231E-04
C(3, 5) 0.63816014E-04
C(3, 6)-0.19316436E-03
C(3, 7) 0.26040481E-03
C(3, 8)-0.28089418E-03
C(3, 9) 0.27511487E-06
C(4, 1)-0.21304004E-07
C(4, 2)-0.20023435E-07
C(4, 3) 0.39203442E-05
C(4, 4) 0.10000206E+01
C(4, 5) 0.94303163E-04
C(4, 6)-0.13382640E-04
C(4, 7)-0.27628615E-04
C(4, 8)-0.26383437E-04
C(4, 9) 0.81490725E-07
C(5, 1)-0.17520506E-07
C(5, 2)-0.49825758E-07
C(5, 3) 0.71500835E-06
C(5, 4) 0.38689817E-04
C(5, 5) 0.10000779E+01
C(5, 6)-0.87544322E-06
C(5, 7)-0.30171126E-04
C(5, 8)-0.32866374E-05
C(5, 9) 0.47963113E-07
C(6, 1)-0.18160790E-07
C(6, 2) 0.48428774E-07
C(6, 3) 0.14611287E-05
C(6, 4)-0.12276927E-04
C(6, 5) 0.31403033E-05
C(6, 6) 0.99974452E+00
C(6, 7)-0.18931925E-03
C(6, 8)-0.63681602E-03
C(6, 9) 0.66217035E-06
C(7, 1)-0.25844201E-07
C(7, 2) 0.88475645E-08
C(7, 3) 0.31800591E-05
C(7, 4)-0.19430416E-04
C(7, 5) 0.98800519E-05
C(7, 6)-0.18454529E-03
C(7, 7) 0.99962841E+00
C(7, 8)-0.53347461E-03
C(7, 9) 0.64121559E-06
C(8, 1)-0.29336661E-07
C(8, 2) 0.50757080E-07
C(8, 3) 0.23762695E-05
C(8, 4)-0.14932826E-04
C(8, 5) 0.75247372E-05
C(8, 6)-0.23660809E-03
C(8, 7)-0.28191879E-03
C(8, 8) 0.99941733E+00
C(8, 9) 0.63981861E-06
C(9, 1) 0.61467290E-07
C(9, 2)-0.26077032E-07
C(9, 3)-0.11604279E-05
C(9, 4) 0.82217157E-05
C(9, 5) 0.40978193E-06
C(9, 6)-0.61586499E-04
C(9, 7) 0.21633506E-03
C(9, 8)-0.19058585E-04
C(9, 9) 0.10000001E+01
```

TABLE VIII
PRODUCT MATRIX $A A^{-1} = C$
E_L (LAMBERT-SECONDS)

```
C(1 , 1)  0.10000000E+01
C(1 , 2)  0.40978193E-07
C(1 , 3)  0.38417056E-07
C(1 , 4)  0.13217796E-05
C(1 , 5)  0.31134114E-05
C(1 , 6)  0.25727786E-07
C(1 , 7) -0.30733645E-07
C(1 , 8) -0.55879354E-07
C(1 , 9) -0.55879354E-08
C(2 , 1)  0.55879354E-08
C(2 , 2)  0.10000001E+01
C(2 , 3)  0.21327287E-06
C(2 , 4)  0.77486038E-06
C(2 , 5)  0.34715049E-05
C(2 , 6) -0.10058284E-06
C(2 , 7)  0.43213367E-06
C(2 , 8) -0.75343996E-06
C(2 , 9)  0.74505806E-08
C(3 , 1) -0.13928602E-07
C(3 , 2)  0.19157596E-07
C(3 , 3)  0.10000026E+01
C(3 , 4)  0.87025755E-05
C(3 , 5)  0.66523175E-04
C(3 , 6)  0.17410298E-06
C(3 , 7) -0.46852620E-06
C(3 , 8)  0.11772136E-06
C(3 , 9)  0.63919286E-08
C(4 , 1) -0.19732397E-07
C(4 , 2)  0.18626451E-07
C(4 , 3)  0.38749567E-05
C(4 , 4)  0.10000147E+01
C(4 , 5)  0.88042259E-04
C(4 , 6)  0.37971768E-06
C(4 , 7) -0.81420876E-06
C(4 , 8) -0.16676495E-06
C(4 , 9) -0.20954758E-08
C(5 , 1) -0.11175871E-07
C(5 , 2) -0.81490725E-06
C(5 , 3) -0.39374572E-06
C(5 , 4)  0.35185891E-04
C(5 , 5)  0.10000660E+01
C(5 , 6)  0.26087218E-06
C(5 , 7)  0.27730130E-06
C(5 , 8) -0.84366184E-06
C(5 , 9) -0.63819032E-08
C(6 , 1)  0.25611371E-06
C(6 , 2) -0.36787242E-07
C(6 , 3) -0.13968692E-05
C(6 , 4)  0.18641585E-05
C(6 , 5) -0.70956703E-05
C(6 , 6)  0.10000003E+01
C(6 , 7) -0.14211982E-05
C(6 , 8)  0.37779100E-05
C(6 , 9)  0.21420419E-07
C(7 , 1)  0.46566129E-09
C(7 , 2) -0.12572855E-07
C(7 , 3) -0.94002462E-06
C(7 , 4)  0.46472996E-06
C(7 , 5) -0.46122586E-05
C(7 , 6) -0.23737084E-06
C(7 , 7)  0.99999981E+00
C(7 , 8)  0.32389071E-05
C(7 , 9)  0.12107193E-07
C(8 , 1)  0.44237822E-08
C(8 , 2) -0.38649887E-07
C(8 , 3) -0.12449455E-05
C(8 , 4)  0.25064219E-05
C(8 , 5) -0.53853728E-05
C(8 , 6)  0.26923954E-06
C(8 , 7) -0.13587996E-05
C(8 , 8)  0.10000042E+01
C(8 , 9)  0.19626451E-07
C(9 , 1)  0.18626451E-08
C(9 , 2)  0.26077032E-07
C(9 , 3)  0.22095628E-06
C(9 , 4)  0.12507662E-05
C(9 , 5)  0.41406602E-05
C(9 , 6)  0.29522926E-06
C(9 , 7) -0.68172812E-06
C(9 , 8)  0.81956387E-07
C(9 , 9)  0.10000000E+01
```

TABLE IX

EXPERIMENTAL DATA BOUNDS

	Minimum Values	Maximum Values
Visual Acuity (A)	0.08	0.33
Source Energy (E_T)	3.164×10^4 td.-sec.	8.913×10^7 td.-sec.
Source Energy (E_L)	3.23×10^{-1} lambert-sec.	1.588×10^3 lambert-sec.
Recovery Target Luminance (L)	7.586×10^{-3} mL.	1.914×10^4 mL.
Recovery Time (T)	2.90×10^{-1} sec.	2.245×10^2 sec.

But within these bounds, recovery time T can be predicted for values of source energy, recovery target luminance, and visual acuity by the following functions.

Case 1 - Source energy E_T in troland-seconds,
Recovery target luminance L in millilamberts,
Visual Acuity A in minutes $^{-1}$,
Recovery time T in seconds:

$$\text{Log } T = 7.0009220 - .34826531 \log L + .0086512441 (\log L)^2 + .0099458175 (\log L)^3 - 1.1146726 A + 4.5215008 A^2 - 1.4977985 A^3 - 4.1308911 \log E_T + .76585211 (\log E_T)^2 - .042097964 (\log E_T)^3 \quad (6)$$

Case 2 - Source energy E_L in lambert-seconds,
Recovery target luminance L in millilamberts,
Visual Acuity A in minutes $^{-1}$,
Recovery time T in seconds:

$$\begin{aligned}\log T = {} & .29860996 - .34750866 \log L = .0084365343 \; (\log L)^2 \\ & +.010592209 \; (\log L)^3 - 1.6884846 \; A + 5.8457139 \; A^2 \\ & -1.8571620 \; A^3 + .37525493 \log E_L + 0.73137494 \; (\log E_L)^2 \\ & - .023532257 \; (\log E_L)^3 \end{aligned} \tag{7}$$

If $\hat{T}$ represents the recovery time predicted by the equation and T represents the corresponding measured value, then T will be within the following bounds approximately 68% of the time.

$$0.64\hat{T} \leq T \leq 1.36\hat{T}$$

A significant amount of the 36% error in predicted recovery time is undoubtedly due to subject differences.

To get some indication of how well the equations predict in some situation other than the ones used to develop the equations, it was decided to compute recovery times for a study reported by Chisum & Hill (11). The experiment reported in their Figure 4 and tabled here in Appendix Table D.2 was used. Input data from this experiment were substituted in the equation. The results are listed in Table X and compared with experimental values. It is noted that the experimental results are an average of three response measures for a single subject. Two points were excluded because they were much below the lower bound of source energy used in obtaining the regression function. The percentage standard deviation for these data is $\sigma_{\%} = 0.469 = 46.9\%$.

TABLE X

Predicted Recovery Times Compared to Measurements made by Chisum and Hill (11)

Visual Acuity = 0.33

L (ml)	E_T (td.-sec.)	$\hat{T}$ (sec.)	T (sec.)	$\frac{\hat{T}-T}{T}$
0.178	3.2×10^6	19.11	85	-0.775
	1.0×10^7	31.94	81	-0.606
	8.8×10^5	9.933	34	-0.708
	2.5×10^5	5.357	10	-0.464
	8.8×10^4	3.490	5	-0.302
	2.5×10^4	2.500	4	-0.375
	4.5×10^6	22.50	55	-0.591
	1.4×10^6	12.60	21	-0.400
	4.5×10^5	7.087	7	+0.012
	1.4×10^5	4.167	5	-0.167
	4.5×10^4	2.835	4	-0.291
	1.4×10^4	2.349	3	-0.217
	4.5×10^3	2.576	2	+0.288
1.0	1.0×10^7	17.48	28	-0.376
	1.0×10^6	5.805	25	-0.768
	8.8×10^5	5.437	12	-0.547
	1.0×10^5	2.001	5	-0.600
	8.8×10^4	1.910	3	-0.363
	1.0×10^4	1.281	1.5	-0.146
	4.5×10^6	12.32	12	+0.027
	1.4×10^6	6.899	8	-0.138
	4.5×10^5	3.879	4	-0.030
	1.4×10^5	2.281	3	-0.240
	4.5×10^4	1.551	1	+0.551
	1.4×10^4	1.286	1	+0.286
178	1.0×10^7	4.131	5	-0.174
	1.0×10^6	1.372	4.5	-0.695
	8.8×10^5	1.285	4	-0.679
	1.0×10^5	0.4729	2	-0.764
	8.8×10^3	0.3042	1	-0.696
	4.5×10^6	2.910	3	-0.030
	1.4×10^6	1.630	2	-0.185
	4.5×10^5	0.9167	2	-0.542
	1.4×10^5	0.5390	1	-0.461

6.0 LINEAR REGRESSION ANALYSIS OF BROWN'S DATA AND AN EQUAL SAMPLE OF MILLER'S DATA

The preceding regression analysis used 257 data points from Brown's data and 1049 data points from Miller's data. All points were weighted equally and hence Miller's data influenced the regression function coefficients more than Brown's data. Figure 14, for example, indicates that Brown's data may have a somewhat steeper slope than the function obtained from the 1306 data points used in the analysis. For this reason, the linear regression program was used to obtain coefficients of a function based on Brown's data and an equal sample of Miller's data. The 257 points were selected from Miller's data to cover that portion of the sample space not included in Brown's data. Matrix inversion difficulties necessitated the use of a function with only six independent variables. The non-linear equation used in the analysis is made equivalent to Equation (5) by the following transformation.

$Y = \log T$, T is recovery time in seconds

$X_1 = \log L$, L is recovery target luminance in millilamberts

$X_2 = (\log L)^2$,

$X_3 = A$, A is the visual acuity

$X_4 = A^2$

$X_5 = \log E_T$, E_T is the source energy in troland-seconds

$X_6 = (\log E_T)^2$

The source energy is also expressed in lambert-seconds which alters the last two variables as follows:

$X_5 = \log E_L$, E_L is the source energy in lambert-seconds

$X_6 = (\log E_L)^2$

The stepwise procedure described in Appendix M was used in the analysis and results are listed for the two cases considered in Table XI and Table XII.

The last set of coefficients in Table XI gives the following function which may be used to predict recovery times (T) as a function of recovery target luminance (L), visual acuity (A) and source energy in troland-seconds (E_T).

$$\log T = -4.1856800 - .32149662 \log L + .033677487 (\log L)^2 + .67523230 A - .092360297 A^2 + 1.1595261 \log E_T - .060274522 (\log E_T)^2 \tag{6a}$$

The percentage standard deviation associated with this function is 43.4% and may be compared with the percentage standard deviation of 35.6% found in the last row of Table V. Since the present analysis gives equal weight to Miller's data and Brown's data, the larger percentage standard deviation is not surprising.

The last set of coefficients in Table XII gives the following function which may be used to predict recovery time (T) as a function of recovery target luminance (L), visual acuity (A) and source energy in lambert-seconds (E_L).

$$\log T = .10599667 - .31755011 \log L + .033342218 (\log L)^2 + .65051730 A - .074533541 A^2 + .55890282 \log E_L - .067115622 (\log E_L)^2 \tag{7a}$$

The percentage standard deviation associated with this function is 43.7% and may be compared with the percentage standard deviation of 36.6% found in the last row of Table VI.

TABLE XI

REGRESSION COEFFICIENTS
BROWN'S DATA AND AN EQUAL SAMPLE OF MILLER'S DATA
ASSOCIATED STANDARD ERROR (σ) AND COEFFICIENT OF DETERMINATION (R^2)
E_T (TROLAND-SECONDS)

STEP	b_o	b_1	b_2	b_3	b_4	b_5	b_6
1	-1.0670459						.048415338
2	- .55574762	-.27451055					.035192419
3	- .55286494	-.30572652	.034964024				.032980951
4	-4.0145162	- .32195363	.034249267			1.1268146	-.056231117
5	-4.0186182	- .32242564	.034478806	.048819595		1.1267893	-.056394971
6	-4.1856800	- .32149662	.033677487	.67523230	-.092360297	1.1595261	-.060274522

	σ_Y	R^2	$\frac{\sigma dT}{T}$
1	.45549471	.63760437	1.049 = 104.9%
2	.23323393	.90516892	0.537 = 53.7%
3	.21124151	.92236188	0.486 = 48.6%
4	.19568193	.93350859	0.451 = 45.1%
5	.19527608	.93391420	0.450 = 45.0%
6	.18865577	.93844059	0.434 = 43.4%

TABLE XII

REGRESSION COEFFICIENTS
BROWN'S DATA AND AN EQUAL SAMPLE OF MILLER'S DATA
ASSOCIATED STANDARD ERROR (σ) AND COEFFICIENT OF DETERMINATION (R^2)
E_L (LAMBERT-SECONDS)

STEP	b_o	b_1	b_2	b_3	b_4	b_5	b_6
1	.12027632					.56507368	
2	.30861827	-.27053097				.41080681	
3	.26016024	-.30104605	.033703122			.38528363	
4	.21839951	-.31557332	.033421827			.55139423	-.058743561
5	.18454091	-.31802354	.033872373	.14622064		.56899939	-.066122090
6	.10599667	-.31755011	.033342218	.65051730	-.074533541	.55890282	-.067115622

	σ_Y	R^2	$\frac{\sigma_{dT}}{T}$
1	.44686589	.65120465	1.029 = 102.9%
2	.22882067	.90872377	0.527 = 52.7%
3	.20813209	.92463069	0.479 = 47.9%
4	.19911709	.93115361	0.458 = 45.8%
5	.19407331	.93472578	0.447 = 44.7%
6	.18987379	.93764313	0.437 = 43.7%

The elements of the product matrix formed by multiplying the working matrix and its inverse (source energy in troland-seconds) are listed in Table XIII. Since the product matrix is very nearly a unit matrix, the inversion process was satisfactory. A similar test was made of the other inversion (source energy in lambert-seconds). In this case, also, the product matrix was very nearly a unit matrix; see Table XIV.

TABLE XIII
PRODUCT MATRIX A A^{-1} = C
EQUAL SAMPLES OF MILLER'S AND BROWN'S DATA
E_T (TROLAND-SECONDS)

```
C(1   ,   1)    0.10000000E+01
C(1   ,   2)   -0.18539140E-07
C(1   ,   3)   -0.23865141E-06
C(1   ,   4)    0.74505806E-08
C(1   ,   5)   -0.14342368E-06
C(1   ,   6)   -0.27939677E-08
C(2   ,   1)   -0.29976945E-08
C(2   ,   2)    0.99999974E+00
C(2   ,   3)   -0.13055251E-06
C(2   ,   4)    0.11062948E-05
C(2   ,   5)   -0.12310920E-05
C(2   ,   6)   -0.11490192E-06
C(3   ,   1)   -0.15133992E-08
C(3   ,   2)   -0.35101402E-06
C(3   ,   3)    0.99999996E+00
C(3   ,   4)    0.52270479E-07
C(3   ,   5)   -0.42258762E-07
C(3   ,   6)   -0.91880793E-07
C(4   ,   1)    0.46566129E-08
C(4   ,   2)    0.14284160E-06
C(4   ,   3)   -0.86438376E-07
C(4   ,   4     0.10000011E+01
C(4   ,   5)   -0.31776726E-05
C(4   ,   6)    0.12107193E-07
C(5   ,   1)    0.97788870E-08
C(5   ,   2)    0.33556717E-07
C(5   ,   3)    0.15308615E-07
C(5   ,   4)   -0.31106174E-06
C(5   ,   5)    0.99999836E+00
C(5   ,   6)    0.48428774E-07
C(6   ,   1)    0.65192580E-08
C(6   ,   2)   -0.11100201E-06
C(6   ,   3)    0.46566129E-09
C(6   ,   4)    0.75250864E-06
C(6   ,   5)    0.59604645E-07
C(6   ,   6)    0.99999993E+00
```

TABLE XIV

PRODUCT MATRIX $A A^{-1} = C$
EQUAL SAMPLES OF MILLER'S AND BROWN'S DATA
E_L (LAMBERT-SECONDS)

```
C(1   ,  1)   0.10000000E+01
C(1   ,  2)   0.80472091E-08
C(1   ,  3)  -0.71013346E-08
C(1   ,  4)  -0.18626451E-07
C(1   ,  5)   0.46566129E-08
C(1   ,  6)   0.14901161E-07
C(2   ,  1)  -0.69994712E-08
C(2   ,  2)   0.99999974E+00
C(2   ,  3)  -0.41423846E-07
C(2   ,  4)  -0.30748197E-07
C(2   ,  5)   0.15948899E-07
C(2   ,  6)   0.51804818E-08
C(3   ,  1)  -0.70576789E-08
C(3   ,  2)  -0.31908348E-06
C(3   ,  3)   0.10000000E+01
C(3   ,  4)   0.84546627E-08
C(3   ,  5)   0.87020453E-08
C(3   ,  6)   0.25611371E-08
C(4   ,  1)   0.30267984E-08
C(4   ,  2)   0.26921043E-08
C(4   ,  3)  -0.11816155E-07
C(4   ,  4)   0.99999974E+00
C(4   ,  5)  -0.52154064E-07
C(4   ,  6)   0.74505806E-08
C(5   ,  1)  -0.37252903E-08
C(5   ,  2)   0.11394150E-07
C(5   ,  3)  -0.33585820E-07
C(5   ,  4)  -0.21513551E-06
C(5   ,  5)   0.99999992E+00
C(5   ,  6)   0.13969839E-07
C(6   ,  1)   0.20489097E-07
C(6   ,  2)  -0.65483619E-08
C(6   ,  3)   0.46566129E-08
C(6   ,  4)   0.37252903E-07
C(6   ,  5)   0.10430813E-06
C(6   ,  6)   0.10000000E+01
```

7.0 A NOTE CONCERNING INDIVIDUAL DIFFERENCES - BASED ON THE LINEAR REGRESSION ANALYSIS OF MILLER'S DATA ALONE

The variables used in this regression analysis are functions of the recovery time, source intensity, and recovery target luminance. The non-linear equation used in the analysis is made equivalent to Equation (5) by the following transformation.

$Y = \log T$, T is recovery time in seconds

$X_1 = \log L$, L is recovery target luminance in millilamberts

$X_2 = (\log L)^2$

$X_3 = (\log L)^3$

$X_4 = \log E_T$, E_T is the source intensity in troland-seconds

$X_5 = (\log E_T)^2$

$X_6 = (\log E_T)^3$

The earlier form (Version I) of the multiple linear regression program used in this analysis of Miller's data did not print out the intermediate regression equations. The following regression equation was obtained when 1049 data points from Miller's experiments were used in the analysis.

