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NAVAL POSTGRADUATE SCHOOL

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THESIS

A LABORATORY EVALUATION OF THE SUITABILITY OF A XENON FLASHTUBE SIGNAL AS AN AID-TO-NAVIGATION

by

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December 1981

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82 02 16 122

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO. AD-A 10729

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
A LABORATORY EVALUATION OF THE SUITABILITY OF A XENON FLASHTUBE SIGNAL AS AN AID-TO-NAVIGATION

5. TYPE OF REPORT & PERIOD COVERED
Master's Thesis;
December 1981

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Donald Francis Murphy

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

12. REPORT DATE
December 1981

13. NUMBER OF PAGES
108

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
multi-flick flashtube, depth perception, flashing lights, aids-to-navigation, fixation, stereoscopic vision, conspicuity, flash duration, condensor discharge beacon, strobe

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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S/N 0102-014-6601

20. (Continued)

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A Laboratory Evaluation of the Suitability of a Xenon Flashtube Signal as an Aid-to-Navigation

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 1981

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ABSTRACT

Single flick xenon flashtubes have periodically been used by the U.S. Coast Guard as visual signals on marine aids-to-navigation. Their deployment has met with mixed responses. The conspicuity of the signal is excellent; it stands out among other visual signals, both flashing and steady lights. However, the flick is apparently too short, approximately 100 μsec, for the mariner to fixate on it. He, therefore, is unable to make an accurate judgement concerning the distance to the light. This thesis utilized a Howard-Dolman Box to examine the depth perception of subjects under various flashing light conditions. Ten subjects qualified for the experiment and were trained. The subjects were then presented single and multi-flick flashtube bursts in an effort to determine which signal(s) provided depth perception that was comparable to that of a flashing incandescent aid-to-navigation. No significant differences between the light sources were found. The lack of differences was attributed, in part, to the unreliability of the test.

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ACKNOWLEDGEMENT

The author wishes to thank his family for being patient and understanding during the writing of this paper. He also wishes to thank CDR William F. Moroney for his interest and support which made this project possible.

I. INTRODUCTION

A. MARINE AIDS TO NAVIGATION

As defined in Title 14, U.S. Code, the United States Coast Guard is charged with establishing, maintaining and operating the system of maritime navigational aids used throughout the United States waters. In addition to fixed position shore aids, the system is comprised of some 22,000 buoys, 4000 of which are lighted. These aids are designed to serve the needs of commerce, the armed forces, and recreational boaters. The Coast Guard establishes, maintains, and operates these floating aids with several types of resources, ranging from a 2 to 3 man aids-to-navigation team using a 12 foot Boston Whaler to a 180 foot sea-going buoy tender with a crew of 50.

All of the lighted aids contain a solid state flasher which provides the signal characteristic, while the signal itself is provided by an incandescent lamp. The lamp's visual signal is focused by an acrylic lens and it may be filtered to provide a white, red or green signal. Additionally, six lamps are housed in the buoy signal package in a multiple lamp changer. Each light signal is energized only during periods of heavy fog, dusk, and darkness.

All lighted buoys operate on 12 volts DC provided by a series or series-parallel combination of air de-polarized cells. Presently some buoys are having a 12 volt photovoltaic system installed.

The solid state flashers provide ten different flash characteristics. Fairways are marked with lighted buoys that produce a short flash followed by a long flash, or a Morse Code alpha (- ---) characteristic. Channel sides are marked with lights that flash every 2.5 seconds, every 4 seconds or every 6 seconds. Wrecks and obstructions are marked with interrupted quick flashing signals. These signal combinations along with the three color choices of white, red, and green provide enough combinations to make each buoy different from its nearest neighbor.

Present requirements dictate that each buoy be serviced on site at least once a year. The purpose of the service is to check the signal, the battery, and the position. A buoy may be serviced more frequently if, because of the intensity or characteristic of the visual signal, the buoy's batteries would expire in less than a year. In fact, many buoys receive 2 or 3 visits per year due to malfunctioning signals, or off station reports. Signal malfunctions can be caused by defective lamps, poorly regulated batteries, or personnel error during maintenance. Collisions and acts of nature also account for buoy signal malfunctions. The operating cost estimates for aids-to-navigation servicing units range from $325 per hour for a sea-going buoy tender to $51 per hour for an aids-to-navigation boat (33 CFR 74.20). These costs are exclusive of salaries.