$$\begin{aligned} \log T = {} & -0.34522704 (\log L) + 0.0086932968 (\log L)^2 \\ & + 0.010272788 (\log L)^3 + 4.5784872 (\log E_T) \\ & - 0.30504344 (\log E_T)^2 + 0.0013180203 (\log E_T)^3 \\ & - 16.398782 \end{aligned} \tag{6b}$$

The standard error of the regression equation was $\sigma_Y = 0.1425$ and the percentage standard deviation in T was $\sigma \frac{dT}{T} = 33\%$. The product matrix S_{ij} is given in Table XV and is very nearly equal to the unit

TABLE XV

PRODUCT MATRIX A $A^{-1} = S$

MILLER'S DATA

```
S 1 1  0.99999992E+00
S 1 2 -0.48221409E-08
S 1 3 -0.15628757E-07
S 1 4  0.48428774E-07
S 1 5  0.72875991E-06
S 1 6 -0.52386895E-09
S 2 1 -0.16414560E-07
S 2 2  0.10000000E+01
S 2 3  0.46566129E-08
S 2 4  0.18738210E-05
S 2 5  0.68545341E-06
S 2 6 -0.46566129E-09
S 3 1 -0.78743324E-06
S 3 2 -0.34895493E-07
S 3 3  0.10000000E+01
S 3 4 -0.21651387E-04
S 3 5  0.53904951E-05
S 3 6 -0.74505806E-08
S 4 1  0.37252903E-08
S 4 2  0.87311491E-09
S 4 3 -0.12223609E-08
S 4 4  0.99999391E+00
S 4 5  0.23115426E-05
S 4 6 -0.58207661E-09
S 5 1  0.11175871E-07
S 5 2 -0.31897798E-07
S 5 3 -0.20489097E-07
S 5 4  0.51534176E-03
S 5 5  0.99999598E+00
S 5 6  0.27939677E-07
S 6 1  0.59604645E-07
S 6 2 -0.81025064E-07
S 6 3 -0.18626451E-06
S 6 4  0.26950836E-02
S 6 5  0.12230873E-03
S 6 6  0.99999969E+00
```

matrix. This indicates that the matrix inversion is satisfactory.

The input data show considerable variation from subject to subject in recovery time. In an effort to study this variation, Miller's data were divided into five subsets by subject. The regression program was used to fit each subset. The percentage standard deviations for the five subsets of subject data are compared with the percentage standard deviation for all the data in Table XVI.

TABLE XVI

PERCENTAGE STANDARD DEVIATION
IN RECOVERY TIME FOR INDIVIDUAL SUBJECTS

SUBJECT	$\frac{\sigma_{dT}}{T}$ STANDARD DEVIATION
J.N.	26%
J.H.	27%
R.B.	20%
J.S.	25%
V.K.	22%
All of Miller's Data	33%

In several cases, the matrix inversion was not satisfactory. It should be noted, however that such errors would be expected to increase the percentage standard deviation of the recovery time for any given subject. The matrix inversion in the case of the total data was adequate as shown in Table XV. Table XVI shows that the percentage standard deviation of experimental data from the regression function obtained by using all of Miller's data is larger than for any individual subject.

8.0 GOMPERTZ FUNCTION

An effort has been made to apply the Gompertz Function (28) to the flashblindness problem. The general equation for the curve may be written

$$T = v.g^{h^{E}} \qquad (8)$$

The dependent variable T is seen to be a double exponential function of E. Let the variable T be the recovery time in seconds and E the flash energy in megatroland-seconds.

The coefficient, v, can be made a function of the target luminance L. The more complex function then reduces to the Gompertz Function for each value of target luminance. The coefficient, v, is the limiting value of T for a particular value of L provided that the constants g and h are both fractional and positive. The visual acuity is included with other random variables such as the subject variation.

The value of v must be determined graphically or by other means. By taking the logarithm of equation (8) twice and substituting T' for $\frac{T}{v}$ the following linear relationship is obtained.

$$\log\,(-\log T') = (\log h)\quad E + \left[\log\,(-\log g)\right]$$

It is possible to determine (log h) and $\left[\log\,(-\log g)\right]$ by linear regression if $\log\,(-\log T')$ is taken as the dependent variable and E as the independent variable. In this sample problem, this was not done. An estimate was made by selecting two representative points and solving simultaneous linear equations. It was apparent that no single straight line would be a good fit to the data. For this reason, the constants g and h were determined for two functions. Equations (9) and (10) are these functions; the ranges in which they apply are indicated.

$$t = \frac{23.2}{\sqrt[3]{L}} (0.2339)^{0.9066^{E}} \qquad (9)$$

when $4 \leq E \leq 31$
$0.007586 \leq L \leq 281.8$

$$t = \frac{23.2}{\sqrt[3]{L}} (0.8183)^{0.9625^{E}} \qquad (10)$$

when $31 \leq E \leq 100$
$0.007586 \leq L \leq 281.8$

Miller's data, Appendix Tables G-1 and G-3 were used to obtain these functions. Specificially, the data for subject R. B. were used; the letter size was 16.2′, a visual acuity of 0.3086. Table XVII is a list of the measured and computed values and the deviation of the measured values from the computed values.

TABLE XVII

VISUAL RECOVERY TIME - GOMPERTZ FUNCTION
SUBJECT R. B., LETTER SIZE 16.2′

L (mL)	E(mega td-sec.)	T (sec.)	$\hat{T}$ (sec.)	$(\hat{T} - T)$sec.	$\left\lvert \frac{\hat{T} - T}{T} \right\rvert$
281.8	11.22	4.0	2.17	-1.83	0.457
"	15.85	4.5	2.59	-1.91	0.424
"	22.39	5.5	3.00	-2.50	0.454
"	31.62	5.0	3.33	-1.67	0.334
"	31.62	4.0	3.33	-0.67	0.167
"	44.67	4.5	3.41	-1.09	0.242
"	63.10	5.0	3.48	-1.52	0.304
"	89.12	5.0	3.52	-1.48	0.296
5.623	3.981	5.0	4.82	-0.18	0.036
"	5.623	4.0	5.59	1.59	0.397
"	7.943	7.0	6.64	-0.36	0.051
"	11.22	10.0	8.00	-2.00	0.200
"	15.85	10.0	9.56	-0.44	0.044
"	22.39	12.0	11.08	-0.92	0.076
"	31.62	11.5	12.29	+0.79	0.068
"	11.22	9.0	8.00	-1.00	0.111
"	15.85	8.0	9.56	+1.56	0.195
"	22.39	10.0	11.08	+1.08	0.108
"	31.62	10.0	12.29	+2.29	0.229
"	44.67	11.0	12.58	+1.58	0.143
"	63.10	10.5	12.82	+2.32	0.220
"	89.12	11.0	12.96	+1.96	0.178

TABLE XVII Con't.

1.995	3.981	7.0	6.81	-0.19	0.027
"	5.623	8.0	7.89	-0.11	0.013
"	7.943	11.0	9.38	-1.62	0.147
"	11.22	13.5	11.29	-2.21	0.163
"	15.85	13.0	13.50	+0.50	0.038
"	22.39	16.0	15.64	-0.36	0.022
"	31.62	15.5	17.36	+1.86	0.120
"	11.22	15.0	11.29	-3.71	0.247
"	15.85	11.5	13.50	+2.00	0.173
"	22.39	14.0	15.64	+1.64	0.117
"	31.62	15.0	17.36	+2.36	0.157
"	44.67	15.5	17.77	+2.27	0.146
"	63.10	17.0	18.10	+1.10	0.064
"	89.12	14.5	18.31	+3.81	0.262
0.4266	3.981	11.0	11.38	+0.38	0.034
"	5.623	12.5	13.20	+0.70	0.056
"	7.943	15.0	15.69	+0.69	0.046
"	11.22	22.0	18.89	-3.11	0.141
"	15.85	21.0	22.58	+1.58	0.075
"	22.39	24.0	26.16	+2.16	0.090
"	31.62	25.0	29.03	+4.03	0.161
"	11.22	20.0	18.89	-1.11	0.055
"	15.85	18.5	22.58	+4.08	0.220
"	22.39	24.5	26.16	+1.66	0.067
"	31.62	28.0	29.03	+1.03	0.036
"	44.67	26.5	29.72	+3.22	0.121
"	63.10	26.0	30.27	+4.27	0.164
"	89.12	23.5	30.61	+7.11	0.302
0.1778	3.981	14.0	15.24	+1.24	0.088
"	5.623	17.0	17.67	+0.67	0.039
"	7.943	22.5	21.00	-1.50	0.066
"	11.22	26.5	25.28	-1.22	0.046
"	15.85	28.0	30.23	+2.23	0.079
"	22.37	28.5	35.02	+6.52	0.228
"	31.62	29.0	38.86	+9.86	0.340
"	11.22	32.0	25.28	-6.72	0.210
"	15.85	33.0	30.23	-2.77	0.083
"	22.39	41.0	35.02	-5.98	0.145
"	31.62	37.5	38.86	+1.36	0.036
"	44.67	44.0	39.79	-4.21	0.095
"	63.10	38.0	40.52	+2.52	0.066
"	89.12	38.0	40.99	+2.99	0.078
0.06310	3.981	17.0	21.53	+4.53	0.266
"	5.623	20.5	24.96	+4.91	0.239
"	7.943	28.0	29.66	+1.66	0.059
"	11.22	35.0	35.71	+0.71	0.020
"	15.85	42.5	42.70	+0.20	0.004
"	22.37	43.0	49.47	+6.47	0.150
"	31.62	55.0	54.89	-0.11	0.002
"	11.22	42.0	35.71	-6.29	0.149

TABLE XVII Con't.

0.06310	15.85	44.00	42.70	-1.30	0.029
"	22.39	56.5	49.47	-7.03	0.124
"	31.62	65.0	54.89	-10.11	0.155
"	44.67	55.5	56.20	+ 0.70	0.012
"	63.10	58.0	57.24	-0.76	0.013
"	89.12	64.5	57.89	-6.61	0.102
0.01122	3.981	23.0	38.28	+15.28	0.664
"	5.623	31.0	44.38	+13.38	0.431
"	7.943	31.5	52.74	+21.24	0.674
"	11.22	47.0	63.50	+16.50	0.351
"	15.85	63.0	75.92	+12.92	0.205
"	22.37	72.0	87.96	+15.96	0.221
"	31.62	76.0	97.60	+21.60	0.284
"	11.22	60.0	63.50	+3.50	0.058
"	15.85	70.0	75.92	+5.92	0.084
"	22.39	90.0	87.96	-2.04	0.022
"	31.62	111.0	97.60	-13.40	0.120
"	44.67	88.0	99.92	+11.92	0.135
"	63.10	94.0	101.78	+7.78	0.082
"	89.12	103.0	102.94	-0.06	0.000
0.007586	3.981	46.0	43.62	-2.38	0.051
"	5.623	40.0	50.57	+10.57	0.264
"	7.943	46.5	60.09	+13.59	0.292
"	11.22	58.0	72.35	+14.35	0.247
"	15.85	89.0	86.50	-2.50	0.028
"	22.37	98.0	100.23	+2.23	0.022
"	31.62	110.0	111.21	+1.21	0.011
"	11.22	87.0	72.35	-14.65	0.168
"	15.85	79.0	86.50	+7.50	0.094
"	22.39	125.0	100.23	-24.77	0.198
"	31.62	120.0	111.21	-8.79	0.073
"	44.67	104.0	113.85	+9.85	0.094
"	63.10	107.0	115.97	+8.97	0.083
"	89.12	135.0	117.29	-17.71	0.131

Figure 16 is a graph of some of the data in Table XVII.

If $\Delta T = \hat{T} - T$, then the standard deviation in ΔT is $\sigma_{\Delta T} = 7.06$ seconds for the data in Table XVII. The ratio $\left|\frac{\hat{T} - T}{T}\right|$ was used to obtain the percentage standard deviation $\sigma\,\% = 0.199 \approx 20\%$.

It will be recalled that R. B.'s data (all 212 points rather than the 106 used here) were also fitted with the power series function. In Table XVI, it may be seen that the percentage standard deviation in recovery time with the power series fit for subject R.B. was $\sigma\frac{dT}{T} = 0.195 \approx 20\%$ even though the matrix inversion was not perfect. It would seem,

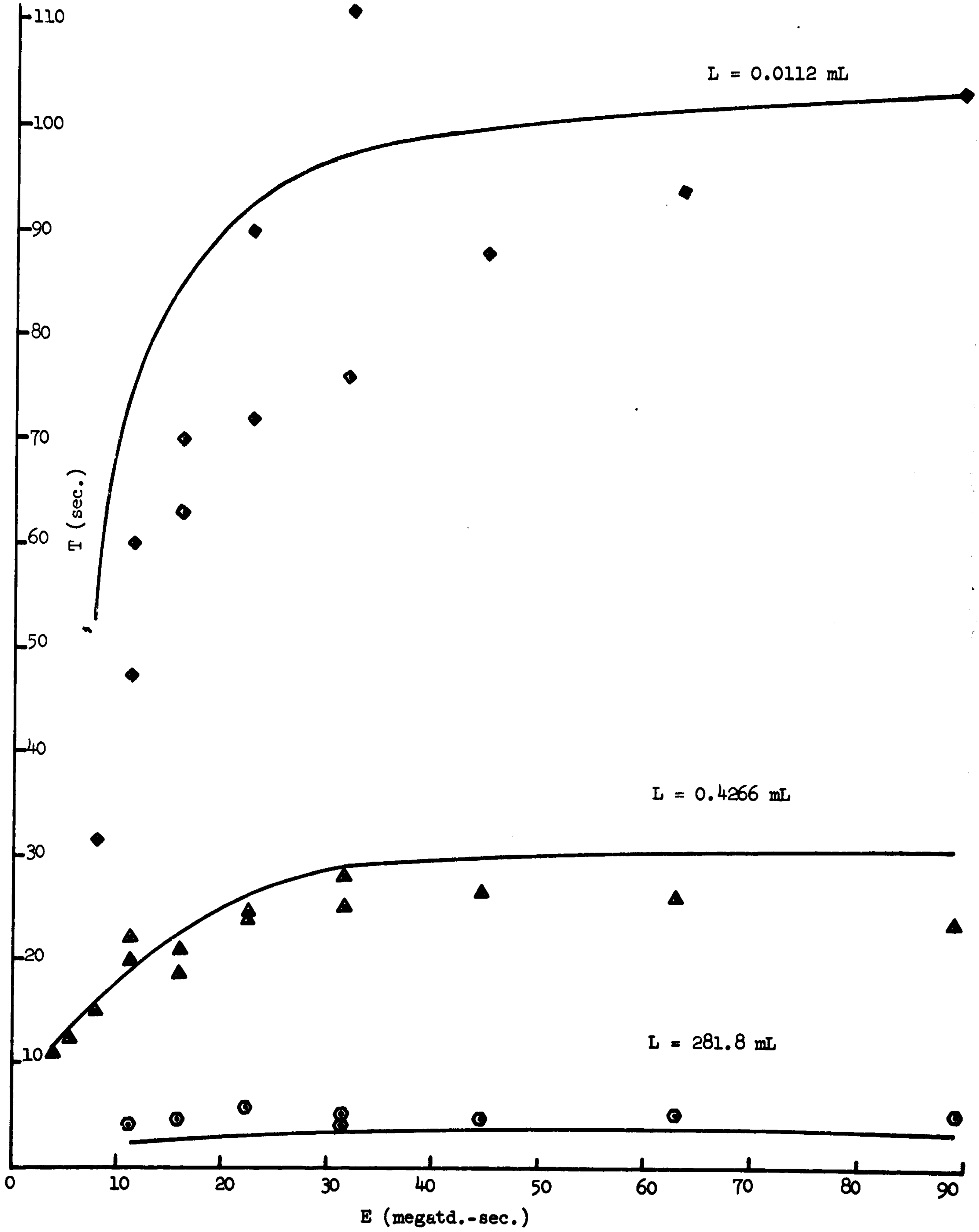

Figure 16. Gompertz function.

then, that the power series function gives a fit to the data as good or better than the Gompertz Function. Based on the results of the sample problem and sample problems which used the power series function, [illegible] considering also the relative flexibility of the power series function, further consideration of the Gompertz Function was not warranted, at least for the time being.

9.0 PREDICTION FROM RECOGNITION THRESHOLD AND AFTERIMAGE BRIGHTNESS MATCHING DATA

Miller is presently engaged in some preliminary studies which attempt to predict recovery time from recognition threshold and afterimage brightness matching data.* The procedure used is essentially as follows:

a. A flash is delivered to the eye so as to create a semi-circular afterimage. The other half of the semi-circle is then illuminated and its intensity is manipulated so as to match the brightness of the afterimage as it decays in time.**

b. A Snellen letter of some brightness is superimposed on a bright field and the field luminance manipulated until the letter can just be seen; i.e., the background field luminance for threshold recognition of the letter is determined.

c. For each combination of flash energy, letter size and letter brightness, the recovery time is measured.

d. The appropriate recognition threshold and afterimage decay curves are combined graphically to determine the time after a flash that an afterimage becomes dim enough just to see a letter of a given size and brightness. This time is the recovery time prediction for the selected conditions.

---

* Mrs. Miller described these studies to Dr. Czeh during the latter's recent visit to the School of Optometry, Ohio State University. She was also kind enough to provide data from her first studies to us.

** Some difficulty is encountered in keeping this afterimage and matching field in proper juxtaposition. Better results are obtained when the afterimage is a circular spot and the matching field is an annulus around it. See Fry (17) for a description of this latter arrangement.

Miller's preliminary data include some 111 pairs of measured and predicted recovery times. The correlation between the measured and predicted values is on the order of .82. On the average, the predicted values underestimate the measured values by about 1 per cent, and the standard deviation of the distribution of the per cent errors is approximately 44. It is to be emphasized that this analysis has been applied to a very preliminary set of data from what should more properly be termed a pilot or feasibility study. With improvement in the experimental procedures and an analytical rather than graphic combination of the threshold and brightness matching data, prediction must almost certainly improve.

10.0 PREDICTION USING BROWN'S EQUATION

Brown (8) recently suggested an equation for predicting recovery time as a function of flash energy, visual acuity and display luminance. This equation was applied to Miller's data, Appendix G, to compare its predictions with the predictions of the multiple linear regression equation. The results of this effort are presented here.

Brown's equation is:

$$t = .2 + b \frac{2.7 - \text{Log } L}{(\text{Log } L - \text{Log } Lo)(2.7 - \text{Log } L_o)} \qquad (11)$$

where:

t = perception (recovery) time in sec.,
$.2$ = t_o, minimum perception time in sec.,
L = display luminance in ft.-lamberts
L_o = minimum luminance in ft.-lamberts at which the display can be perceived under optimum conditions (Log L_o = -1.2 for acuity = .33)

2.7 = Log L max, the log of the luminance in ft.-lamberts at which t_o is reached,

and,

$$b = g A^h$$

where:

A = Flash energy in ft.-lambert-sec.

and

g and h = functions of visual acuity.

Brown determined values for g and h empirically from his data. For a visual acuity of .33 and a flash duration of 9.8 msec.,

$$b_{0.33} = 0.01 A^{0.8} \qquad (12)$$

None of Miller's experimental conditions matches this visual acuity - flash duration combination exactly. One of her sets of conditions (flash duration of 5 msec., visual acuity of 0.3086) was fairly close, however and Equation (12) for $b_{0.33}$ was used to approximate $b_{0.3086}$ for the various flash energies, converted to ft.-L-sec., used by Miller. Recovery times computed using these values of b differed markedly from the times measured by Miller; these results are shown in Table XVIII. The errors are so large that there seemed no need to calculate the per cent error.

TABLE XVIII

COMPARISON OF RECOVERY TIMES PREDICTED (FROM Eq. 11) and MEASURED (FROM MILLER)

Log L (ft-L)	Log A (ft-L-sec.)	t (calculated) (sec.)	t (observed) (sec.)