B. USING FLOATING AIDS TO NAVIGATION

Floating aids-to-navigation, as well as aids that are fixed to land, are used differently by various mariners. A large oil or ore carrier must be aware of his position relative to nearby shoals and the channel. As an example, when standing into a harbor or bay after dark he will first encounter a fairway buoy which indicates that he is at the point where he starts his approach into the harbor or bay. Up until this point he may have been using LORAN C or some other electronic means as well as radar for navigation. Now he is likely to switch to a combination of visual and radar navigation. As he nears the channel he will start to pick out buoy lights from the background lighting. The degree to which a buoy light signal stands out from the surrounding or background lights is very important and may vary from area to area. For example, New York Harbor has heavy background lighting into which the buoys blend, while at the entrance to the Delaware Bay (Port of Wilmington) the buoys are much more conspicuous due to the low level of background lighting.

As the vessel approaches the channel, the master must use his navigational equipment, usually his radar, to determine the range to the first set of buoys prior to making his turn up the channel. An experienced ship captain, familiar with the area, may rely solely on the buoys. He may use their brightness, or interposition with other objects to make his turn up the channel. Once in the channel, the master usually relies on the aspect of the line of the side channel buoys to judge his distance to the right or left of center channel.

With a channel turn or channel junction approaching, he will use the junction buoy to estimate his time to start his turn. He will use its brightness, and its position relative to the other buoys and landmarks. He will also use the relative motion of the buoys with the background to judge distance to buoys. He will probably confirm a buoy's range with his radar. It is necessary to keep in mind that a large bulk-carrying merchant vessel does not handle like an automobile. Such a vessel may advance several hundred yards at 12-15 knots before it has completed a small 15 to 20 degree course change. Throughout this process the ship captain is relying on lighted buoys to assist him in directing his vessel. He needs a conspicuous signal from the buoy, one that cannot be confused with any other buoy in the immediate vicinity. He also needs to be able to have his eye fixate on the signal to enable him to make a decision or judgement.

At the mouth of the harbor or bay, the vessel may have acquired a qualified harbor/bay pilot for that local area. This is a qualified captain who has usually made several hundred transits of the area. He directs the movement of the vessel through the familiar waters with even more reliance on the buoys than the ship's captain. The pilot concentrates on the buoy's interposition with other objects, relative position among the buoys themselves, and relative motion of the buoy and background. Harbor pilots have been known to report buoys as being 25-50 yards off station, which may seen insignificant, but which frequently is critical. Their ability to make such precise judgements of the buoy's position comes from their experience in maximizing the information content of the buoys. A large part of this skill may be attributed to their ability to fixate visually on the buoy and perceive the buoy within a context. The buoys are used for estimating the vessel's position until the ship is finally docked. The degree to which the buoys are used over other aids is dependent on the types of aids and the configuration of each harbor. However, during a transit of a harbor or waterway the majority of position information is gained from buoys.

The scenario for departing a harbor at night is very similar to the arrival. However, as the vessel gets closer and closer to the open bay or ocean, background lighting disappears. There are fewer and fewer land objects and lights with which to line up a buoy. In the worst case situation, the captain may have a lighted buoy against a black background. Although conspicuity of the signal would be excellent, there would be no interposition or relative motion with other objects, by which the mariner could gain some distance information from the buoy. He would probably rely more heavily on the buoy's brightness for range information or perhaps resort to his radar.

A transit of a bay and harbor would be less complex on a small boat. Because of its shallower draft, a small boat probably does not need to stay in the channel. The skipper of the boat may even operate outside the channel or cut outside the channel at turns. However, he probably does not have radar and because his height of eye is closer to the water, he can't see as many aids as the master can on a larger vessel. His lower height of eye will, however, give him more interposition and bearing rate cues from buoys. However, like the master of a large vessel, he relies heavily on the fact that he can fixate on the buoy light, and he can estimate its position or distance.

C. FLASHTUBES AS AIDS TO NAVIGATION

Over the past 15-20 years the Coast Guard has occasionally replaced the incandescent lamps in aids-to-navigation with xenon flashtubes. These flashtubes have been limited-use signals, being employed where a conspicuous aid was necessary. The most prominent example of flashtube usage is Ambrose Light Tower at the entrance to New York Harbor. The operation of a flashtube is described and diagrammed in Appendix A.