2.418	5.718	7.7	5.3
	5.568	5.9	4.7
	5.418	4.5	5.1
	5.268	3.6	3.9
.718	5.718	99.66	13.3
	5.568	75.63	12.8
	5.418	57.23	10.5
	5.268	43.60	9.9
	5.118	33.13	8.0
	4.968	25.2	5.8
	4.818	19.2	6.6
.268	5.718	159.60	20.2
	5.568	121.13	18.2
	5.418	91.95	15.2
	5.268	69.78	14.0
	5.118	53.00	12.1
	4.968	40.25	9.4
	4.818	30.57	10.4
-.4019	5.718	374.3	37.4
	5.568	283.9	31.1
	5.418	215.5	26.6
	5.268	163.4	21.8
	5.118	124.1	19.0
	4.968	94.2	14.2
	4.818	70.5	13.0

-.7819	5.718	801.8	49.7
	5.568	608.1	40.5
	5.418	460.4	39.5
	5.268	349.9	33.0
	5.118	265.6	26.5
	4.968	200.6	18.8
	4.818	152.9	17.4

Brown's equation was also used to compare computed recovery times with times taken from Appendix Table D.2.* Only part of the data were used; specifically, the four highest points for the 9.8 msec. flash at the three levels of target luminance. The percentage standard deviation was $\sigma\% \cong 78$. The multiple linear regression equation for flash energy in lambert-seconds (Equation 7), applied to the same points, yields a percentage standard deviation $\sigma\% \cong 60$.**

It is quite clear from this analysis that Brown's function is not easily applicable to some arbitrarily chosen set of data such as Miller's. The main difficulty apparently lies in the resolution of the coefficient b; this is so critical that the assumption $b_{.33} = b_{.3086}$ is not a valid one. Thus, an error so large was introduced in the prediction of Miller's recovery times that a mathematical treatment of error was beside the point. This error is not entirely attributable to the selection of $b_{.33}$, however, for the values used for L_o and L_{max} may also be in error. Still, it appears that, in general, Brown's equation may yield errors as large or larger than those resulting from the application of the m.l.r. function to the same data. In addition, the m.l.r. function is a great deal easier to apply.

---

* Appendix Table D.2 is from Hill and Chisum (23) and Chisum and Hill (11). Brown's (8) Figure 4 is the corresponding graph, and is replotted in Figure 5 above.

** See also Table X preceding.

11.0 DISCUSSION

The model presented here is a purely mathematical model developed only for the purpose of predicting recovery time. The equations integrate data from several sources, but do not, and were not intended to, integrate knowledge of the chemical and neural aspects of visual recovery. The main consideration was to find equations which meet the mathematical criterion of minimizing the sum of the squared deviations of the predicted values from the observed values. The equations are of practical value in that they can predict recovery times given the flash energy, target brightness and target visual acuity (within certain bounds) with an accuracy somewhat higher than can be achieved by other presently available techniques. Still, from the point of view of advancing the fundamental knowledge of flashblindness, and of recovery from it, the equations leave much to be desired because of their complete isolation from the physiological mechanisms involved.

The applicability of the equations to the pilot's visual tasks cannot be stated definitely. Indeed, of the various studies surveyed, only Whiteside and Bazarnik (54) used an aircraft instrument as the recovery target. However, since the model does cover visual acuities ranging from 0.08 to 0.33 (visual angles of critical detail between 12.5′ and 3′), and since the critical detail of most dimly illuminated instrument markings do subtend visual angles greater than 3′ (see Appendix A), there is almost certainly some applicability. Errors in prediction will, of course, be larger, and not only because of considerations involving statistical logic, but also because the pilot's visual tasks certainly involve more than merely the recognition of single letters or numerals or the detection of the orientation of a line. Studies using aircraft instruments (or photos or mockups of them) would be valuable. One should probably begin with the instruments needed for the most critical post-flash tasks. It is likely that the tasks will vary with the nature and phase of the mission, but surely attitude indicators will be high on the list.

Whiteside and Bazarnik (54) used flash energies that are, for the most part, well above the upper bound that had to be set (and, indeed, no other study used flash energies as high as their highest). This is really unfortunate since the equations as they now stand are absolutely incapable of predicting the positive acceleration in recovery time which apparently starts beyond approximately 1600 lambert-seconds (8.0 log troland-seconds).

However, assuming some average visual acuity, their flash energies which do fall below the multiple linear regression function's upper limit yield recovery times consistent with expectations. Brown (8) suggests that the leveling off of recovery time at about 1600 lambert-seconds results from a maximum possible bleaching of the photochemical substances and that the positive acceleration at higher energies results from actual, but reversible, damage; ultimately, of course, the damage becomes irreversible and the recovery time infinite for the portion of the retina affected. It would be interesting to try to relate the various positive and negative accelerations to what is known about the photochemical and heat absorption and diffusion processes in the retina.

The results of the brief examination of Brown's (8) equation led to rather disappointing results. The main difficulty is in determining values for the variable $b = g A^h$ (where g and h are functions of visual acuity, and A is the flash energy). Brown determined g and h empirically. Presumably, with a good number of additional data points for a number of different visual acuities, one could write a function to determine g and h for any visual acuity. But at present, one must cut and try, and small variations in g and h can cause large variations in t- predicted.

The technique used to convert lambert-seconds to troland-seconds by estimating pupil size and pupil size changes during a flash is mathematically straight-forward and apparently reasonably accurate. The accuracy will be improved by Miller's newer data concerning the pupil response. The technique should be a help in allowing the use of trolands (or troland-seconds) as the standard unit of measurement for flash intensity (or energy). Some modification of the technique is, however, clearly required to take account of the pupil response latency and, perhaps, of a greater Stiles-Crawford effect when the pupil opening is large as compared to the effect when the pupil is small.

One variable, in particular, which it has been impossible to treat directly, is the level of dark (or light) adaptation achieved prior to the flash; there just are not enough relevant data. The variable does, of course, enter the troland-second equation indirectly since a source of a given intensity and duration will deliver a higher energy (in troland-seconds) to the retina of the dark adapted eye than to the retina of the light adapted eye. One study that varied pupil size directly (Severin et al, 42) gave such unique results that a replication is essential. Another study (Miller, 32) that directly varied the level of pre-flash adaptation used only one target luminance after the flash and is, therefore, quite limited in the generalizations it allows.

There are a number of other variables which have not been treated here but which may be of importance. The spectral characteristics of the flash and of the display illumination almost certainly have to be taken into account. The display illumination technique (i.e., front-illumination vs. transillumination) may affect recovery time, as may also figure-ground relations and contrast.

12.0 SUMMARY

Equations have been developed for predicting recovery time from flashblindness. The equations are limited to the variables flash energy, display visual acuity, and display luminance, and to certain ranges of those variables. Within these limits, however, prediction appears possible. There are, of course, errors in prediction, but these appear to be related primarily to subject differences.

REFERENCES

1. Allinikov, S. Application of Enzymes in Photochromic Optical Shutters for Nuclear Flash Protection. 11th Annual Air Force Science and Engineering Symposium, Brooks AFB, Texas. 20-22 October 1964, 27 p.

2. Bartley, S. H. The psychophysiology of vision. In Stevens, S. S. (Ed.) Handbook of Experimental Psychology. New York: Wiley, 1951.

3. Bowman, R. E., et al. Research and Reports on Photochromic Materials Which May Be Used As Eye Protective Devices. Final Report on Contract AF 41(657)-406, National Cash Register Company, Dayton, Ohio, April 1963, 161 p. (AD-427 601)

4. Britten, A. J. "Eye Protective Devices", Ordnance, Vol. 49, No. 267, November-December 1964, pp. 312-315.

5. Brown, J. L. The Use of Colored Filter Goggles for Protection Against Flashblindness. Aviation Medical Acceleration Laboratory, NADC-MA-5917, October 1959, 24 p. (AD-229 350)

6. Brown, J. L. Flash Blindness. General Electric Company, Missile and Space Vehicle Department, Philadelphia, Pennsylvania, Report No. 61SD179, November 1961, 32 p.

7. Brown, J. L. "Time Required for Detection of Acuity Targets Following Exposure to Short Adapting Flashes". Journal of Engineering Psychology, Vol. 3, April 1964, pp. 53-71.

8. Brown, J. L. "Experimental Investigations of Flash Blindness". J. Human Factors Soc., 1964, Vol. 6, 503-516.

9. Byrnes, V. A., et al. "Retinal Burns, New Hazard of the Atomic Bomb". Journal of the American Medical Association, Vol. 157, January 1955, pp. 21-22.

10. Chapanis, A. How we see: A summary of basic principles. In A survey report on human factors in undersea warfare. Prepared by the Panel on Psychology & Physiology for the Committee on Undersea Warfare of the National Research Council. Washington, D.C.: 1949.

11. Chisum, G. T. and Hill, J. H. Flashblindness Recovery Time Following Exposure to High Intensity Short Duration Flashes. Aviation Medical Acceleration Laboratory, NADC-MA-6142, November 1961, 13 p. (AD-272 285)

12. Chisum, G. T. and Hill, J. H. *Dynamic Simulation of the A4D Flashblindness Protective System.* Aviation Medical Acceleration Laboratory, U.S. NADC, NADC-MA-6312, July 1963, 16 p. (AD-414 398)

13. Culver, J. F. and Alder, A. V. *Protective Glasses Against Atomic Flash.* School of Aerospace Medicine, Brooks AFB, Texas. April 1961, 7 p. (AD-400 121)

14. Efroymson, M. A. Multiple regression analysis. In Ralston, A. and Wilf, H. S. (Eds.) *Mathematical Methods for Digital Computers.* New York: Wiley, 1962, pps. 191-203.

15. Fox, R. E. *Research Reports and Test Items Pertaining to Eye Protection of Air Crew Personnel.* National Cash Register Company, Final Report on Contract AF 41(657)-215, April 1961, 257 p. (AD-440 226)

16. Fry, G. A. and Alpern, M. *Effect of Flashes of Light on Night Visual Acuity*, Part I. WADC TR 52-10, 1951. (AD-13 833)

17. Fry, G. A. *The Positive Afterimage and Measurements of Light and Dark Adaptation.* Ohio State Research Foundation Report. 1964. (AD-610 733)

18. Glasstone, S. (Ed), *The Effects of Nuclear Weapons*, U.S. Atomic Energy Commission Revised ed., April 1962.

19. Ham, W. T., Jr., Wiesinger, H., Schmidt, F. H., Williams, R. C., Ruffin, R. S., Shaffer, M. C., & Guerry, D., III. "Flash Burns in the Rabbit Retina as a Means of Evaluating the Retinal Hazard from Nuclear Weapons". *American Journal of Ophthalmology*, Vol. 46, 1958, pp. 700-723. (AD-605 797)

20. Harries, R. W. *The Dynacell and Focal Plane Concepts of Phototropic Systems Application to Ophthalmic Nuclear Flash-Protective Devices.* Polocoat, Inc. MRL-TDR-62-46, May 1962, 12 p. (AD-284 059)

21. Hauser, S. M., et al. *Design and Fabrication of Experimental Stressed-Plate Shutter Systems.* Final Report on Frankford Arsenal Contract DA-04-495-ORD-1995-1510, May 1961, 86 p. (AD-259 451)

22. Hill, J. H. & Chisum, G. T. *Eye Protection For Nuclear Weapons Delivery Pilots: In-flight Research Studies to Obtain Quantitative Performance Data.* Naval Air Development Center Progress Report No. MA-L 6035, 1960.

23. Hill, J. H. and Chisum, G. T. "Flashblindness Protection", *Aerospace Medicine*, Vol. 33, August 1962, pp. 958-964.

24. Hill, J. H. and Chisum, G. T. Flashblindness: A Problem of Adaptation. Aviation Medical Acceleration Laboratory, U. S. NADC, Report No. NADC-MA-63-27, December 1963, 8 p. (AD-429 241)

25. Hill, J. H. and Chisum, G. T. The Nature of Radiation From Nuclear Weapons in Relation to Flashblindness. Aviation Medical Acceleration Laboratory, NADC, Report No. NADC-MA-64-12, August 1964, 16 p. (AD-453 622)

26. Jenkins, F. A. and White, H. E. Fundamentals of Optics. (2nd ed.) New York: McGraw-Hill, 1950.

27. Laxar, K. V., Critical Visual Areas of Explosive-Activated Lens Filter (ELF) System for Prevention of Flash Blindness. Naval Medical Research Laboratory, New London, Connecticut. Report No. NMRL-MR-64-1, January 1964, 7 p. (AD-442 740)

28. Lewis, D. Quantitative Methods in Psychology. New York: McGraw-Hill, 1960.

29. Lowry, E. M. Feasibility Study of the Explosive Lens Anti-Flash System for Use in Fire Control Optical Instruments. Bermite Powder Company, Report No. 330, July 1963, 30 p. (AD-427 262)

30. Metcalf, R. D. and Horn, R. E. Visual Recovery Times from High Intensity Flashes of Light. WADC TR-58-232, October 1958, 10 p. (AD-205 543)

31. Metcalf, R. D. and Horn, R. E. Flashblindness During Nuclear Operations. WADC TR 58-642, December 1959, (Confidential Restricted Data). (AD-338 028)

32. Miller, N. D. Visual Recovery from Brief Exposure to Very High Luminance Levels. Final Report, Part I, on Contract AF 33(657)-9229, May 1964, 74 p. (AD-450 072)

33. Minners, H. A., et al. "A Simple Method of Chorioretinal Burn Protection". Aerospace Medicine, Vol. 35, July 1964, pp. 627-629.

34. Parker, J. F. Visual Impairment from Exposure to High Intensity Light Sources. Biotechnology, Inc., Report No. 63-2, Contract NONR-4022(00), May 1963, 39 p. (AD-412 960)

35. Parkhurst, D. J. Operational Test and Evaluations of Phototropic Goggles. Report No. ADC/73AD/63-26, November 1963, 25 p. (AD-428 073)

36. Pisano, F. Feasibility Study of an Explosively Actuated Flash Protection Device. Frankford Arsenal, Philadelphia, Pennsylvania, Report No. R-1640, January 1964, 16 p. (AD-430 250)

37. Pitts, D. G. and Loper, L. R. "Ambient and Cockpit Luminance Measurements". Journal of Aerospace Medicine, Vol. 34, February 1963, pp. 145-149.

38. Plum, W. B. and Crillz, J. B. Eye Protective Devices. Naval Civil Engineering Laboratory, Port Hueneme, California, Report No. TN-N643, September 1964, 15 p. (AD-450 637)

39. Russell, J. L. The Temporary Blinding Effect of Flashes of Light. Royal Aircraft Establishment, Farnborough, England, Report No. E and I 1085, October 1937, 9 p.

40. Severin, S. L., Newton, N. L., and Culver, J. F. "An Experimental Approach to Flash Blindness". Aerospace Medicine, Vol. 33, 1962, pp. 1199-1205.

41. Severin, S. L., Newton, N. L., and Culver, J. F. "A New Approach to the Study of Flash Blindness: Use of the Zeiss Light Coagulator". Archives of Ophthalmology, Vol. 67, May 1962, pp. 578-582.

42. Severin, S. L., Newton, N. L., and Culver, J. F. "A Study of Photostress and Flashblindness". American Journal of Opthalmology, Vol. 56, October 1963, pp. 589-595.

43. Severin, S. L., Adler, A. V., Newton, N. L., and Culver, J. F. Photostress and Flashblindness in Aerospace Operations. School of Aerospace Medicine, Brooks AFB, Texas. Report No. USAF SAM-TDR-63-67, September 1963, 15 p. (AD-600 402)

44. Sneed, R. J., Knight, G. C. and Hartouni, E. Flash Protection Device, General Dynamics/Pomona, California, Final Report Contract DA 19 129QM 1965, October 1963, 72 p. (AD-453 018)

45. Sneed, R. J., Sacks, P. and Knight, G. C. Flash Protection Device. General Dynamics/Pomona, California. Quarterly Progress Report No. 2, Report No. TM 349-91, Contract DA 19 129QM 1965, December 1962, 25 p. (AD-452 866)

46. Thomsen, R. K. Feasibility Study of the Explosive Lens Anti-Flash System For Use in the XM 112 Periscope. Frankford Arsenal Contract DA 04-495 -AMC-1(A), Bermite Powder Company, BPC Report No. 370, December 1963, 38 p. (AD-429 423)

47. Timm, W. Development of A Device to Provide Protection for the Eyes Against the Dazzle Effect of a Nuclear Weapon. Final Report on Contract DA-19-129-QM-144B, Mine Safety Appliance Company, Report No. A-220804, July 1960, 15 p. (AD-254 046)

48. Vergamini, P. L. Simplified Method for Predicting Radiation in the Vicinity of Nuclear Detonations. ASD Technical Report 61-60, May 1961. (AD-262 643)

49. Vos, J. J., Frederikse, J. W., Walraven, P. L. and Boogaard, J. Some Reflections On the Danger of and the Protection Against Nuclear Flash Blindness and Retinal Burn. Inst. for Perception RVO-TNO, Soesterberg, The Netherlands. Report No. IZF 1964-25, 1964. (AD-456 728)

50. Wayne-George Corporation. High Speed Electromechanical Goggle, WADC TR-59-114, May 1959, 21 p. (AD-215 828)

51. Whiteside, T. C. D. Problems of Vision in Flight at High Altitude. London: Pergamon Press, 1957.

52. Whiteside, T. C. D. "Dazzle From Nuclear Weapons". Vision Research Reports, NAS-NRC publ. no. 835, 1960.

53. Whiteside, T. C. D. The Observation and Luminance of a Nuclear Explosion. Flying Personnel Research Committee, Air Ministry, Farborough, England, Report No. FPRC 1075.1, March 1960, 27 p. (AD-239 858)

54. Whiteside, T. C. D. and Bazarnik, K. The Dazzle Effect of an Atomic Explosion at Night. Flying Personnel Research Committee, Air Ministry, Farnborough, England. FPRC 787, May 1952, 18 p.

55. 4750th Test Squadron, Tactics and Applications Engineering, Tyndall AFB, Florida. Evaluation of OT and E Electromechanical Goggles, Final Report, TS ADC 73AD 63 13, April 1963, 20 p. (AD-404 639)

Appendix A

A DESCRIPTION OF SELECTED FEATURES OF THE AIRCREW VISUAL ENVIRONMENT*

Introduction

The visual environment of the pilot is never static. It is constantly changing, not only in a qualitative but also a quantitative manner. Because of this constant change it is not possible to adequately describe the total visual environment at any given time, or even one aspect of the total environment over a significant period of time. Even if such a description were possible, it would have only limited applicability in establishing the wide range of visual parameters related to the aviation environment. The pervasiveness of this constant variability can readily be appreciated when, for example, it is realized that the daylight ambient illumination in the cockpit of an aircraft is determined by the cockpit, windshield, and canopy design characteristics of the particular aircraft, the altitude and direction of the flight, the time of day, and the prevailing meteorological conditions.

To avoid the inherent complexity of accounting for all the multiple significant interactions that would normally have to be considered in attempting a comprehensive description of the visual environment, the data here to be presented have been derived, not from specific operational environments, but rather from design criteria imposed by applicable standards and specifications together with such supporting information that is considered to be good human factors practices. Some additional information has also been supplied that has been derived from actual physical measurements of broadly applicable and generalizable situations.

A perusal of the supplied data makes it immediately evident that little or no direct account has been taken of the pilot's physiological or

---

*This material was prepared by Paul C. Rasmussen.

psychophysical abilities and limitations. The data are oriented toward a general description of selected quantitative and qualitative potential stimuli available to the pilot regardless of his immediate ability to effectively utilize them. The extent to which these selected parameters become useful and/or available to the pilot under varying levels of adaptation to his environment must be related to the effect the variable under consideration, in this case high intensity light flashes, has on the pilot's visual capabilities.

In the Cockpit

The visual environment within the cockpit is subject to considerably more control than the external environment. Though the external environment does influence visability in the cockpit, the careful design of instruments and indicators and provisions for artificial illumination go a long way toward minimizing excessive variability and maintaining adequate visibility for the tasks to be performed.

Table A-I presents a compilation of visual angles subtended by the various dimensions of each characteristic on the control configurations and markings employed on instruments, display panels, and plastic lighting plates at selected viewing distances. Table A-II presents a similar compilation for recommended scale indexes designed for dimly lighted aircraft dials. The visual angle of a target or test object is only one parameter in determining visibility and legibility.

Consideration must also be given to brightness or intensity and the contrast ratio between the figure and ground. Table A-III gives the required ranges of brightness and contrast ratios for integrally lighted instruments and Table A-IV gives comparable figures for plastic lighting plates.

Integrally lighted displays frequently require secondary floodlighting. A relatively low level is employed to orient the visual field and minimize the autokinetic effect that often occurs where visual orientation reference cues are minimal. A higher level of floodlighting serves to supply adequate illumination levels to read the control configurations and markings in the event of failure of the integral lighting system. The particular illumination levels employed are generally a function of the specific requirements imposed by other design requirements but are generally limited in their upper range by the consideration of the necessity for maintaining adequate dark adaptation. Table A-V gives ranges of light intensities required for various work stations and functions to be supplied by the secondary lighting system. The maximum intensity permitted at a work station requiring dark adaptation maintenance is 6.0 ft. C. It is generally accepted that for dial reading purposes and similar activities the markings must have a subjective brightness of at least 0.02 ft. L. with adequate contrast between markings and ground. Some aircraft are equipped with an emergency floodlighting source generally referred to as thunderstorm lights. Where such lights are available they must have a minimum intensity of 100 ft. C. to be distributed over the floor and instruments of the flight compartment. This is essentially an emergency device since it is likely to seriously impair dark adaptation under the conditions they are most likely to be utilized.