1. Positive Aspects of Flashtubes

A single flash from a xenon flashtube is called a flick and a series of flicks is called a flash or burst. Xenon flashtubes used as aids-to-navigation have generally been single flick. The duration of the flick has been approximately 100 µ seconds, and it is partially due to this very short flick that the flashtube gets its high conspicuity. Conspicuity is the attention attracting value of a (flashing) light signal (Holmes, 1971). The light signal stands out to the human eye when located among other light signals. There is no standard method for numerically determining the "attention getting value." A field evaluation of xenon flashtubes as a warning signal on railroad train locomotives resulted in the finding that "Under all conditions the strobes (sic) were unanimously judged to be readily visible and attention getting." (FRA, 1975).

Other advantages of the flashtube were well documented by Montonye and Clark (1970). They stated that the extremely short duration of a flick provides a higher effective intensity than a longer flash of equal integrated intensity. Furthermore, the tests that they performed on a xenon flashtube lamp indicated a lamp life several times that of the combined lamp life of six incandescent lamps. Also, the efficacy (conversion of input energy to visible output) at the light source is greater than that of an incandescent lamp. The total result of these several positive factors is a more reliable light source which for the same luminous range is more conspicuous and more economical than an incandescent source (USCG, 1970).

Flashtubes for marine usage are presently produced by several companies and some of these are purchased by the Coast Guard. Using energy consumption and luminous range output figures for flashtubes and the Coast Guard's energy consumption and luminous range data (USCG, 1972), Figure 1 was produced. It is clear that buoy batteries last about 50% longer with a flashtube than with an incandescent source. With the cost of batteries for a recharge approaching $500 per buoy and a recharge lasting about 1.5 years, the possibility of realizing a tremendous savings through more wide spread usage of flashtubes is apparent. Assuming 4000 lighted buoys, the savings could exceed over one million dollars per year.