Since most detail design of instruments and other information displays are oriented toward detectability, legibility, and readability at low levels of ambient and integral lighting, the presence of high daytime ambient illumination in the flight station is seldom a problem as it relates to these

TABLE A-I

VISUAL ANGLE SUBTENDED BY CONTROL CONFIGURATIONS AND MARKINGS AT SELECTED VIEWING DISTANCES

	Dimension (in inches)	**Visual Angle at 24"**	**Visual Angle at 28"**	**Visual Angle at 30"**	**Visual Angle at 36"**
Letter and Numeral Height (Regular)	.125	17' 54"	15' 21"	13' 26"	11' 56"
Letter and Numeral Height (Emphasized)	.156	22' 21"	19' 08"	16' 46"	14' 54"
Letter Width (Regular Narrow)	.075	10' 44"	9' 12"	8' 3"	7' 10"
Letter Width (Regular Wide)	.125	17' 54"	15' 21"	13' 26"	11' 56"
Letter Width (Emphasized Narrow)	.094	13' 28"	11' 32"	10' 06"	8' 59"
Letter Width (Emphasized Wide)	.156	22' 21"	19' 08"	16' 46"	14' 54"
Letter Stroke Width (Narrow)	.018	2' 35"	2' 13"	1' 56"	1' 43"
Letter Stroke Width (Wide)	.025	3' 35"	3' 04"	2' 41"	2' 23"
Numeral Stroke Width (Narrow)	.013	1'52"	1'36"	1' 24"	1' 14"
Numeral Stroke Width (Wide)	.020	2' 52"	2' 27"	2' 09"	1' 55"

TABLE A - II
VISUAL ANGLE SUBTENDED BY SCALE INDICES DESIGNED FOR DIMLY LIGHTED AIRCRAFT DIALS TO BE VIEWED AT 28 INCHES

	Dimension	Visual Angle at 24"	Visual Angle at 28"	Visual Angle at 32"	Visual Angle at 36"
Minor Index Width	.025"	3' 35"	3' 04"	2' 41"	2' 23"
Minor Index Height	.100	14' 19"	12' 17"	10' 45"	9' 33"
Intermediate Width	.030"	4' 18"	3' 41"	3' 13"	2' 52"
Intermediate Height	.160"	22' 55"	19' 39"	17' 11"	15' 17"
Major Index Width	.035"	5' 01"	4' 18"	3' 46"	3' 21"
Major Index Height	.220	31' 31"	27' 01"	23' 38"	21' 00"
Spacing of Minor Indices (Edge to Edge)	.040"	5' 44"	4' 55"	4' 18"	3' 49"

Note: For scales designed for optimal viewing at other distances the values of visual angle presented for the 28 inch viewing distance are applicable.

TABLE A-III

INTEGRAL INSTRUMENT LIGHTING

	White Light (MIL-L-27160)	Red Light* (MIL-L-25467)	Electro-Luminescent (MIL-L-25467)
White Areas (FED-STD-595) #37875)	0.5 to 1.5 ft. L	0.5 to 1.5 ft. L	0.3 to 0.7 ft. L
Gray Areas (FED-STD-595 #36440)	0.3 to 0.9 ft. L	0.3 to 0.9 ft. L	0.1 to 0.3 ft. L
Black Areas (FED-STD-595 #37038	0.02 to 0.08 ft. L (Reflected) 0.02 to 0.06 ft. L (Backlighted)	0.02 to 0.1 ft. L	.005 to .035 ft. L
Pointers, Lubbers & Other Reference Marks	0.7 to 1.7 ft. L	Not to exceed 1.8 ft. L but must be brightest display marking	Not to exceed 1.8 ft. L but must be brightest display marking
Red Areas	0.5 to 1.5 ft. L		
Minimum Contract	W/B 12 G/B 5	W/B 12 G/B 5 (without cover glass)	W/B 12 G/B 5

* Aviation Red per MIL-C-25050

TABLE A-IV

PLASTIC LIGHTING PLATES

TYPE I & II
(Light Conducting Panels)

Intensity of unobstructed markings - Not less than .75 ft. L
Intensity of obstructed markings - Not less than .50 ft. L
Contrast - Not less than 12

TYPE III
(Duo Panels)

Intensity on a 2.188" radius from lamp - 2.5 ft. L
Intensity with two nearest lamps extinguished - 2.0 ft. L
Contrast - Not less than 12

TABLE A-V

LEVELS OF ILLUMINATION FOR SECONDARY LIGHTING

Location	Light Intensity in Foot Candles		Dimming Required
	Minimum	Maximum	
Cabin area passenger*	0.5	2.0	Yes
Cargo compartments*	0.1	0.7	No
Compartments containing unlighted equipment that requires adjustment*	0.5	2.0	Yes
Crew station locations where map reading, course plotting, et cetera, are required (on working area)*	3.5	6.0	Yes
Walkways - aisles*	0.1	0.7	No
Auxiliary power plant compartments and engines where light is required	4.0	8.0	No
Cabin area (passenger)	4.0	15.0	Yes
Cargo compartments on floor	0.2	2.0	No
Crew station locations where map reading, course plotting, et cetera, are required	8.0	15.0	Yes
Electronic equipment controls that are not lighted and require adjustment	0.5	5.0	Yes
Compartments requiring inspection	0.5	2.0	Yes
Loading and ramp areas (on the loading area)	0.2	2.0	No
Passageways on floor	0.2	2.0	No
Tie down locations on floor with cargo in place	0.2	2.0	No

*Areas where dark adaptation must be maintained

Notes:

Light intensities apply to all colors of light.

capabilities. Some modification of the effects of excessive ambient illumination levels can be achieved in special situations, such as CRT viewing, through the use of visors, glare shields, hoods, and similar devices.

Quite distinct from the necessity to discriminate relatively small and often complex stimuli such as instrument markings and operational legends is the utilization of aircrew station signal lights. Table A-VI lists the basic brightness ranges and color requirements, as well as some additional factors that enter into determining their effectiveness for the purpose they are intended to serve. These signals are used as warning, caution, and advisory indicators that require varying degrees of attention and priorities by the pilot.

The visual characteristics of controls are not easily defined by visual characteristics alone. Certain elements of appearance are part of the total integrated process related to the utilization of controls but location and shape coding tends to minimize the dependence on visual cues.

The External Environment

Though the particular flight conditions existing at a given time, and the specific activity to be performed during a segment of the flight profile may vary the ratio somewhat, the pilot spends the greatest part of his time observing the external environment. Such activity may be directed toward terrain following, checking for reference points, take-off and landing, obstacle avoidance, and formation flying. Though other factors may play a significant role, it can be said that most of this effort is directed at collision avoidance which in itself is inherent in many of the mentioned activities. The data presented in this section are generally oriented toward this approach with particular attention to air-to-air visibility.

TABLE A-VI
AIRCREW STATION SIGNALS
(From MIL-STD-411)

	Brightness (High)	Brightness (Low)	Color	Legend	Presentation Mode	Location
Warning Light	150 ft. L	15 ft. L	Aviation Red (FED-STD-#3)	Opaque on translucent; Letter Height .125"	2 to 3 flashes per sec.; Light to Dark ratio .5	30° cone of vision on upper instrument panel
Master Caution Light	150 ft. L	15 ft. L	Aviation Yellow (FED-STD-#3)	Opaque on translucent; Letter height .125"	Steady on	30° cone of vision on upper instrument panel
Caution Light	150 ft. L	1.5 ft. L	Aviation Yellow (FED-STD-#3)	Opaque on translucent; Letter height	Steady on	Lower right instrument panel or forward portion of right hand console or subpanel.
Advisory Light	150 ft. L	1.5 ft. L May be higher at stations other than flight compartment when ambient levels dictates higher brightness.	Green White Blue Color based on particular type of information to be presented. Non legend white not to be used.	Opaque on translucent; Letter height .125"; Translucent legend against opaque contrast may be utilized at stations other than flight compartment. Labels on panel may be used rather than integral indicator legend	Steady on	Any position observance from operator position

One feature of modern aviation that imposes certain demands on the visual capabilities of the aviator, without being a functional aspect of vision, is the potential and actual high speeds of operational aircraft. The great distances that can be covered in a matter of seconds intensifies the demands for obstacle or target detection at ever great distances. In many instances such requirements have already exceeded the limits of the psycho-physiological limits of the human element in modern aviation. Table A-VII, for example, illustrates some representative distances traveled not only during the relatively short period of time necessary to react to a complex stimulus under the most ideal conditions but also at other intervals during which the pilot may be occupied with other tasks or have his vision temporarily impaired by loss of dark adaptation or the veiling influence of short, high intensity light flashes.

The data in Table A-VII can be compared to the representative data in Table A-VIII which illustrate the visual angle subtended by targets, such as other aircraft, presenting effective major dimensions at right angles to the line of sight at viewing distances comparable to the distances traveled as given in Table A-VII. In these conditions there are other factors to consider which play an important role in the probability of detection at a given distance under varying conditions. Sky brightness becomes a dominant factor and that in itself is a highly variable condition. It has been suggested that a value of 2950 ft. L. is representative of the brightness of sunlit sand, water, and sky and a value of 17.5 ft. L. is a reasonable approximation of ambient brightness during civil twilight (La Mar, E.S., et al., J. Opt. Soc. Amer., 37, 1947). These values are of limited

TABLE A-VII

DISTANCES TRAVELED IN FEET FOR SELECTED TIME INTERVALS AT REPRESENTATIVE SPEEDS

Time in Seconds *Speed of Aircraft	**5.445	10	20	30	60	120
600 MPH	4,792	8,800	17,600	26,400	52,800	105,600
1200 MPH	9,584	17,600	35,200	52,800	105,600	211,200
1800 MPH	14,375	26,400	52,800	79,200	158,400	316,800
2400 MPH	19,168	35,200	70,400	105,600	211,200	422,400
3000 MPH	23,960	44,000	88,000	132,000	264,000	528,000
3600 MPH	28,752	52,800	105,600	158,400	316,800	633,600

* For two aircraft on a collision course select the speed that represents the closing rate to find the distance the aircraft will travel toward each other during given time interval.

** Estimated minimum total system reaction time under ideal conditions.

TABLE A-VIII

VISUAL ANGLES SUBTENDED BY TARGETS OF SELECTED EFFECTIVE MAJOR DIMENSIONS AT REPRESENTATIVE DISTANCES

Target Dimension in Feet / Distance in Feet	40'	60'	80'	100'
5,000	27' 30"	41' 15"	55' 00"	1° 08' 45"
10,000	13' 45"	20' 38"	27' 30"	24' 23"
15,000	9' 10"	13' 45"	18' 20"	22' 55"
20,000	6' 53"	10' 19"	13' 45"	17' 11"
30,000	4' 35"	6' 53"	9' 10"	11' 28"
40,000	3' 26"	5' 09"	6' 53"	8' 36"
50,000	2' 45"	4' 08"	5' 30"	6' 53"
75,000	1' 50"	2' 45"	3' 40"	4' 35"
100,000	1' 23"	2' 04"	2' 45"	3' 26"
150,000	* -	1' 23"	1' 50"	2' 18"
200,000	-	1' 02"	1' 23"	1' 43"
300,000	-	-	-	1' 08"
Over/ 300,000	-	-	-	-

* Values of less than 1' of visual angle not included since they are probably meaningless in operational situation

applicability since they apply primarily to viewing at ground level and possibly very low altitudes. The apparent brightness of the daylight sky decreases with altitude. Direct measurements of zenith brightness at 10,000 feet on 11 separate "clear" days within 200 miles of Washington, D.C., yielded values ranging from 87 to 153 candles per square foot (Tousey, R. and Hulbert, O., J. Opt. Soc. Amer., 37, 1947). With the increase in altitude and darkening sky, the sun may become 30 per cent brighter than when viewed at ground level. These conditions, with the predominance of the illumination now coming from below the aircraft, and the increased sun-sky brightness ratio, increases visual discomfort and increases the difficulty of detecting a target against the sky.

Aluminum aircraft reflectivity varies from very low to as high as 80 per cent. The general contrast with the background sky is very low and may be either positive or negative. Under these conditions the probability of visual detection generally depends upon "glinting" when reflectivity is high or when it passes from one value of contrast through zero to a reversed contrast with the background sky.

Other factors that would normally increase the liklihood of detection may not operate effectively against the relatively unvarying background of the sky. Relative motion, for example, may not be readily apparent. Increased speed may increase noticeability rather than detectability due to the lesser time available for detection. The relatively unvarying background may also induce "empty field myopia" in the observer reducing detection range by as much as 50 per cent.

Nighttime flying introduces its own visual demands. Extremely low ambients and effective zero contrast ratios of the targets to the sky background reduces target visibility to nil. To overcome this problem numerous systems of signal lights have been devised for various functions such as formation flying, anti-collision, and aircraft orientation. Tables A-IX, A-X, A-XI, and A-XII give basic information for intensity, position, and color for such lights. Table A-XIII gives candle power requirements for signal lights of various colors to be detected at 5000 yards for comparative purposes. Though these values are based on observation at or near ground level the values for the clear atmospheric conditions should probably represent maximum requirements for altitudes above 10,000 feet if the aircraft is flying "above the weather".

A number of detectability and visibility studies has been conducted, but most of these are not translatable into quantitative unit values of visual parameters. The results of one such study are summarized in Table A-XIV. No supporting data relating to the conditions in effect at the time of the study are available. Along the same line of investigation it has been calculated that for two planes closing at 1000 knots there is only a 64 per cent probability that one pilot will detect the presence of the other plane at a distance greater than one nautical mile and that the probability drops to 26 per cent for distances beyond two nautical miles.

Such figures are tempered by a great number of factors in addition to those considered under the variables discussed elsewhere. One factor that weighs heavily in the aviation situation is that due to design restrictions the proportion of the available visual field devoted to scanning of the external environment is relatively small. Restricting the visual field to that attainable by head and eye movements only, one can scan approximately 75 per cent of the sphere surrounding the head. A survey study of a number of transport

TABLE A-IX

ANTICOLLISION LIGHTS
LIGHT INTENSITIES (WITH RED COLOR FILTER)

Angle Above or Below Mounting Plane of Light in Degrees	Minimum Effective Candlepower - Red Light Design Goals	Minimum Effective Candlepower - Red Light Required
0 to 5	100	100
5 to 10	100	60
10 to 20	60	20
20 to 30	60	10
30 to 40	60	
40 to 50	20	

Notes

Color:

Aviation Red
Flash Rate:

80-100 Per Min.

Number:
One Or More

TABLE A-X

DISTRIBUTION OF FUSELAGE LIGHTS

Light Distribution	Minimum Intensity
In hemisphere above horizontal plane	25 candles
In hemisphere below horizontal plane	25 candles

Note:
Fuselage Lights are White

TABLE A-XI

WING POSITION LIGHTS

Candlepower distribution in any plane containing the light center and parallel to the normal line of flight				
Angle from 0° (forward) Direction		Minimum cp[1] design goals	Minimum cp[1] required	Maximum cp[1]
Inboard	Outboard			
180° to 30°				3
30° to 10°				10
2				
	0° to 10°	60	40	
	10° to 20°	50	40	
	20° to 30°	30	30	
	30° to 40°	20	20	
	40° to 50°	15	15	
	50° to 70°	15	10	
	70° to 80°	15	6	
	80° to 100°	10	6	

[1] Red for left light assembly, green for right assembly.

[2] No light specified from 0° to 10° inboard to permit light to be reduced from minimum values specified at 0° to maximum values specified at 10° inboard.

TABLE A-XII

TAIL POSITION LIGHT

Candlepower distribution in any plane containing the light center and parallel to the normal line-of-flight		
Angle on each side of 0° (astern) direction	Minimum	Maximum
	CP white	CP
0° to 20°	30	
20° to 50°	21	
50° to 80°	12	
[1]		
100° to 120°		3
120° to 135°		2

[1] No light specified 90° to 100° to permit light to be reduced from minimum values specified at 80° to maximum value at 100°.

TABLE

TABLE A-XIII

CANDLE POWER REQUIREMENTS FOR DETECTION OF LIGHT AT 5,000 YARDS

Atmospheric Condition	Color of Light			
	Red	Amber	White	Green
NIGHT				
Clear	1.0	2.0	2.5	2.8
Light Rain	1.2	2.1	3.0	3.2
Overcast Haze	3.2	4.1	3.1	5.9
Heavy Rain	8.9	33.5	132.0	33.5
Light Snow	222.0	835.0	1556.0	567.0
DAY				
Overcast and Haze	2000.0	2111.0	3222.0	4000.0
Clear	4778.0	7556.0	11,111.0	10,000.0

Approximations of other ranges and values can be calculated by inverse square law.

TABLE A-XIV

DETECTION RANGES OF AIRCRAFT ON COLLISION COURSE

Bearing To Collision Aircraft	Observer Knowing Where To Look	Pilot Warned Of Collision Course Aircraft But Not Of Angle Of Approach	No Warning To Pilot
0° (Head-On)	11.0 Miles	5.00 Miles	3.5 Miles
30° Left	14.0 Miles	4.50 Miles	5.0 Miles
60° Left	12.0 Miles	4.50 Miles	4.5 Miles
100° Left	10.5 Miles	4.75 Miles	3.5 Miles

aircraft showed that only between 14 and 21 per cent of this available field of vision could be devoted to viewing outside the aircraft.

The increasing structural demands put on windshields and canopies by the requirements of modern, high-speed aircraft import further limitations on visibility from the cockpit. Table A-XV gives experimental data for the loss of visual range in the detection of targets as a function of the angle of inclination of the windshield. Table A-XVI is comparable to Table A-XV except that it is based on the measured light transmission as a function of angle of incidence of the light.

Table A-XVII gives the standards for transmission and haze in windshields. Considering Tables A-XV, A-XVI, and A-XVII together, some estimation can be made of the degree the target stimulus may become modified before it becomes available to the pilot.

Those design characteristics that have been presented in the discussion of limited fields of vision also tend to reduce the brightness of disabling flashes of light in the same ratio as they impair visibility though it remains to be determined if the degree of functional impairment is comparably reduced.

Other Considerations

There are some visual phenomena that are extremely important in aviation that defy adequate description in quantitative sensory terms. The landing of an aircraft for example, though relying almost exclusively on visual cues, becomes a cognitive or intellectual process far removed from simple intensity and contrast discrimination and visual acuity. Even the depth perception mechanism operating in such a situation is ill understood and cannot be defined in simple functional terms. It seems unlikely that a pilot would choose to land an aircraft while his vision is only temporarily impaired for a relatively short period.

TABLE A-XV

LOSS OF VISUAL RANGE AS A FUNCTION OF ANGLE OF INCLINATION OF WINDSHIELD

Angle of Inclination From Sightline	Loss of Visual Range in Percent		
	Plate Glass	Plastic	
		Clean	Dirty
0°	2.4	2.8	7.3
45°	6.7	9.3	16.8
70°	11.0	24.1	39.3
80°	15.6	37.8	48.2

TABLE A-XVI

LIGHT TRANSMISSION AND REFLECTED LIGHT FACTOR AS A FUNCTION OF ANGLE OF INCIDENCE

Angle of Incidence (Degrees)	Light Transmission Factor	Reflected Light Factor
0	1.000	1.00
10	.999	1.00
20	.997	1.00
30	.990	1.01
40	.980	1.07
50	.954	1.33
60	.890	2.00
70	.700	3.53
80	.450	7.10

(Figures based on two pieces of .125" glass laminated with .08" vinyl plastic)

TABLE A-XVII

STANDARDS FOR LIGHT TRANSMISSION AND HAZE IN PERCENT

	Windshield (Angle of Incidence)				Canopies	Visors
	50°	60°	65°	70°		
Highly Desirable						
Transmission	71	74	83	99	89	90
Haze	.5	.5	.5	.5	.5	.5
Acceptable						
Transmission	66	69	78	93	83	86
Haze	1.0	1.0	1.0	1.0	1.0	1.0
Minimum Transmission	64	67	75	89	77	79
Maximum Haze	2	2	2	2	2	2

Note: Haze is defined as light scattering within the transmitting media.

Conclusion

In describing the visual environment of the members of the aircrew, attention has been restricted to that immediately identifiable information that would serve primarily to assure their immediate survival should their vision be temporarily impaired by a brief high intensity flash of light. This orientation has focused on collision avoidance, formation flying, and the maintenance of a relatively stable flight pattern. No specific attention has been given to the visual demands that might be made upon the aircrew in the performance of specific tactical or other operational activities that might be required or desirable to fulfill a particular mission segment due to the lack of specific quantifiable information that is broadly applicable to all possible situations.

Appendix B - Brown (7)

Brown's Table 2 was transformed into the following table (Table B.1) from which Figure 10 was plotted.

Table B.1

Median Perception Times (log seconds) for Six Display Luminances and Six Adapting Luminances, Display Visual Acuity Requirements: 0.26 and 0.08. Observers JB, FS, and FN.

Subject	Display Luminance (log mL)	Adapting Flash Energy (Lambert.Sec)											
		102.3		32.3		10.23		3.23		1.023		0.323	
		Visual Acuity											
		0.08	0.26	0.08	0.26	0.08	0.26	0.08	0.26	0.08	0.26	0.08	0.26
JB	-1.218	1.773	-	1.360	1.846	1.285	-	0.854	1.649	0.688	1.534	0.595	0.712
	-0.968	1.875	-	1.142	1.767	1.039	1.304	0.747	1.041	0.486	0.856	0.364	0.717
	-0.468	1.583	1.722	1.120	1.462	0.848	1.020	0.389	0.456	0.264	0.290	-0.046	0.196
	0.532	1.198	1.222	0.900	0.954	0.453	0.696	0.130	0.097	-0.149	-0.086	-0.260	-0.252
	1.532	0.640	0.800	0.446	0.498	0.117	0.223	-0.180	-0.113	-0.356	-0.482	-0.367	-0.215
	2.532	0.350	0.354	0.173	0.310	0.034	0.042	-0.180	-0.168	-0.194	-0.432	-	-
FS	-1.218	-	-	1.766	-	1.336	1.252	1.256	1.724	0.805	-	0.753	-
	-0.968	-	1.889	1.728	1.940	0.842	1.766	0.772	1.136	0.652	0.827	0.507	0.694
	-0.468	1.654	1.622	1.282	1.476	0.868	0.708	0.332	0.482	0.310	0.545	0.137	0.258
	0.532	0.978	1.188	0.712	0.872	0.487	0.152	0.086	0.130	-0.046	-0.086	-0.174	-0.207
	1.532	0.682	0.672	0.403	0.450	0.243	0.188	-0.180	-0.187	-0.347	-0.260	-0.252	-0.337
	2.532	0.560	0.517	0.276	0.220	0.033	-0.097	-0.180	-0.310	-0.328	-0.398	-0.310	-0.468
FN	-1.218	1.784	-	1.135	1.561	0.951	1.747	0.791	1.088	0.344	0.930	0.346	0.652
	-0.968	1.028	1.428	1.197	1.246	0.634	1.027	0.431	0.760	0.415	0.456	0.204	0.318
	-0.468	1.201	1.269	0.802	0.806	0.540	0.490	0.188	0.338	0.130	0.079	-0.108	-0.143
	0.532	0.886	0.845	0.662	0.687	0.330	0.210	-0.097	-0.092	-0.229	-0.180	-0.236	-0.328
	1.532	0.436	0.591	0.274	0.417	0.086	0.053	-0.377	-0.301	-0.468	-0.347	-	-
	2.532	0.352	0.334	0.158	0.210	-0.046	0.025	-0.347	-0.301	-	-0.538	-	-

Appendix C - Brown (5)

Brown's Table I for subject JB and Table I for AM were transformed into the following table, Table C.1. Figure 8 was plotted from Table C.1.

Table C.1

Mean Perception Times (in log sec) Presented in Table I for Subjects JB and AM, i.e., Perception Times Required for the Identification of Orientation of Parallel Line Test Displays. Data Presented for Each of Three Adapting Flash Luminances, Two Display Visual Acuity Requirements and Five Display Luminances.

Subject	Display Luminance (log mL)	Adapting Flash Energy (L.sec)					
		96.8		48.4		12.1	
		Visual Acuity					
		0.13	0.33	0.13	0.33	0.13	0.33
JB	-0.718	1.429	1.409	1.237	1.222	0.813	0.802
	-0.218	1.200	1.254	1.035	1.027	0.638	0.660
	0.782	1.006	1.039	0.850	0.806	0.480	0.516
	2.282	0.571	0.612	0.470	0.482	0.320	0.402
	4,282	0.412	0.478	0.393	0.398	0.212	0.262
AM	-0.718	1.417	1.522	1.262	1.285	0.775	0.758
	-0.218	1.406	1.219	0.955	1.136	0.536	0.681
	0.782	1.045	1.018	0.716	0.973	0.569	0.586
	2.282	0.730	0.609	0.580	0.552	0.305	0.358
	4.282	0.441	0.474	0.340	0.425	0.322	0.318

Appendix D - Chisum and Hill (11,23)

Chisum and Hill's Figures 4 and 5 were transformed to the following two tables, Table D.1 and D.2. Figures 4 and 5 were plotted from these two tables.

Table D.1

Derived from Figure 4 of Chisum and Hill (11,23). Time Required to Perceive an Acuity Target as a Function of the Total Energy of the Adapting Flash, Log (td.sec). Adapting Flash Luminance, Adapting Flash Duration and Visual Acuity Level were Constant During Each Experimental Session and the Display Luminance was Varied. Each Datum Point is the Median of Five Response Measures. Subject JHH, Display acuity 0.33.

Adapting Flash Duration sec.	Display Luminance mL	Recovery Time sec.	Recovery Time log sec.	log mL-sec	Adapting Flash Luminance mL-sec	Adapting Flash Luminance td.sec	log td.sec
$9.8\text{x}10^{-3}$	1.0	45	1.65	5.1	$1.3\text{x}10^5$	$1.0\text{x}10^7$	7.0
		16	1.20	4.1	$1.3\text{x}10^4$	$1.0\text{x}10^6$	6.0
		7	0.85	3.6	$4.0\text{x}10^3$	$3.2\text{x}10^5$	5.5
		3	0.48	3.1	$1.3\text{x}10^3$	$1.0\text{x}10^5$	5.0
		? 1	0.00	2.2	$1.6\text{x}10^2$	$1.3\text{x}10^4$	4.1
$0.165\text{x}10^{-3}$	1.0	19.5	1.29	4.8	$6.3\text{x}10^4$	$5.0\text{x}10^6$	6.7
		5	0.70	3.8	$6.3\text{x}10^3$	$5.0\text{x}10^5$	5.7
		2	0.30	2.8	$6.3\text{x}10^2$	$5.0\text{x}10^4$	4.7
$9.8\text{x}10^{-3}$	178	7	0.85	5.1	$1.3\text{x}10^5$	$1.0\text{x}10^7$	7.0
		5	0.70	4.1	$1.3\text{x}10^4$	$1.0\text{x}10^6$	6.0
		2	0.30	3.6	$4.0\text{x}10^3$	$3.2\text{x}10^5$	5.5
		2	0.30	3.1	$1.3\text{x}10^3$	$1.0\text{x}10^5$	5.0
		? 1	0.00	2.2	$1.6\text{x}10^2$	$1.3\text{x}10^4$	4.1
$0.165\text{x}10^{-3}$	178	5	0.70	4.8	$6.3\text{x}10^4$	$5.0\text{x}10^6$	6.7
		2	0.30	3.8	$6.3\text{x}10^3$	$5.0\text{x}10^5$	5.7
		1	0.00	2.8	$6.3\text{x}10^2$	$5.0\text{x}10^4$	4.7
$9.8\text{x}10^{-3}$	0.178	132	2.12	5.1	$1.3\text{x}10^5$	$1.0\text{x}10^7$	7.0
		63	1.80	4.1	$1.3\text{x}10^4$	$1.0\text{x}10^6$	6.0
		11	1.04	3.6	$4.0\text{x}10^3$	$3.2\text{x}10^5$	5.5
		4	0.60	3.1	$1.3\text{x}10^3$	$1.0\text{x}10^5$	5.0
		2	0.30	2.1	$1.3\text{x}10^2$	$1.0\text{x}10^4$	4.0
$0.165\text{x}10^{-3}$	0.178	65	1.81	4.8	$6.3\text{x}10^4$	$5.0\text{x}10^6$	6.7
		10	1.00	3.8	$6.3\text{x}10^3$	$5.0\text{x}10^5$	5.7
		5	0.70	2.8	$6.3\text{x}10^2$	$5.0\text{x}10^4$	4.7

Table D.2

Derived from Figure 5 of Chisum and Hill (11,23). Time Required to Perceive an Acuity Targe as a Function of the Total Energy of the Adapting Flash, log (td.sec). Display Luminance, Adapting Flash Duration and Visual Acuity Level were Constant During Each Experimental Session, and the Adapting Flash Luminance was Varied. Each Datum Point is the Median of Three Response Measures. Subject JHH. Display Acuity 0.33.

Adapting Flash Duration sec	Display Luminance mL	Recovery Time		Adapting Flash Luminance			
		sec	log sec	log mL-sec	mL-sec	td.sec	log td.sec
9.8×10^{-3}	0.178	85	1.93	4.6	4.0×10^4	3.2×10^6	6.5
		81	1.91	5.1	1.3×10^5	1.0×10^7	7.0
		34	1.53	4.05	1.1×10^4	8.8×10^5	5.9
		10	1.00	3.5	3.2×10^3	2.5×10^5	5.4
		5	0.70	3.05	1.1×10^3	8.8×10^4	4.9
		4	0.60	2.5	3.2×10^2	2.5×10^4	4.4
		1	0.00	2.05	1.1×10^2	8.8×10^3	3.9
		1	0.00	1.05	1.1×10^1	8.8×10^2	2.9
0.165×10^{-3}	0.178	55	1.74	4.75	5.6×10^4	4.5×10^6	6.6
		21	1.32	4.25	1.8×10^4	1.4×10^6	6.2
		7	0.85	3.75	5.6×10^3	4.5×10^5	5.6
		5	0.70	3.25	1.8×10^3	1.4×10^5	5.2
		4	0.60	2.75	5.6×10^2	4.5×10^4	4.6
		3	0.48	2.25	1.8×10^2	1.4×10^4	4.2
		2	0.30	1.75	5.6×10^1	4.5×10^3	3.6
9.8×10^{-3}	1.0	28	1.45	5.1	1.3×10^5	1.0×10^7	7.0
		25	1.40	4.5	1.3×10^4	1.0×10^6	6.0
		12	1.08	4.05	1.1×10^4	8.8×10^5	5.9
		5	0.70	3.5	1.3×10^3	1.0×10^5	5.0
		3	0.48	3.05	1.1×10^3	8.8×10^4	4.9
		1.5	0.18	2.5	1.3×10^2	1.0×10^4	4.0
0.165×10^{-3}	1.0	12	1.08	4.75	5.6×10^4	4.5×10^6	6.6
		8	0.90	4.25	1.8×10^4	1.4×10^6	6.2
		4	0.60	3.75	5.6×10^3	4.5×10^5	5.6
		3	0.48	3.25	1.8×10^3	1.4×10^5	5.2
		1	0.00	2.75	5.6×10^2	4.5×10^4	4.6
		1	0.00	2.25	1.8×10^2	1.4×10^4	4.2
9.8×10^{-3}	178	5	0.70	5.1	1.3×10^5	1.0×10^7	7.0
		4.5	0.65	4.5	1.3×10^4	1.0×10^6	6.0
		4	0.60	4.05	1.1×10^4	8.8×10^5	5.9
		2	0.30	3.5	1.3×10^3	1.0×10^5	5.0
		?1	0.00	2.05	1.1×10^2	8.8×10^3	3.9
0.165×10^{-3}	178	3	0.48	4.75	5.6×10^4	4.5×10^6	6.6
		2	0.30	4.25	1.8×10^4	1.4×10^6	6.2
		2	0.30	3.75	5.6×10^3	4.5×10^5	5.6
		1	0.00	3.25	1.8×10^3	1.4×10^5	5.2

Appendix E - Metcalf and Horn (30)

Metcalf and Horn's Figure 6 was converted to Table E.1, replotted in Figures 4 and 5. Metcalf and Horn's Figure 7 was converted to Table E.2 and is part of Figure 1.

Table E.1

Taken from Figure 6 of Metcalf and Horn (30).

Calculated Adapting Flash Luminance		Calculated Adapting Flash Energy (td.sec)	Log Recovery Time (log sec)
ft.L	td.		
7.78×10^{6}	9.60×10^{8}	9.60×10^{7}	2.01
3.89×10^{6}	4.80×10^{8}	4.80×10^{7}	1.93
7.78×10^{5}	9.60×10^{7}	9.60×10^{6}	1.82
3.89×10^{5}	4.80×10^{7}	4.80×10^{6}	1.74
7.78×10^{4}	9.60×10^{6}	9.60×10^{5}	1.08

Table E.2

Taken from Figure 7 of Metcalf and Horn (30).

Target Luminance			Recovery Time	
ft.L	mL	Log mL	sec	log sec
7.0	7.5	0.9	11	1.05
0.45	0.48	-0.32	35	1.55
0.07	0.075	-1.12	93	1.97

Appendix F - Miller (32)

Miller's Figure 1 was replotted and is reproduced here as Figure 1. Some of her other data appear here in Figures 3 and 9.

Appendix G - Miller (unpublished data)

Tables G.1 - G.12 present the results of five experiments recently completed and not yet reported in the literature.

Experiment (1)

A constant flash duration of 5 msec, with the flash luminance reduced by 0.15 Neutral filter steps to a total reduction of 0.9 log units.

Experiment (2)

Constant Intensity x Time of Flash held at 3×10^7 td. sec.
Duration ranging from 0.54 - 5.0 msec.
Each subject ran a complete series on each of two days.

Experiment (3)

Constant flash duration of 1.5 msec.
Flash luminance reduced by 0.15 log unit steps.

Experiment (4)

Constant Intensity x Time Held at 6×10^7 td. sec.
Flash durations varied from 1.10 to 3.4 msec with one flash having an exponential decay of the typical flash lamp form B.

Experiment (5)

Constant Intensity x Time held at 4.5×10^7 td. sec.
Durations from 0.78 to 3.4 msec.

To convert these data to log time of recovery, 2.0 seconds have to be subtracted from each time (or mean time) since the experimental procedure measures the recovery time as the time to two successive correct responses to letters presented at 1 second intervals.

Table G.1

Recovery Times (sec)
for Flash Duration of 5.0 msec, Letter Size 16.2'
(Two seconds subtracted from all times)

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
7.5	RB	7.0	13.5	17.5	27.0	31.0	57.0	78.0	112.0
	JH	8.5	18.0	25.5	49.5	67.5	102.5	145.5	-
	VK	8.0	17.5	26.0	44.5	60.0	69.5	164.5	-
	JN	6.5	15.0	21.5	38.5	59.0	79.0	99.0	150.0
	JS	6.5	12.5	20.5	37.5	41.0	64.0	76.0	108.5
	Avg(sec)	7.3	15.3	22.2	39.4	51.7	74.4	112.6	123.5
	Avg(log sec)	0.724	1.124	1.330	1.573	1.696	1.860	2.044	2.085
7.35	RB	7.5	14.0	18.0	26.0	30.5	45.0	74.0	100.0
	JH	8.0	17.0	25.5	48.0	60.5	72.5	183.0	-
	VK	7.5	16.5	20.5	41.5	52.5	67.5	129.0	148.0
	JN	5.5	9.0	16.0	21.0	29.0	33.0	49.0	153.5
	JS	5.0	17.5	21.0	29.0	40.0	55.0	90.0	101.5
	Avg(sec)	6.7	14.8	20.2	33.1	42.5	54.6	105.0	125.7
	Avg(log sec)	0.672	1.107	1.260	1.493	1.608	1.721	2.013	2.092
7.20	RB	6.5	12.0	15.0	23.0	30.0	44.5	65.0	91.0
	JH	10.0	16.5	21.0	38.0	60.5	96.0	122.0	145.0
	VK	6.5	11.0	18.0	32.5	45.0	59.5	72.0	108.0
	JN	7.0	14.0	19.5	31.5	41.0	48.0	97.0	128.5
	JS	5.5	9.0	12.5	18.0	31.0	37.0	46.5	80.5
	Avg(sec)	7.1	12.5	17.2	28.6	41.5	57.0	80.5	110.6
	Avg(log sec)	0.708	1.021	1.182	1.425	1.596	1.740	1.895	2.036
7.05	RB	6.0	12.0	15.5	24.0	28.5	37.0	49.0	60
	JH	7.0	11.5	15.5	23.5	55.0	60.0	90.0	163.5
	VK	6.5	11.5	17.5	26.0	34.0	60.5	102.5	144.0
	JN	6.0	17.0	20.0	29.5	36.5	42.5	89.0	105.0
	JS	4.0	7.5	11.5	16.0	21.0	23.5	41.0	51.5
	Avg(sec)	5.9	11.9	16.0	23.8	35.0	44.7	74.3	104.8
	Avg(log sec)	0.592	0.996	1.146	1.338	1.518	1.630	1.859	2.012
6.90	RB	-	9.0	13.0	17.0	24.5	30.0	33.5	48.5
	JH	8.0	12.0	16.5	28.5	33.0	56.0	89.0	99.0
	VK	-	9.0	13.5	18.5	32.5	53.5	89.0	139.5
	JN	-	11.5	15.5	24.5	31.5	39.5	75.5	82.5
	JS	-	8.5	12.0	16.5	21.0	28.0	42.5	56.5
	Avg(sec)		10.0	14.1	21.0	28.5	41.6	65.9	85.2
	Avg(log sec)		0.903	1.083	1.279	1.424	1.598	1.806	1.920

{questionable data