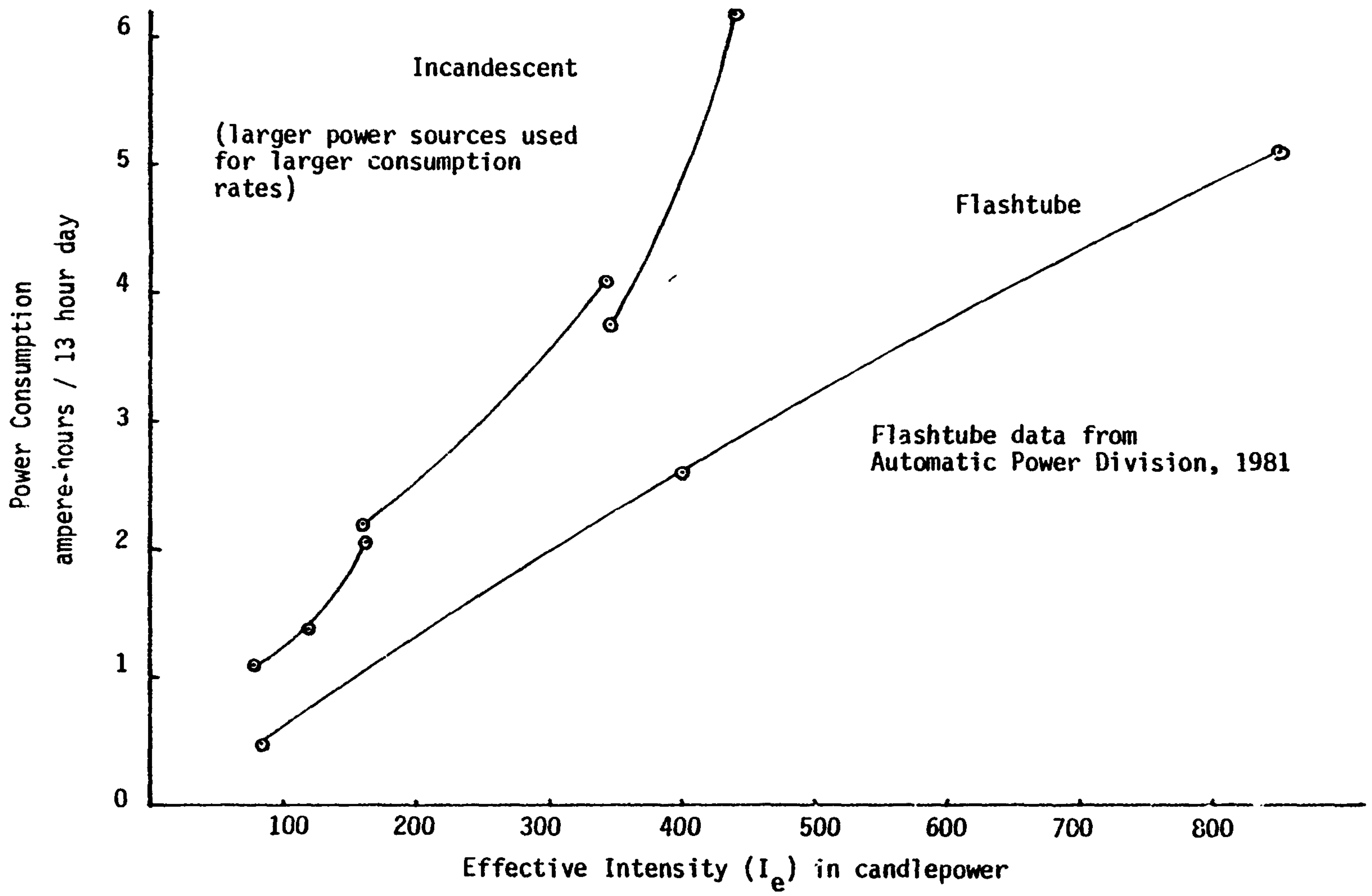

Figure 1. POWER CONSUMPTION vs EFFECTIVE INTENSITY FOR INCANDESCENT LAMP AND XENON FLASHTUBE WITH 4 SECOND DUTY CYCLES UTILIZING 12 VOLTS

2. Negative Aspects of Flashtubes

Despite the positive aspects of condenser discharge lamps, their use as an aid-to-navigation remains limited. This is due primarily to their non-acceptance by the mariner. The "excessive brilliance at relatively close quarters" and "lack of depth perception" are the two major complaints of mariners (ISFL, pp. 165-166, 1971).

The excessive brilliance when close aboard is commonly called the "flashbulb effect." It can be partially explained by considering the spectrum of a xenon flashtube signal (Figure 2), and the mariners task of navigating a channel. As a buoy gets closer and closer the mariner is likely to shift his concentration to buoys that lie farther along the channel line. As he focuses on those buoys ahead, buoy lights from the side or abeam begin to impact on his retina. Consequently, the blue spike in the xenon spectrum has more impact scotopically than it did photopically, creating a sensation of a flash of greater apparent brightness. This is not a fully adequate and complete explanation of the flashbulb effect. However, it does serve to partially explain the effect, and allows concentration on the more serious deficiency of flashtube signals, the lack of depth perception of the signal.

This lack of depth perception from the flashtube signal has been attributed to the short pulse length (USCG,