Table G.1 (continued)

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
6.75	RB	-	6.0	10.0	14.5	19.0	22.5	33.0	42.0
	JH	6.5	10.0	13.0	19.5	25.5	32.0	61.0	129.0
	VK	-	8.5	12.5	19.0	22.5	26.0	44.5	64.5
	JN	-	9.0	12.5	16.0	22.0	27.0	56.0	66.0
	JS	-	5.5	9.0	12.0	15.0	18.5	22.0	45.0
	Avg(sec)		7.8	11.4	16.2	20.8	25.2	43.3	69.3
	Avg(log sec)		0.764	0.973	1.152	1.274	1.366	1.616	1.828
6.60	RB	-	7.0	9.0	13.0	16.0	19.0	25.0	48.0
	JH	9.5	14.5	18.0	21.5	29.0	37.0	47.0	66.5
	VK	-	7.0	10.5	14.5	19.0	22.5	31.5	51.0
	JN	-	8.5	12.0	16.0	20.0	23.0	36.5	51.0
	JS	-	6.0	-	10.0	13.0	15.5	22.5	29.0
	Avg(sec)		8.6	12.4	15.0	19.4	23.4	32.1	49.1
	Avg(log sec)		0.820	1.017	1.114	1.240	1.330	1.479	1.673

Table G.2

Recovery Times (sec)
for Flash Duration of 5.0 msec, Letter Size 28.4'

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
7.5	RB	7.5	13.5	17.0	28.0	36.0	45.0	55.0	74.5
	JH	8.0	16.0	19.5	30.5	42.5	65.0	85.0	119.0
	VK	7.0	14.0	18.0	30.5	36.5	54.5	72.5	99.0
	JN	6.0	13.0	19.0	28.5	40.0	54.5	91.0	101.0
	JS	5.5	11.5	16.0	24.0	33.0	48.0	62.0	70.0
	Avg(sec)	6.8	13.6	17.9	28.3	37.6	53.4	73.1	92.7
	Avg-2 sec	4.8	11.6	15.9	26.3	35.6	51.4	71.1	90.7
	Avg(log sec)	0.681	1.064	1.201	1.420	1.551	1.711	1.852	1.958
7.35	RB	7.0	10.0	14.0	21.0	27.0	32.0	48.0	80.5
	JH	7.0	13.5	21.5	33.0	38.5	58.0	88.0	101.5
	VK	7.0	14.0	18.0	25.0	34.0	56.5	77.5	92.5
	JN	5.0	12.5	18.5	26.5	37.0	52.5	83.0	111.5
	JS	4.0	9.0	13.5	17.5	32.0	35.0	58.5	82.5
	Avg(sec)	6.0	11.8	17.1	24.6	33.7	46.8	71.0	93.7
	Avg-2sec)	4.0	9.8	15.1	22.6	31.7	44.8	69.0	91.7
	Avg(log sec)	0.602	0.991	1.179	1.354	1.501	1.651	1.839	1.962
7.20	RB	6.0	10.0	14.0	18.5	23.5	32.0	53.0	58.0
	JH	7.0	13.5	17.0	28.0	40.0	60.0	74.5	125.0
	VK	7.0	13.0	16.5	26.5	39.0	61.0	75.5	87.5
	JN	4.5	13.0	17.5	22.5	31.5	36.0	67.0	76.0
	JS	4.5	15.0	19.0	22.5	26.0	39.0	46.0	51.5
	Avg(sec)	5.8	12.9	16.8	23.6	32.0	45.6	63.2	79.6
	Avg-2 sec	3.8	10.9	14.8	21.6	30.0	43.6	61.2	77.6
	Avg(log sec)	0.580	1.037	1.170	1.334	1.477	1.639	1.787	1.890
7.05	RB	6.0	10.0	13.0	16.5	20.0	24.0	35.5	51.0
	JH	6.0	11.0	14.5	21.5	28.5	40.0	79.0	101.0
	VK	5.5	10.0	13.5	17.5	23.0	35.5	77.0	88.0
	JN	5.5	10.5	14.0	20.5	24.5	34.0	57.5	64.0
	JS	4.0	8.0	11.5	17.0	20.5	25.0	34.0	44.5
	Avg(sec)	5.4	9.9	13.3	18.6	23.3	31.7	56.6	69.7
	Avg-2 sec	3.4	7.9	11.3	16.6	21.3	29.7	54.6	67.7
	Avg(log sec)	0.531	0.898	1.053	1.220	1.328	1.473	1.737	1.831

Table G.2 (continued)

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
6.90	RB	-	7.0	12.0	15.0	21.0	27.0	38.0	45.0
	JH	-	9.5	14.0	17.5	21.0	28.0	54.5	70.5
	VK	-	9.0	13.0	17.0	21.0	25.0	44.0	55.5
	JN	-	9.0	13.0	19.5	23.5	32.5	56.5	61.5
	JS	-	6.5	10.5	14.0	18.0	22.0	25.5	31.5
	Avg(sec)		8.2	12.50	16.6	20.9	26.9	43.7	52.8
	Avg-2 sec		6.2	10.5	14.6	18.9	24.9	41.7	50.8
	Avg(log sec)		0.792	1.021	1.164	1.276	1.396	1.620	1.706
6.75	RB	-	7.0	12.0	18.0	22.5	27.0	31.0	35.0
	JH	-	8.5	11.5	15.5	22.0	25.5	39.5	68.0
	VK	-	8.0	14.0	17.5	20.5	24.5	40.0	43.5
	JN	-	7.5	11.0	14.5	18.0	29.0	53.5	64.0
	JS	-	5.0	-	10.5	15.0	19.0	24.0	29.5
	Avg(sec)		7.2	9.7	15.2	19.6	25.0	37.6	48.0
	Avg-2 sec		5.2	7.7	13.2	17.6	23.0	35.6	46.0
	Avg(log sec)		0.716	0.886	1.121	1.245	1.362	1.551	1.663
6.60	RB	-	6.5	10.0	14.0	11.5	21.0	27.0	31.0
	JH	-	6.0	10.0	13.5	17.0	21.5	33.0	41.5
	VK	-	6.5	9.5	13.0	16.5	20.0	26.0	30.5
	JN	-	7.5	11.0	14.5	18.0	20.5	23.5	29.5
	JS	-	5.0	-	8.5	12.0	16.0	19.0	22.5
	Avg(sec)		6.3	8.1	12.7	15.0	19.8	25.7	31.0
	Avg-2 sec		4.3	6.1	10.7	13.0	17.8	23.7	29.0
	Avg(log sec)		0.633	0.785	1.029	1.114	1.250	1.375	1.462

Table G.3

Recovery Times (sec)
for Flash Duration of 1.5 msec, Letter Size 16.2'

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
7.95	RB	7.0	13.0	16.5	25.5	40.0	66.5	105.0	137.0
	JH	9.0	15.0	20.5	64.5	86.5	130.0	183.0	-
	VK	10.0	18.0	24.0	43.0	60.5	78.5	163.5	168.0
	JN	7.0	19.0	23.5	42.0	53.0	83.0	173.0	-
	JS	6.0	14.0	19.0	22.5	37.5	52.5	129.5	142.5
	Avg(sec)	7.8	15.8	20.7	39.5	55.5	82.0	150.8	149.2
	Avg-2 sec	5.8	13.8	18.7	37.5	53.5	80.1	148.8	147.2
	Avg(log sec)	0.764	1.140	1.272	1.574	1.728	1.904	2.173	2.167
7.80	RB	7.0	12.5	19.0	28.0	40.0	60.0	96.0	109.0
	JH	9.0	15.0	20.0	56.0	-	131.0	212.5	-
	VK	8.5	17.5	24.0	48.0	82.5	103.5	197.0	-
	JN	-	16.5	22.0	38.0	52.0	76.0	134.0	164.0
	JS	5.5	14.0	18.5	28.0	51.0	67.5	82.5	117.5
	Avg(sec)	7.5	15.1	20.7	39.6	56.4	87.6	144.4	130.2
	Avg-2 sec	5.5	13.1	18.7	37.6	54.4	85.6	142.4	128.2
	Avg(log sec)	0.740	1.117	1.272	1.575	1.736	1.933	2.152	2.107
7.65	RB	6.5	13.0	17.5	28.5	46.0	57.5	90.0	106.0
	JH	10.5	16.0	22.5	64.5	85.0	101.0	142.0	-
	VK	8.5	18.0	23.0	43.5	55.0	100.0	178.0	196.0
	JN	7.0	13.0	23.0	42.5	58.0	80.0	139.0	151.0
	JS	5.5	16.0	19.5	39.0	56.0	67.5	108.0	126.0
	Avg(sec)	7.6	15.2	21.1	43.6	60.0	81.2	131.4	144.7
	Avg-2 sec	5.6	13.2	19.1	41.6	58.0	79.2	129.4	142.7
	Avg(log sec)	0.748	1.121	1.290	1.619	1.763	1.899	2.111	2.155
7.50	RB	6.0	12.0	17.0	30.0	39.5	67.0	113.0	122.0
	JH	9.0	16.0	25.5	52.5	83.0	117.5	201.0	226.5
	VK	8.5	19.0	23.0	39.0	75.5	103.5	183.5	202.0
	JN	6.0	15.0	23.0	37.0	49.0	86.0	141.0	198.0
	JS	6.0	12.5	16.0	29.0	51.5	58.5	87.5	105.5
	Avg(sec)	7.1	14.9	20.9	37.5	59.7	86.5	145.2	170.8
	Avg-2sec	5.1	12.9	18.9	35.5	57.7	84.5	143.2	168.8
	Avg(log sec)	0.708	1.111	1.277	1.550	1.761	1.927	2.155	2.228

Table G.3 (continued)

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
7.35	RB	-	12.0	16.0	26.5	43.0	58.5	92.0	127.0
	JH	-	28.0	32.5	41.5	69.0	94.5	112.5	173.5
	VK	-	19.0	23.0	36.5	57.0	84.0	97.5	166.5
	JN	-	12.0	21.0	31.0	45.0	66.0	154.0	180.5
	JS	-	12.5	16.5	26.5	34.0	44.5	87.0	138.5
	Avg(sec)	-	16.7	20.8	32.4	49.6	69.5	108.6	157.2
	Avg-2 sec	-	14.7	18.8	30.4	47.6	67.5	106.6	155.2
	Avg(log sec)	-	1.167	1.274	1.483	1.678	1.829	2.029	2.190
7.20	RB	-	10.0	13.5	20.5	35.0	46.0	72.0	81.0
	JH	-	16.0	21.0	46.5	66.0	90.5	138.5	-
	VK	7.5	15.0	19.5	30.5	42.5	62.5	117.5	129.5
	JN	-	15.0	19.0	26.0	43.0	62.0	88.0	123.0
	JS	-	11.5	14.5	19.5	26.5	30.0	57.5	66.5
	Avg(sec)		13.5	17.5	28.6	42.6	58.2	94.7	100.0
	Avg-2 sec		11.5	15.5	26.6	40.6	56.2	92.7	98.0
	Avg(log sec)		1.061	1.190	1.425	1.609	1.750	1.967	1.991
7.05	RB	-	11.0	17.0	22.0	34.0	44.0	62.0	89.0
	JH	-	13.0	19.5	32.0	59.5	72.0	102.0	136.5
	VK	-	12.5	16.0	25.0	46.0	56.5	80.5	102.5
	JN	-	11.0	15.0	29.0	40.0	48.0	70.0	105.5
	JS	-	8.5	12.0	15.5	24.0	33.5	64.5	76.5
	Avg(sec)	-	11.2	15.9	24.7	40.7	50.8	75.8	102.0
	Avg-2 sec	-	9.2	13.9	22.7	38.7	48.8	73.8	100.0
	Avg(log sec)	-	0.964	1.143	1.356	1.588	1.688	1.868	2.000

Table G.4

Recovery Times (sec)
for Flash Duration of 1.5 msec, Letter Size 28.4'

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
7.95	RB	6.0	11.0	15.5	23.0	28.5	36.5	64.5	71.0
	JH	8.0	13.5	17.5	43.0	58.5	76.5	109.5	135
	VK	9.5	16.0	22.0	36.0	40.5	76.5	109.5	201.5
	JN	8.0	15.0	20.0	32.5	43.0	63.0	96.5	110.5
	JS	5.0	11.0	16.0	25.0	35.5	44.0	78.0	82.5
	Avg(sec)	7.3	13.3	18.2	31.9	41.2	59.3	91.6	120.1
	Avg-2 sec	5.3	11.3	16.2	29.9	39.2	57.3	89.6	118.1
	Avg(log sec)	0.724	1.053	1.209	1.476	1.593	1.758	1.952	2.072
7.8	R3	7.0	12.0	15.0	19.0	33.0	41.5	78.5	85.0
	JH	8.5	16.0	21.0	37.5	53.0	83.0	102.5	111.5
	VK	7.5	14.0	17.5	28.5	44.5	74.0	80.0	98.0
	JN	6.5	13.5	20.0	32.0	37.0	66.0	85.0	105
	JS	5.0	13.5	18.5	25.0	31.0	41.0	99.0	107.5
	Avg(sec)	6.9	13.8	18.4	28.4	39.7	61.1	89.0	101.4
	Avg-2 sec	4.9	11.8	16.4	26.4	37.7	59.1	87.0	99.4
	Avg(log sec)	0.690	1.072	1.215	1.422	1.576	1.772	1.939	1.997
7.65	RB	6.0	11.0	15.0	18.5	27.0	35.0	54.0	75.5
	JH	7.5	14.0	18.5	36.5	42.0	79.0	103	116.5
	VK	8.0	14.5	19.5	31.0	43.5	72.0	91.5	132
	JN	6.0	13.0	17.0	27.0	38.0	51.0	80.0	122
	JS	4.5	10.5	14.5	25.5	31.0	53.0	75.0	87.5
	Avg(sec)	6.4	12.6	16.9	27.7	36.3	58.0	80.7	106.7
	Avg-2 sec	4.4	10.6	14.9	25.7	34.3	56.0	78.7	104.7
	Avg(log sec)	0.643	1.025	1.173	1.410	1.535	1.748	1.896	2.021
7.5	RB	6.5	11.0	14.0	23.5	27.5	38.0	59.5	78.0
	JH	6.5	13.0	18.0	31.0	44.0	70.0	101.5	119.5
	VK	8.0	15.5	22.0	35.0	56.4	76.5	109.5	122.5
	JN	6.0	12.0	16.5	24.0	32.0	45.0	72.0	104
	JS	5.5	10.0	14.0	23.0	30.0	34.0	67.5	88.5
	Avg(sec)	6.5	12.3	16.9	27.3	36.0	52.7	82.0	102.5
	Avg-2 sec	4.5	10.3	14.9	25.3	34.0	50.7	80.0	100.5
	Avg(log sec)	0.653	1.013	1.173	1.403	1.531	1.705	1.903	2.000

Table G.4 (continued)

Log Flash Energy td.sec	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
7.35	RB	-	12.0	15.0	19.0	22.5	33.0	50.5	60.0
	JH	-	15.0	19.0	28.5	50.5	75.0	134	159.5
	VK	-	14.0	20.0	28.0	44.0	57.5	98.5	139.5
	JN	-	13.0	17.0	23.0	33.0	46.0	66.0	104
	JS	-	9.5	14.0	23.5	27.5	41.5	46.5	80.0
	Avg(sec)		12.7	17.0	24.4	35.5	50.6	79.1	108.6
	Avg-2 sec		10.7	15.0	22.4	33.5	48.6	77.1	106.6
	Avg(log sec)		1.029	1.176	1.350	1.525	1.687	1.887	2.029
7.2	RB	-	10.0	15.0	20.0	27.5	35.0	51.0	88.0
	JH	-	15.0	19.0	30.5	43.5	61.0	109	131
	VK	-	11.5	15.0	21.0	34.0	47.0	82.0	99.0
	JN	-	12.0	15.5	19.0	29.0	42.0	57.0	92.0
	JS	-	7.5	11.0	16.0	21.0	26.0	30.0	62.5
	Avg(sec)		11.2	15.1	21.3	31.0	42.2	65.8	94.5
	Avg-2 sec		9.2	13.1	19.3	29.0	40.2	63.8	92.5
	Avg(log sec)		0.964	1.117	1.286	1.462	1.604	1.805	1.966
7.05	RB	-	9.0	13.0	17.5	21.0	34.0	49.5	61.5
	JH	-	13.0	19.5	32.0	59.5	72.0	102	136.5
	VK	-	10.0	15.0	19.5	24.5	34.5	61.8	83.0
	JN	-	13.0	17.0	25.0	29.5	45.0	65.0	98.5
	JS	-	7.0	10.0	14.5	18.0	25.0	46.0	51.5
	Avg(sec)		10.4	14.9	21.7	30.5	42.1	64.9	86.2
	Avg-2 sec		8.4	12.9	19.7	28.5	40.1	62.9	84.2
	Avg(log sec)		0.924	1.111	1.294	1.455	1.603	1.799	1.925

Table G.5

Recovery Times (sec)
for Log Flash Energy of 7.5 td.sec, Letter Size 16.2'

Flash Duration (sec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
0.54	RB	5.0	11.0	16.0	24.0	32.5	49.0	99.0	121.5
	JH	8.0	13.5	23.5	36.5	64.0	94.0	-	-
	VK	10.0	14.0	18.5	65.5	77.0	130.0	217.0	-
	JN	6.5	15.0	21.0	28.0	51.5	69.5	132.0	169.5
	JS	5.0	12.0	19.0	32.0	37.0	45.0	69.0	147.0
	Avg(sec)	6.9	13.1	19.6	37.2	52.4	77.5	129.2	146.0
	Avg-2 sec	4.9	11.1	17.6	35.2	50.4	75.5	127.2	144.0
	Avg(log sec)	0.690	1.041	1.230	1.544	1.699	1.875	2.103	2.158
0.78	RB	8.5	14.0	18.0	39.0	45.5	57.0	93.0	132.5
	JH	9.5	15.5	27.0	56.5	108.0	136.0	191.0	-
	VK	8.0	15.0	20.0	52.5	64.0	139.5	230.5	-
	JN	7.0	13.5	19.5	37.0	51.0	70.0	119.5	195.0
	JS	4.0	11.5	16.0	27.0	36.0	46.0	91.5	110.0
	Avg(sec)	7.4	13.9	20.1	42.4	60.9	89.7	145.1	145.8
	Avg-2 sec	5.4	11.9	18.1	40.4	58.9	87.7	143.1	143.8
	Avg(log sec)	0.723	1.041	1.255	1.602	1.763	1.939	2.155	2.158
1.10	RB	6.5	13.5	18.0	39.0	46.0	63.0	105.0	152.0
	JH	8.5	17.0	23.0	53.5	67.0	123.0	268.0	-
	VK	7.0	15.0	19.0	48.0	56.0	89.0	130.0	194.0
	JN	7.0	16.0	23.0	36.0	67.5	87.5	132.5	144.0
	JS	5.0	9.0	14.5	23.5	30.0	48.0	79.0	120.0
	Avg(sec)	6.8	14.1	19.5	40.0	53.3	82.1	142.9	152.5
	Avg-2 sec	4.8	12.1	17.5	38.0	51.3	80.1	140.9	150.5
	Avg(log sec)	0.681	1.079	1.230	1.579	1.707	1.903	2.146	2.176
1.54	RB	7.0	14.0	16.5	26.5	34.0	53.0	90.0	148.0
	JH	8.0	16.5	31.5	69.0	93.0	113.5	158.0	-
	VK	8.0	16.0	22.0	47.5	91.0	146.5	174.0	238.5
	JN	6.5	18.0	21.5	40.0	49.0	70.0	110.0	156.0
	JS	5.5	12.5	17.0	25.0	33.0	52.5	95.0	127.0
	Avg(sec)	7.0	15.4	21.7	41.6	60.0	87.1	125.4	167.3
	Avg-2 sec	5.0	13.5	19.7	39.6	58.0	85.1	123.4	165.3
	Avg(log sec)	0.699	1.113	1.278	1.591	1.763	1.929	2.089	2.217

Table G.5 (continued)

Flash Duration (sec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
2.4	RB	8.0	13.0	16.5	25.0	45.0	61.0	93.0	119.0
	JH	9.5	20.0	29.0	61.0	75.0	118.0	134.5	-
	VK	8.5	14.5	23.0	61.0	82.0	117.5	146.5	173.5
	JN	6.5	15.5	22.0	40.5	55.5	74.5	108.0	136.5
	JS	5.5	11.5	15.0	25.0	42.5	67.0	76.0	120.5
	Avg(sec)	7.6	14.9	21.1	42.5	60.0	87.6	111.6	137.4
	Avg-2 sec	5.6	12.9	19.1	40.5	58.0	85.6	109.6	135.4
	Avg(log sec)	0.748	1.113	1.278	1.602	1.763	1.929	2.037	2.130
3.4	RB	8.0	13.0	18.0	31.0	37.0	72.0	93.5	145.0
	JH	12.5	19.0	28.0	53.0	75.0	112.0	203.5	-
	VK	8.0	16.5	23.0	55.5	66.0	99.0	166.5	200.0
	JN	7.5	17.5	34.0	40.0	65.0	80.5	118.0	140.5
	JS	5.0	14.5	18.0	27.5	52.0	58.0	130.5	168.5
	Avg(sec)	8.2	16.1	24.2	41.4	59.0	84.3	142.4	163.5
	Avg-2 sec	6.2	14.1	22.2	39.4	57.0	82.3	140.4	161.5
	Avg(log sec)	0.792	1.146	1.342	1.591	1.755	1.913	2.146	2.206
5.0	RB	6.5	13.0	18.0	26.0	44.0	63.5	85.0	99.0
	JH	10.0	19.5	28.5	54.0	89.0	108.0	178.0	-
	VK	9.5	18.5	41.0	56.0	110.0	115.0	136.5	221.5
	JN	10.0	17.0	23.5	37.5	49.5	62.0	95.0	107.5
	JS	5.0	12.0	20.0	29.0	36.0	57.0	66.5	98.5
	Avg(sec)	8.2	16.0	26.2	40.5	65.7	82.1	112.2	131.3
	Avg-2 sec	6.2	14.0	24.2	38.5	63.7	80.1	110.2	129.3
	Avg(log sec)	0.792	1.146	1.380	1.579	1.799	1.903	2.041	2.110

Table G.6

Recovery Times (sec)
for Log Flash Energy of 7.5 td.sec, Letter Size 16.2'

Flash Duration td.sec	Subject	Log Target Luminance (mL) 2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
0.54	RB	7.0	11.0	15.0	23.0	37.0	54.0	68.0	101.0
	JH	9.0	20.0	30.0	69.5	91.5	272.0	-	-
	VK	8.5	15.5	20.0	41.0	51.0	81.0	141.0	164.5
	JN	8.0	14.0	20.0	43.5	69.0	90.0	136.0	196.5
	JS	4.0	8.5	12.5	16.0	24.0	32.0	63.0	81.0
	Avg(sec)	7.3	17.5	19.5	38.6	54.5	105.8	102.0	135.8
	Avg-2 sec	5.3	15.5	17.5	36.6	52.5	103.8	100.0	133.8
	Avg(log sec)	0.724	1.190	1.243	1.564	1.720	2.017	2.00	2.127
0.78	RB	7.0	11.5	16.0	27.0	37.5	65.5	103.0	112.0
	JH	14.5	21.0	32.5	75.5	114.0	185.5	257.5	-
	VK	9.0	14.0	20.0	44.0	59.5	94.5	157.5	228.5
	JN	7.0	14.5	21.5	34.5	57.0	73.5	115.0	158.0
	JS	4.5	9.0	13.0	17.5	25.0	30.0	68.5	82.5
	Avg(sec)	8.4	14.0	20.6	39.7	58.6	89.8	140.3	145.3
	Avg-2 sec	6.4	12.0	18.6	37.7	56.6	87.8	138.3	143.3
	Avg(log sec)	0.806	1.079	1.270	1.576	1.753	1.944	2.140	2.155
1.10	RB	6.0	10.0	14.0	36.5	43.5	61.5	75.0	114.5
	JH	9.5	21.5	33.5	98.0	112.0	142.0	309.0	-
	VK	9.5	15.5	24.0	46.5	52.0	94.0	137.0	225.5
	JN	7.5	16.0	23.0	50.5	75.5	88.0	131.5	186.5
	JS	3.5	8.5	12.0	16.5	22.5	36.5	75.0	82.5
	Avg(sec)	7.2	14.3	21.3	49.6	61.1	84.4	145.5	152.3
	Avg-2 sec	5.2	12.3	19.3	47.6	59.1	82.4	143.5	150.3
	Avg(log sec)	0.716	1.090	1.286	1.678	1.777	1.925	2.155	2.176
1.54	RB	7.0	11.5	19.0	36.5	44.0	55.0	86.5	109.0
	JH	12.0	18.0	39.5	57.5	97.0	183.0	271.0	-
	VK	9.0	18.0	26.0	53.0	77.5	105.0	140.0	166.5
	JN	7.5	17.0	21.5	39.0	68.0	79.0	133.5	214.5
	JS	4.5	8.5	14.0	18.0	25.0	28.5	58.0	69.5
	Avg(sec)	8.0	14.6	24.0	40.8	62.3	90.1	137.8	139.9
	Avg-2 sec	6.0	12.6	22.0	38.8	60.3	88.1	135.8	137.9
	Avg(log sec)	0.778	1.100	1.346	1.589	1.780	1.945	2.133	2.140

Table G.6 (continued)

Flash Duration td.sec	Subject	Log Target Luminance (mL) 2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
2.4	RB	7.5	12.5	17.0	30.0	37.5	67.5	95.5	130.0
	JH	12.0	22.5	34.5	62.0	100.5	163.0	196.0	-
	VK	7.0	14.5	22.5	38.5	57.5	83.5	125.5	198.5
	JN	6.5	17.5	25.5	50.0	65.5	81.0	100.5	139.0
	JS	5.0	11.5	16.5	28.0	37.5	52.5	96.0	105.5
	Avg(sec)	7.6	15.7	23.2	41.7	59.7	89.5	122.7	114.6
	Avg-2 sec	5.6	13.7	21.2	39.7	57.7	87.5	120.7	112.6
	Avg(log sec)	0.748	1.137	1.326	1.599	1.754	1.942	2.828	2.053
3.4	RB	7.5	13.5	18.0	26.0	38.0	60.0	105.0	135.0
	JH	9.0	16.5	28.0	78.5	89.0	136.5	174.5	-
	VK	9.5	20.0	25.0	41.0	82.5	102.0	128.5	172.0
	JN	7.0	18.0	24.0	31.5	53.0	98.5	129.0	148.0
	JS	4.0	10.0	13.5	19.5	24.0	36.0	65.0	84.5
	Avg(sec)	7.4	15.6	21.7	39.3	57.3	86.6	120.4	134.9
	Avg-2 sec	5.4	13.6	19.7	37.3	55.3	84.6	118.4	132.9
	Avg(log sec)	0.732	1.134	1.295	1.572	1.743	1.927	2.072	2.124
5.0	RB	7.0	13.0	17.5	29.5	47.0	64.5	83.0	106.0
	JH	16.5	20.0	33.0	47.0	72.0	167.0	311.5	-
	VK	9.0	16.0	25.0	51.0	63.0	87.5	128.5	191.0
	JN	7.5	20.5	27.5	47.5	67.5	89.5	121.0	197.0
	JS	7.0	13.0	16.5	22.5	41.0	50.0	100.0	114.5
	Avg(sec)	9.4	16.5	23.9	39.5	58.1	91.7	168.8	152.1
	Avg-2 sec	7.4	14.5	21.9	37.5	56.1	89.7	166.8	150.1
	Avg(log sec)	0.869	1.161	1.340	1.574	1.749	1.953	2.223	2.176

Table G.7

Recovery Times (sec)
for Log Flash Energy of 7.5 td.sec, Letter Size 28.4'

Flash Duration (sec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
0.54	RB	6.0	10.0	14.0	18.5	25.0	33.0	54.0	70.0
	JH	8.5	12.0	17.0	27.0	42.0	58.0	113.5	-
	VK	7.0	12.5	16.0	31.0	43.5	50.5	162.5	170.5
	JN	6.0	10.5	14.0	19.0	25.0	45.0	77.0	90.5
	JS	4.5	9.0	12.0	18.0	21.5	34.5	66.0	80.5
	Avg(sec)	6.4	10.8	14.6	22.7	31.4	44.2	94.6	102.8
	Avg-2 sec	4.4	8.8	12.6	20.7	29.4	42.2	92.6	100.8
	Avg(log sec)	0.643	0.944	1.079	1.301	1.462	1.623	1.963	2.004
0.78	RB	6.0	11.0	14.5	20.0	29.0	35.0	56.0	75.0
	JH	8.0	12.5	16.5	28.0	41.5	67.0	114.0	-
	VK	7.5	13.5	17.5	39.0	50.0	62.0	71.0	153.0
	JN	7.0	12.5	16.0	25.0	36.5	62.0	95.0	109.0
	JS	5.5	9.0	13.0	18.5	25.5	32.0	54.0	71.5
	Avg(sec)	6.8	11.7	15.5	26.1	36.4	51.6	78.0	102.1
	Avg-2 sec	4.8	9.7	13.5	24.1	34.4	49.6	76.0	100.1
	Avg(log sec)	0.681	0.986	1.113	1.380	1.531	1.690	1.880	2.000
1.10	RB	6.0	11.0	16.0	24.0	31.0	37.0	70.0	85.0
	JH	8.5	15.0	20.5	36.0	56.0	97.0	133.0	-
	VK	7.0	12.5	18.0	31.0	52.0	74.0	125.5	137.0
	JN	7.0	14.5	21.5	34.5	42.5	61.5	89.0	101.5
	JS	5.0	11.5	16.0	26.0	39.0	50.5	88.0	118.5
	Avg(sec)	6.7	12.9	18.4	30.3	44.3	64.0	101.1	110.5
	Avg-2 sec	4.7	10.9	16.4	28.3	42.3	62.0	99.1	108.5
	Avg(log sec)	0.672	1.041	1.204	1.447	1.623	1.792	1.995	2.033
1.54	RB	6.5	11.5	16.5	20.5	27.0	38.0	53.5	74.5
	JH	8.5	14.0	19.5	32.0	52.0	68.0	122.0	-
	VK	8.5	13.0	18.0	50.0	57.0	94.0	126.0	137.0
	JN	7.5	14.5	19.5	29.0	45.0	57.0	92.0	116.5
	JS	5.0	10.5	14.5	23.5	28.5	48.5	64.0	68.5
	Avg(sec)	7.2	12.7	17.6	31.0	41.9	61.1	91.5	99.1
	Avg-2 sec	5.2	10.7	15.6	29.0	39.9	59.1	89.5	97.1
	Avg(log sec)	0.716	1.029	1.176	1.462	1.602	1.770	1.949	1.986

Table G.7 (continued)

Flash Duration (sec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
2.4	RB	6.0	11.0	14.0	22.5	30.0	40.0	81.0	85.5
	JH	8.0	15.0	21.0	33.0	57.0	78.0	118.5	-
	VK	8.0	14.0	18.5	29.0	47.0	64.5	-	-
	JN	7.5	15.0	20.5	30.5	39.0	69.5	86.0	108.5
	JS	6.0	13.0	17.0	25.0	29.0	48.5	94.0	113.0
	Avg(sec)	7.1	13.6	18.2	28.0	40.4	60.1	94.8	103.3
	Avg-2 sec	5.1	11.6	16.2	26.0	38.4	58.1	92.8	101.3
	Avg(log sec)	0.707	1.041	1.204	1.415	1.579	1.763	1.968	2.004
3.4	RB	7.5	12.5	16.0	24.0	29.0	43.0	62.5	86.0
	JH	8.5	17.0	22.0	31.0	48.5	83.0	119.5	-
	VK	8.0	15.0	19.0	33.5	46.0	74.0	98.0	140.0
	JN	7.5	13.0	17.5	35.0	39.5	50.5	95.0	102.5
	JS	5.0	12.5	16.0	21.0	26.0	48.0	80.0	84.5
	Avg(sec)	7.3	14.0	18.1	28.9	37.8	59.7	91.0	103.2
	Avg-2 sec	5.3	12.0	16.1	26.9	35.8	57.7	89.0	101.2
	Avg(log sec)	0.724	1.079	1.204	1.431	1.544	1.755	1.949	2.004
5.0	RB	6.0	12.5	17.0	21.5	28.0	39.5	72.0	91.5
	JH	9.5	15.5	21.0	40.0	65.0	87.0	127.0	-
	VK	9.0	17.0	24.0	44.0	55.0	97.0	150.0	192.0
	JN	9.0	16.0	23.0	32.0	45.5	58.5	76.5	99.5
	JS	6.0	12.5	16.0	20.0	35.0	46.0	88.5	98.5
	Avg(sec)	7.9	14.7	20.2	31.5	45.7	65.6	102.8	120.3
	Avg-2 sec	5.9	12.7	18.2	29.5	43.7	63.6	100.8	118.3
	Avg(log sec)	0.770	1.079	1.255	1.462	1.633	1.799	2.004	2.071

Table G.8

Recovery Times (sec)
for Log Flash Energy of 7.5 td.sec, Letter Size 28.4'

Flash Duration (sec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
0.54	RB	6.5	10.5	14.0	17.5	26.0	34.0	60.5	85.0
	JH	9.0	14.5	19.5	40.0	52.5	84.0	148.5	-
	VK	7.0	12.0	16.5	25.0	34.0	42.0	74.0	113.5
	JN	6.0	12.0	17.5	24.0	35.0	44.0	81.0	111.5
	JS	3.0	7.0	10.0	15.0	18.0	22.0	35.0	40.5
	Avg(sec)	6.3	11.2	15.5	24.3	33.1	45.2	79.8	87.6
	Avg-2 sec	4.3	9.2	13.5	22.3	31.1	43.2	77.8	85.6
	Avg(log sec)	0.633	0.963	1.113	1.342	1.491	1.633	1.886	1.929
0.78	RB	6.5	11.0	14.5	22.5	29.0	36.5	70.0	106.5
	JH	9.5	14.0	21.0	43.0	68.5	91.5	155.0	-
	VK	7.5	12.0	16.5	21.5	30.0	49.5	72.0	107.5
	JN	5.0	14.0	20.0	31.5	41.0	60.0	103.0	127.0
	JS	4.0	11.0	15.5	22.5	39.0	56.5	72.0	89.5
	Avg(sec)	6.5	12.4	17.5	28.2	41.5	58.8	94.4	107.6
	Avg-2 sec	4.5	10.4	15.5	26.2	39.5	56.8	92.4	105.6
	Avg(log sec)	0.653	1.000	1.176	1.415	1.591	1.748	1.963	2.021
1.10	RB	6.0	11.5	15.0	20.0	30.0	43.0	68.5	95.5
	JH	9.5	17.5	22.0	36.0	54.0	67.0	129.0	-
	VK	6.5	13.0	16.5	24.5	44.0	68.0	131.5	140.5
	JN	7.0	13.0	18.0	27.5	39.0	54.0	67.0	94.0
	JS	9.0	14.0	18.0	25.5	31.5	41.0	63.0	76.0
	Avg(sec)	7.6	13.8	17.9	26.7	39.7	54.6	91.8	101.5
	Avg-2 sec	5.6	11.8	15.9	24.7	37.7	52.6	89.8	99.5
	Avg(log sec)	0.748	1.041	1.176	1.380	1.568	1.716	1.949	1.995
1.54	RB	6.5	11.5	16.0	21.5	30.0	38.5	72.0	86.5
	JH	9.5	17.0	21.5	34.5	67.5	88.5	134.5	-
	VK	7.5	15.0	19.0	31.0	59.0	71.0	92.0	109.5
	JN	8.5	14.0	20.0	27.5	48.0	63.0	87.5	117.5
	JS	6.5	11.0	15.0	20.0	32.0	39.0	60.0	69.5
	Avg(sec)	7.7	13.7	18.3	26.9	47.3	60.0	89.2	95.8
	Avg-2 sec	5.7	11.7	16.3	24.9	45.3	58.0	87.2	93.8
	Avg(log sec)	0.755	1.041	1.204	1.380	1.653	1.763	1.939	1.968

Table G.8 (continued)

Flash Duration (sec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
2.4	RB	6.5	11.5	16.0	21.0	30.0	38.0	66.0	91.5
	JH	11.0	17.5	26.5	38.5	81.5	159.0	220.5	-
	VK	8.5	15.0	20.0	33.0	47.0	89.5	95.0	138.5
	JN	7.0	14.0	21.0	41.0	51.5	57.0	106.0	116.5
	JS	5.5	12.5	17.0	28.0	37.0	56.0	81.0	94.5
	Avg(sec)	7.7	14.1	20.1	32.3	49.4	79.9	113.7	110.3
	Avg-2 sec	5.7	12.1	18.1	30.3	47.4	77.9	111.7	108.3
	Avg(log sec)	0.755	1.079	1.255	1.477	1.672	1.886	2.082	2.033
3.4	RB	6.0	11.0	14.5	19.0	29.5	37.5	70.0	93.0
	JH	9.0	19.0	25.0	60.5	73.5	102.5	154.5	-
	VK	10.0	16.0	23.0	38.5	50.5	77.0	123.0	160.0
	JN	8.5	15.0	20.0	38.0	45.0	68.5	83.5	105.5
	JS	4.0	10.5	15.0	18.5	23.0	27.5	52.0	61.0
	Avg(sec)	7.5	14.3	19.5	34.9	44.3	62.6	96.6	104.9
	Avg-2 sec	5.5	12.3	17.5	32.9	42.3	60.6	94.6	102.9
	Avg(log sec)	0.740	1.079	1.230	1.505	1.623	1.778	1.973	2.008
5.0	RB	6.5	11.5	16.0	22.0	26.0	36.5	65.0	86.5
	JH	10.0	19.0	24.0	53.0	65.0	75.0	119.0	-
	VK	7.5	15.0	21.0	30.5	39.5	58.0	113.5	124.5
	JN	8.0	16.5	21.0	34.0	47.0	61.0	79.5	101.0
	JS	4.5	9.5	12.5	16.0	20.5	24.5	44.0	51.5
	Avg(sec)	7.3	14.3	18.9	31.1	39.6	51.0	84.2	90.9
	Avg-2 sec	5.3	12.3	16.9	29.1	37.6	49.0	82.2	88.9
	Avg(log sec)	0.724	1.079	1.204	1.462	1.568	1.690	1.913	1.944

Table G.9

Recovery Times (sec)
for Log Flash Energy of 7.65 td.sec, Letter Size 16.2'

Flash Duration (msec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
0.78	RB	7.0	11.0	14.5	25.0	33.0	38.0	112.5	143.5
	JH	9.0	19.5	37.0	67.5	115.0	162.0	204.5	-
	VK	9.0	15.0	25.0	51.5	69.0	88.5	105.5	146.0
	JN	6.0	13.0	23.0	36.5	61.0	81.0	112.5	152.0
	JS	6.5	16.5	20.5	44.0	63.0	75.0	119.0	130.0
	Avg(sec)	7.5	15.0	24.0	44.9	68.2	88.9	130.8	142.9
	Avg-2 sec	5.5	13.0	22.0	42.9	66.2	86.9	128.8	140.9
	Avg(log sec)	0.740	1.113	1.322	1.623	1.819	1.934	2.107	2.146
1.10	RB	7.0	12.0	17.0	33.0	39.0	57.0	97.5	155.0
	JH	9.0	18.0	29.5	68.0	144.0	213.5	-	-
	VK	9.0	16.0	20.0	40.0	63.0	96.0	117.0	128.0
	JN	8.0	15.0	21.0	45.0	54.0	90.0	127.0	147.0
	JS	6.5	12.5	20.5	35.0	56.0	87.5	127.0	173.5
	Avg(sec)	7.9	14.7	21.6	44.2	71.2	108.8	117.1	150.9
	Avg-2 sec	5.9	12.7	19.6	42.2	69.2	106.8	115.1	148.9
	Avg(log sec)	0.770	1.079	1.278	1.	1.	2.	2.	2.
1.54	RB	7.0	13.0	16.5	30.5	47.5	60.0	94.5	139.0
	JH	9.0	17.5	32.0	69.0	76.0	106.5	183.5	-
	VK	8.0	17.5	27.5	44.5	64.0	115.5	140.0	177.0
	JN	6.5	15.0	20.5	35.5	55.5	62.5	103.5	143.0
	JS	6.0	14.0	19.0	30.0	44.0	83.5	133.0	192.0
	Avg(sec)	7.3	15.4	23.1	41.9	57.4	85.6	130.9	162.8
	Avg-2 sec	5.3	13.4	21.1	39.9	55.4	83.6	128.9	160.8
	Avg(log sec)	0.726	1.113	1.322	1.591	1.740	1.919	2.107	2.204
2.4	RB	7.0	12.0	18.5	33.0	39.5	48.5	88.0	158.5
	JH	11.0	25.0	37.0	83.5	122.5	159.5	236.0	-
	VK	9.5	18.0	24.5	62.0	75.0	82.0	109.5	212.5
	JN	7.0	16.0	21.0	55.0	63.0	83.0	126.5	146.5
	JS	7.5	15.0	20.0	30.5	35.5	74.0	105.0	115.5
	Avg(sec)	8.4	17.2	24.2	52.8	67.1	89.4	133.0	158.3
	Avg-2 sec	6.4	15.2	22.2	50.8	65.1	87.4	131.0	156.3
	Avg(log sec)	0.806	1.176	1.342	1.699	1.812	1.939	2.117	2.193

Table G.9 (continued)

Flash Duration (msec)	Subject	Log Target Luminance (mL) 2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
3.4	RB	7.0	12.0	16.5	32.5	38.0	56.5	93.0	119.0
	JH	9.5	23.0	29.5	69.5	111.0	127.0	140.5	-
	VK	9.0	21.0	28.0	55.0	81.0	96.0	123.0	230.0
	JN	7.5	18.5	24.0	53.5	68.5	90.0	100.5	155.0
	JS	7.0	10.5	21.0	35.0	44.5	64.5	88.0	115.5
	Avg(sec)	8.0	17.0	23.8	49.1	68.6	86.8	109.0	154.9
	Avg-2 sec	6.0	15.0	21.8	47.1	66.6	84.8	107.0	152.9
	Avg(log sec)	0.778	1.176	1.322	1.672	1.819	1.924	2.029	2.181

Table G.10

Recovery Times (sec)
for Log Flash Energy of 7.65 td.sec, Letter Size 28.4'

Flash Duration (msec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
0.78	RB	6.5	10.5	14.0	19.5	26.5	41.0	81.0	89.5
	JH	12.5	16.5	21.5	43.0	61.0	76.0	157.0	188.0
	VK	7.0	14.0	18.0	22.0	32.0	85.0	100.0	182.0
	JN	6.0	13.5	17.5	24.0	39.5	51.0	93.5	112.0
	JS	7.0	11.0	16.0	28.0	32.5	54.5	65.0	117.5
	Avg(sec)	7.8	13.1	17.4	28.3	38.3	61.5	99.3	137.8
	Avg-2 sec	5.8	11.1	15.4	26.3	36.3	59.5	97.3	135.8
	Avg(log sec)	0.763	1.041	1.176	1.415	1.556	1.770	1.986	2.130
1.10	RB	5.5	11.5	15.5	21.0	32.0	41.0	63.5	83.5
	JH	9.0	12.5	19.5	55.0	73.0	92.0	119.5	139.5
	VK	8.0	15.0	19.0	34.0	42.0	65.0	101.0	154.0
	JN	6.5	13.5	21.5	29.0	41.5	60.5	84.5	102.5
	JS	5.0	8.5	17.0	31.0	34.5	53.5	94.0	113.5
	Avg(sec)	6.8	12.2	18.5	34.0	44.6	62.4	92.5	118.6
	Avg-2 sec	4.8	10.2	16.5	32.0	42.6	60.4	90.5	116.6
	Avg(log sec)	0.681	1.000	1.204	1.505	1.623	1.778	1.954	2.064
1.54	RB	6.5	11.0	15.0	24.0	29.5	39.5	74.0	85.5
	JH	8.0	15.5	21.0	42.5	54.0	65.0	102.0	121.0
	VK	7.0	14.0	17.5	28.5	50.0	79.0	103.0	156.0
	JN	6.0	14.0	17.0	28.5	40.0	50.0	82.5	90.0
	JS	5.5	12.0	13.5	35.0	49.5	63.5	85.5	112.0
	Avg(sec)	6.6	13.3	17.8	31.7	44.6	59.4	89.4	112.9
	Avg-2 sec	4.6	11.3	15.8	29.7	42.6	57.4	87.4	110.9
	Avg(log sec)	0.662	1.041	1.176	1.462	1.623	1.755	1.939	2.041
2.4	RB	6.5	11.0	14.5	24.5	29.0	32.5	56.0	115.5
	JH	10.5	18.0	24.0	49.0	81.5	99.0	152.0	178.5
	VK	8.5	15.0	19.0	45.0	51.0	62.0	100.0	149.0
	JN	7.0	15.0	19.0	30.5	42.0	64.5	91.0	102.5
	JS	5.0	12.5	17.5	28.0	33.0	57.0	105.0	125.5
	Avg(sec)	7.5	14.3	18.8	35.4	47.3	63.0	100.8	134.2
	Avg-2 sec	5.5	12.3	16.8	33.4	45.3	61.0	98.8	132.2
	Avg(log sec)	0.740	1.079	1.204	1.518	1.653	1.785	1.991	2.120

Table G.10 (continued)

Flash Duration (msec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
3.4	RB	6.5	11.0	15.0	24.5	30.5	46.5	71.5	91.5
	JH	10.0	16.5	20.0	25.5	50.5	90.5	110.0	179.5
	VK	7.5	15.5	20.0	35.0	58.0	63.0	87.5	136.5
	JN	8.0	14.0	18.5	33.0	41.0	55.0	90.0	101.0
	JS	6.5	14.0	17.0	26.0	45.5	65.0	100.0	123.0
	Avg(sec)	7.7	14.2	18.1	28.8	45.1	64.0	91.8	126.3
	Avg-2 sec	5.7	12.2	16.1	26.8	43.1	62.0	89.8	124.3
	Avg(log sec)	0.755	1.079	1.204	1.415	1.633	1.792	1.949	2.093

Table G.11

Recovery Times (sec)
for Log Flash Energy of 7.8 td.sec, Letter Size 16.2'

Flash Duration (msec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
1.10	RB	7.5	12.0	17.0	32.0	40.5	70.0	133.0	158.0
	JH	10.5	19.5	26.5	57.0	72.5	97.0	144.0	-
	VK	9.5	16.0	24.0	34.0	74.0	82.0	193.0	201.5
	JN	7.5	19.5	24.0	50.0	62.5	85.5	130.5	191.5
	JS	5.5	13.0	16.5	30.0	40.0	58.5	130.0	152.0
	Avg(sec)	8.1	16.0	21.6	40.6	57.9	78.6	146.1	175.8
	Avg-2 sec	6.1	14.0	19.6	38.6	55.9	76.6	144.1	173.8
	Avg(log sec)	0.785	1.146	1.278	1.579	1.740	1.880	2.158	2.238
1.54	RB	7.5	13.0	18.0	30.5	51.0	64.0	103.5	127.0
	JH	11.0	19.0	27.0	54.0	77.5	106.5	223.5	-
	VK	10.0	16.5	22.0	44.0	54.0	61.0	135.0	170.0
	JN	9.0	15.0	21.0	43.5	57.5	72.5	153.5	207.0
	JS	6.0	12.5	20.0	25.0	40.0	49.0	78.5	136.0
	Avg(sec)	8.7	15.2	21.6	39.4	56.0	70.6	138.8	160.0
	Avg-2 sec	6.7	13.2	19.6	37.4	54.0	68.6	136.8	158.0
	Avg(log sec)	0.826	1.113	1.278	1.568	1.732	1.832	2.133	2.198
2.4	RB	7.0	15.0	18.5	36.5	52.5	66.0	106.0	126.0
	JH	10.5	19.5	25.5	74.5	90.0	104.5	199.0	-
	VK	10.0	16.5	22.5	36.0	49.0	104.0	142.5	158.5
	JN	8.0	16.5	21.0	35.5	48.5	88.0	133.5	170.0
	JS	6.0	14.0	20.0	35.0	46.0	59.0	86.0	129.0
	Avg(sec)	8.3	16.3	21.5	43.5	57.2	84.3	133.4	145.9
	Avg-2 sec	6.3	14.3	19.5	41.5	55.2	82.3	131.4	143.9
	Avg(log sec)	0.799	1.146	1.278	1.612	1.740	1.913	2.117	2.155
3.4	RB	7.5	13.0	18.0	38.0	51.0	74.0	116.0	135.0
	JH	10.5	20.0	30.5	61.0	80.0	125.0	-	-
	VK	9.0	17.5	26.0	49.0	72.5	103.0	177.5	195.5
	JN	8.5	16.0	21.0	37.5	53.5	66.5	110.0	143.0
	JS	7.0	15.5	23.0	30.0	47.0	64.0	118.0	156.5
	Avg(sec)	8.5	16.4	23.7	43.1	60.8	86.5	130.4	157.5
	Avg-2 sec	6.5	14.4	21.7	41.1	58.8	84.5	128.4	155.5
	Avg(log sec)	0.812	1.146	1.322	1.612	1.763	1.924	2.107	2.190

Table G.11 (continued)

Flash Duration (msec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
2 Cond.	RB	8.0	13.5	17.5	38.0	50.0	60.0	115.5	140.0
	JH	12.0	23.0	32.0	60.5	98.5	126.0	278.0	-
	VK	8.0	16.5	23.0	33.0	68.0	81.0	157.0	194.5
	JN	8.5	18.0	25.5	37.5	60.5	80.0	139.0	207.5
	JS	5.5	9.0	21.0	38.0	46.0	57.0	111.0	125.0
	Avg(sec)	8.4	16.0	23.8	41.4	64.6	80.8	160.1	166.8
	Avg-2 sec	6.4	14.0	21.8	39.4	62.6	78.8	158.1	164.8
	Avg(log sec)	0.806	1.146	1.322	1.591	1.792	1.892	2.198	2.214

Table G.12

Recovery Times (sec)
for Log Flash Energy of 7.8 td.sec, Letter Size 28.4'

Flash Duration (msec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
1.10	RB	6.5	13.0	17.5	30.5	37.0	47.0	90.5	99.5
	JH	10.5	17.0	21.5	37.0	55.0	84.5	123.0	141.0
	VK	7.0	13.0	17.0	29.0	47.5	63.5	90.0	124.0
	JN	8.0	13.0	16.5	29.5	36.0	57.5	79.5	120.5
	JS	4.5	11.0	15.0	23.0	31.0	44.0	75.5	92.5
	Avg(sec)	7.3	13.4	17.5	29.8	41.3	59.3	91.7	115.5
	Avg-2 sec	5.3	11.4	15.5	27.8	39.3	57.3	89.7	113.5
	Avg(log sec)	0.724	1.041	1.176	1.431	1.591	1.755	1.949	2.053
1.54	RB	7.5	11.5	15.0	25.0	36.0	47.0	81.5	100.0
	JH	10.5	16.0	24.0	39.0	70.5	96.5	142.0	245.0
	VK	7.0	15.0	-	34.0	50.0	67.0	110.0	118.0
	JN	7.5	12.0	19.5	24.5	39.5	62.5	89.0	114.0
	JS	6.0	10.0	19.0	27.0	47.0	58.0	78.5	100.5
	Avg(sec)	7.7	12.9	19.3	29.9	48.6	66.2	100.2	135.5
	Avg-2 sec	5.7	10.9	17.3	27.9	46.6	64.2	98.2	133.5
	Avg(log sec)	0.755	1.041	1.230	1.431	1.662	1.806	1.991	2.123
2.4	RB	7.5	11.0	14.5	24.0	33.5	48.5	80.5	87.5
	JH	10.0	19.5	25.0	41.5	58.0	79.5	136.0	182.0
	VK	8.0	13.5	20.0	38.5	53.5	61.0	135.0	161.5
	JN	6.5	14.0	18.5	30.0	40.0	53.0	95.0	104.0
	JS	6.0	12.0	17.5	22.5	29.0	39.0	54.0	61.0
	Avg(sec)	7.6	14.0	19.1	31.3	42.8	56.2	100.1	119.2
	Avg-2 sec	5.6	12.0	17.1	29.3	40.8	54.2	98.1	117.2
	Avg(log sec)	0.748	1.079	1.230	1.462	1.602	1.732	1.991	2.068
3.4	RB	8.0	12.5	17.0	24.0	34.0	44.0	83.0	101.5
	JH	9.5	16.5	22.0	44.5	57.5	79.5	116.0	151.0
	VK	11.0	16.0	24.5	34.0	55.0	85.0	131.5	186.5
	JN	7.5	14.0	19.5	33.5	40.0	55.0	91.5	107.5
	JS	5.5	11.0	16.0	21.0	33.0	44.0	71.0	88.0
	Avg(sec)	8.3	14.0	19.8	31.4	43.9	61.5	98.6	126.9
	Avg-2 sec	6.3	12.0	17.8	29.4	41.9	59.5	96.6	124.9
	Avg(log sec)	0.799	1.079	1.230	1.462	1.612	1.770	1.982	2.093

Table G-12 (continued)

Flash Duration (msec)	Subject	Log Target Luminance (mL)							
		2.45	0.75	0.30	-0.37	-0.75	-1.20	-1.95	-2.12
2 Cond.	RB	7.5	12.0	18.5	26.5	33.0	52.5	89.5	105.5
	JH	9.5	18.5	23.5	45.0	58.0	82.0	118.0	145.0
	VK	10.0	15.5	20.5	45.0	55.5	63.5	135.0	140.5
	JN	8.0	16.0	20.0	28.5	35.5	51.0	91.0	101.5
	JS	4.0	12.0	17.0	23.0	38.0	43.0	74.0	81.0
	Avg(sec)	7.8	14.8	19.9	33.6	44.0	58.4	101.5	114.7
	Avg-2 sec	5.8	12.8	17.9	31.6	42.0	56.4	99.5	112.7
	Avg(log sec)	0.763	1.079	1.230	1.491	1.623	1.748	1.995	2.049

Appendix H - Russell (39)

Russell's Figure 2 is part of our Figure 1.

Appendix I - Severin, et al. (40, 41)

Severin *et al's* Table I was converted to Table I.1 and is plotted in Figure 2.

Table I.1

Log Recovery Times (mean of four subjects)

Testing Patch Brightness (Target Luminance)			Calculated Adapting Source (Diffusing Screen) Luminance x Flash Duration Lambert.sec				
ft.L	mL	log mL	0.0351	0.288	0.585	1.46	3.06
0.06	.065	-1.119	0.564	0.722	0.800	0.905	1.125
0.013	0.014	-1.854	0.896	1.081	1.268	1.381	1.572

Appendix J - Whiteside & Bazarnik (54)

Five curves were fitted by eye to Whiteside and Bazarnik's Figure 6. The five curves, plus one already fitted by Whiteside and Bazarnik, were converted to Table J.1. Our Figure 6 is plotted from J.1.

Table I.1

Recovery Times from Different Degrees of Stimulus to Three Brightness Levels of Test Object

Adapting Flash Energy (Lambert-seconds)	Recovery Times (log sec)					
	Foveal			Peripheral		
	Display Luminance (log mL)					
	+0.703	-0.968	-1.492	+0.703	-0.968	-1.492
3.14×10^1	-	-	1.57	-	-	-
1.57×10^2	-	-	1.78	-	-	-
3.14×10^2	-	-	1.84	-	-	-
9.43×10^2	-	1.40	1.94	-	-	1.04
1.57×10^3	-	1.43	1.99	-	1.00	1.32
3.14×10^3	-	1.48	2.02	-	1.08	1.52
6.28×10^3	-	1.52	2.08	-	1.15	1.65
1.57×10^4	-	1.61	2.10	-	1.32	1.81
3.14×10^4	-	1.70	2.20	-	1.43	1.98
6.28×10^4	1.26	1.84	2.43	1.15	1.57	2.20
9.43×10^4	1.30	1.93	2.60	1.20	1.70	2.35
1.57×10^5	1.36	2.30	3.00	1.26	2.00	2.72

Appendix K - Whiteside (53)

Whiteside (53) presents tabular data of a field trial with an actual nuclear explosion and a curve (Figure 13) comparing other experimenters' results with his field trial and with his experiment using a modified calibration source. Whiteside's data were transformed into the following two tables. Table K.1 presents the results of the field trial and was presented earlier as Table II. Table K.2 presents the results of the experiment with the modified calibration source.

Table K.1

Adaptometer Luminance			Foveal Recovery Time log sec	Recovery Time thru Fireball Afterimage log sec	Fireball Luminance Integrated to 100 msec	
ft.L	mL	log mL				
1.04	1.12	0.049	0.70	1.45	5.53×10^{8} td.sec	1.382×10^{4} L.sec
0.41	0.44	-0.356	1.23	1.60		
0.14	0.15	-0.824	1.76	1.95		

Table K.2

Modified Calibration Source Luminance			Recovery Time log sec	Target Luminance	
$\frac{\text{candles}}{\text{cm}^2\ \text{sec}}$	td.sec	log td.sec		ft.L	mL
20	2.51×10^{6}	6.40	1.45	0.14	0.15
7.1	8.92×10^{5}	5.95	1.20		
5	6.28×10^{5}	5.80	0.84		

Appendix L - Severin, et al. (42)

Their Tables 3 and 7 present the mean recovery times of 15 subjects for three different corneal illuminances (in lux) for target luminances of 0.06 ft.L and 0.013 ft.L, respectively, and under large or small pupil conditions. In order to plot Figure 11, Tables 3 and 7 were transformed into Table L.1 by calculating the source luminances in candles/m^2. It was assumed that the experimental set-up was identical to that described in (40). The mean small pupil diameter was 2.20 mm; the mean large pupil diameter was 7.43 mm.

Table L-1

Corneal Illumination (Lux)	Calculated Adapting Source Luminance Candles/ M^2	Calculated Adapting Source Luminance X Flash Duration X Pupil Area		Mean Recovery Times		Target Luminance mL
		Small Pupil log td.sec	Large Pupil log td.sec	Small Pupil log sec	Large Pupil log sec	
86,080	9.93×10^4	4.753	5.807	0.948	1.019	0.065
150,640	1.74×10^5	5.000	6.050	1.090	1.173	
242,100	2.79×10^5	5.202	6.256	1.227	1.441	
86,080	9.93×10^4	4.753	5.807	1.298	1.249	0.014
150,640	1.74×10^5	5.000	6.050	1.444	1.446	
242,100	2.79×10^5	5.202	6.256	1.564	1.648	

APPENDIX M

CALCULATION METHOD

The Multiple Linear Regression Program will compute the coefficients providing the best fit for a set of observations by an equation of the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + . . . + b_nX_n$$

where Y is the dependent variable; $X_1, X_2, . . . , X_n$ are the independent variables; and $b_0, b_1, b_2, . . ., b_n$ are the coefficients to be determined. The regression also provides statistical quantities giving a measure of the reliability of the computed coefficients.

The Regression Program can be used to fit non-linear equations of the form:

$$Y = b_0 + b_1f_1(Z_1) + b_2f_2(Z_2) + . . . + b_nf_n(Z_1,.Z_2, . . . Z_m)$$

This equation is made equivalent to the simple linear equation (above) by the substitution (or transformation):

$$\begin{aligned} X_1 &= f_1(Z_1) \\ X_2 &= f_2(Z_2) \\ \cdot \quad & \quad \cdot \\ \cdot \quad & \quad \cdot \\ X_n &= f_n(Z_1, Z_2, \ldots Z_m) \end{aligned}$$

This Regression Program uses the stepwise procedure outlined by M. A. Efroymson in <u>Mathematical Methods for Digital Computers</u>, John Wiley and Sons., 1960. In this stepwise procedure, intermediate regression equations are obtained as well as the final equation. These equations are obtained by adding one variable at a time giving the following intermediate equations:

$$Y = b_0 + b_1X_1$$

$$Y = b'_0 + b'_1X'_1 + b'_2X'_2$$

$$Y = b''_0 + b''_1X''_1 + b''_2X''_2 + b''_3X''_3$$

.

.

.

In this manner it is possible to obtain valuable statistical results at each step of the calculation. These intermediate results may be used to control the succeeding calculation since the next variable added is the one which makes the most improvement in the fit. A variable may also be removed from the fit if it drops below the specified significance level.

EQUATIONS

The equations presented in this section represent the specific calculation method as used by this program.

PHASE I EQUATIONS

1. LEAST SQUARES (PRODUCT MOMENT) MATRIX

The general term of the matrix is:

$$P_{i,j} = \sum_{n} (X_i X_j)$$

The matrix is stored in upper triangular form by the program and the specific terms are:

$$\begin{array}{ccccc}
\Sigma X_1^2 & \Sigma X_1 X_2 & \Sigma X_1 X_3 & \Sigma X_1 X_4 & \cdots \\
 & \Sigma X_2^2 & \Sigma X_2 X_3 & \Sigma X_2 X_4 & \cdots \\
 & & \Sigma X_3^2 & \Sigma X_3 X_4 & \cdots \\
 & & & \Sigma X_4^2 & \cdots
\end{array}$$

2. VARIANCE - COVARIANCE MATRIX

The general term of the matrix is:

$$\mathrm{Cov}_{i,j} = \frac{\Sigma (X_1 - X_i) (X_j - X_i)}{N - 1}$$

This matrix is also stored in upper triangular form by the program.

3. MEANS

$$\bar{X}_i = \frac{\Sigma\ X_i}{N}$$

4. STANDARD DEVIATION

$$\sigma_i = \sqrt{\frac{\Sigma (X_i - \bar{X}_i)\ (X_i - \bar{X}_i)}{N - 1}} = \sqrt{\frac{\Sigma (X_i - X_i)^2}{N - 1}}$$

5. SIMPLE CORRELATION MATRIX

The general term of the matrix is:

$$r_{i,j} = \frac{\mathrm{Cov}_{\ i,j}}{\sigma_i\ \sigma_j}$$

This matrix is also stored in upper triangular form by the program.

PHASE II EQUATIONS

1. DEFINITIONS

k - Dependent variable index

j - independent variable index

$Z_{k,j}$ - Working matrix element

2. RESIDUAL SUM OF SQUARES

$$RSS = Z_{k,k}\ \sigma_k^2\ (N-1)$$

3. STANDARD ERROR OF REGRESSION EQUATION

$$SEE = \sqrt{\frac{RSS}{\text{Degrees of freedom}}}$$

4. DEGREES OF FREEDOM

DOF = Sum of weights - Number of pivots - 1

5. INITIAL SUM OF SQUARES

$$ISS = \sigma_k^2 \quad (N - 1)$$

6. REGRESSION SUM OF SQUARES

$$RGSS = ISS - RSS$$

7. COEFFICIENT OF DETERMINATION (R^2)

$$R^2 = 1 - \frac{RSS}{ISS}$$

8. COEFFICIENT OF REGRESSION EQUATION

$$B_j = Z_{k,j} \frac{\sigma_k}{\sigma_j}$$

9. STANDARD ERROR OF REGRESSION COEFFICIENT

$$SRC_j = \frac{\sqrt{Z_{j,j}}}{\sigma_j} \cdot \frac{SEE}{\sqrt{N - 1}}$$

10. F-STATISTIC

$$F_j = \left(\frac{B_j}{SRC_j} \right)^2$$

11. PARTIAL CORRELATION COEFFICIENT

$$PCC_{k,j} = \frac{Z_{k,j}}{\sqrt{(Z_{k,j})^2 + Z_{j,j} \cdot Z_{k,k}}}$$

12. CONSTANT TERM

$$C_k = \overline{X}_k - \sum b_i \overline{X}_i$$

13. CALCULATED VALUE

$$\widehat{Y} = (\overline{X}_k - \sum b_i \overline{X}_i) + \sum b_i X_i$$

14. RESIDUAL

$$RES = Y - \widehat{Y}$$

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) General Electric Company 4000 N. W. 39th Street Oklahoma City, Oklahoma	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
A Mathematical Model of Flashblindness

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report; 1 Nov 64 through 31 Aug 65

5. AUTHOR(S) (Last name, first name, initial)
Czeh, Robert S.
Casper, Arthur W.
Segraves, Ernest C.

6. REPORT DATE October 1965	7a. TOTAL NO. OF PAGES 164	7b. NO. OF REFS 55

8a. CONTRACT OR GRANT NO. AF41(609)2644	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. Task No. 630103	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. AVAILABILITY/LIMITATION NOTICES
Qualified requestors may obtain copies of this report from DDC. This document may be released to OTS.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY USAF School of Aerospace Medicine Aerospace Medical Division Brooks Air Force Base, Texas

13. ABSTRACT

In planning certain military missions it is desirable to know the extent to which vision may be impaired by the flashblindness that can result from the intense light of a nuclear explosion. This report describes an attempt to provide assistance to such planning by constructing a mathematical model of flashblindness. The literature was surveyed to determine whether or not the construction of a model was feasible. Using selected data, two equations were developed for predicting recovery time from flash energy, display luminance, and display visual acuity. The prediction errors made were determined in a few situations and compared with the errors made by other prediction techniques. Limitations of the applicability of the equations were noted.

DD FORM 1 JAN 64 1473

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flashblindness						
Eye; Flashblindness						
Eye Hazards						
Retina						
Vision						
Visual Perception						
Mathematical Models						
Models						
Aviation Medicine						
Air Force Research						
Nuclear Explosions, eye effects						
Photosensitivity, eye						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
____ ."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
____ ."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
____ ."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.