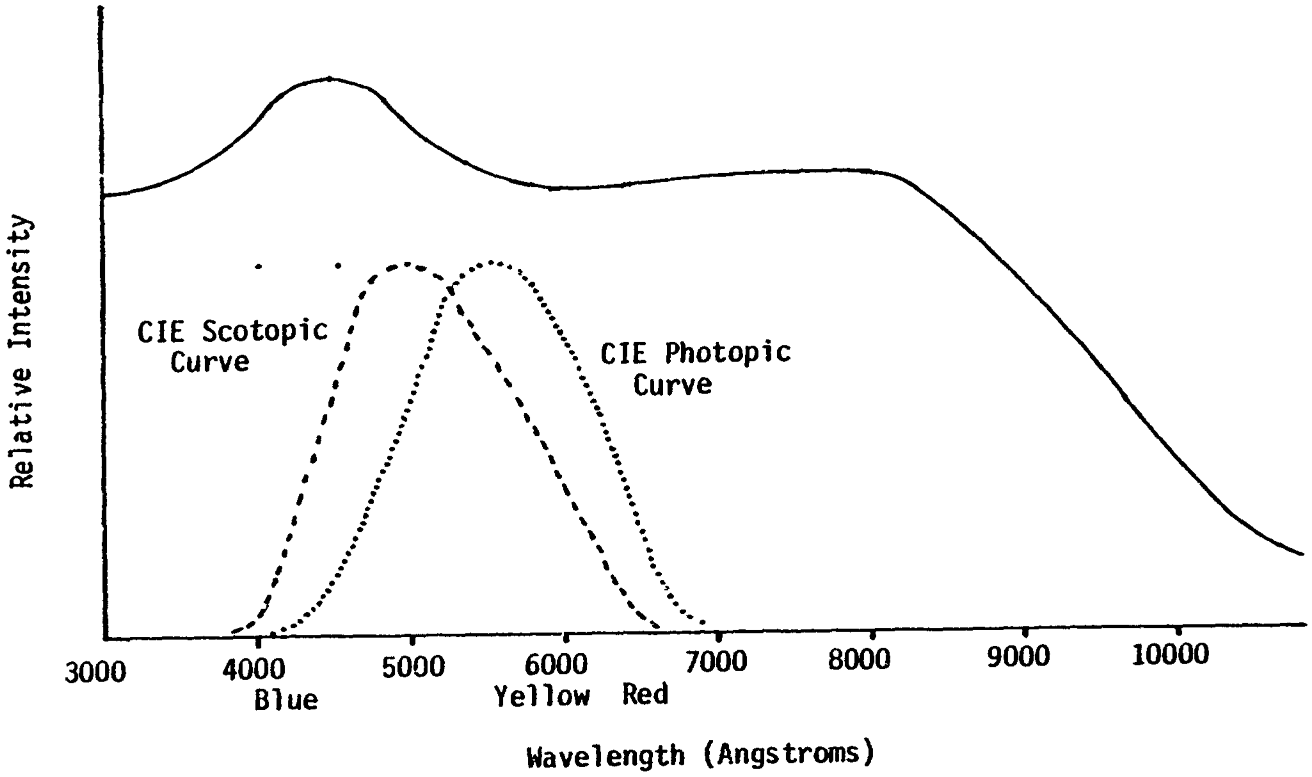

Figure 2. SPECTRAL DISTRIBUTION OF A XENON FLASH COMPARED WITH THE CIE PHOTOPIC AND SCOTOPIC SENSITIVITY CURVES

Xenon flash spectrum (IES Lighting Handbook, 1981)
Photopic and Scotopic curves (Graham, 1964)

1970). Xenon flashtube signal pulses are described as being from 3 to 120 μ seconds in duration, depending partially on the intensity level at which the flick is considered to be off. Flick duration is also dependent on the distance between electrodes and the charged voltage of the capacitor. Regardless of what is considered to be the duration of the pulse, it is too short to permit the eye to fixate on it.

When viewed without a reference point, a single flick flashtube signal will appear to jump from position to position with each flick. I have encountered the same effect when taking a bearing on a flashtube signal. The flash is too short to allow the mariner to fixate on it and align his alidade. This is an apparent contradiction to research showing "that the time required to take a bearing on a flashing light is independent of flash length" (White, 1965).

White's work involved having experienced navigation personnel take bearings on a single flick flashtube (100 μ second flick) and a flashing incandescent lamp with various flash durations from 0.1 sec to 2.0 sec. This was done in a dark lab using an alidade mounted on an illuminated gyro repeater on a non-rotating, stable platform. The time to take an accurate bearing was the dependent variable. His observers had a reference point on the compass card for their bearing observations, which, in my opinion, enabled him to arrive at his conclusions. In addition, White did point out further study with relative motion was necessary to confirm his laboratory findings, which were performed without relative motion.

However, Montonye and Clark stated after thorough field evaluation of a flashtube that the lack of depth perception was due to the eye's inability to fixate on the signal. One field test position was on the Mississippi River near Memphis with heavy background lighting. According to a report by the Second Coast Guard District Office, responses concerning the light were favorable, principally because of its conspicuity, but, "A few mariners observed that the light could be improved if the flash period could be made longer. The short flash period causes some difficulty in lining up the light." (USCG, 1970).

Information on depth perception deficiencies of flashtube signals is nearly all anecdotal. The limited use of flashtube signals as aids-to-navigation results in a very small data base for these signals. Consequently, it is difficult to link marine collisions or groundings to these signals because of the small, nearly non-existent, data base.

D. FLASHING LIGHT THEORY

The use of flashing lights as opposed to fixed lights for marine navigation makes the aids more conspicuous when contrasted with the lights on shore. Therefore, a summarization of flashing light theory, and its laws and effects is necessary to understand the problem and its possible solutions. The reader who is familiar with this topic may desire to read the "Depth Perception Review," which follows this section.

1. Threshold of Vision

The absolute illumination threshold is a measurement of the amount of energy spread over one square sea mile that can just be perceived by an individual. The aids to navigation threshold is not the absolute threshold, however, but is a more practical threshold about 2 log units above the absolute threshold. The illumination threshold used in aids-to-navigation computations is 0.67 sea-mile candles. It can be converted to foot-candles by using the fact that there are 2000 yards per nautical mile (nmi) and dividing 0.67 by 3.6×10^7, the number of square feet in a square sea mile. The 0.67 sea-mile candles assumes a clear, moonlit night with no background lighting, and the observer moderately dark adapted. This threshold is adjusted upward by 1 and 2 log units for cases of intermediate and heavy background lighting. A figure of

0.2 micro-lux is equal to 0.67 sea-mile candles, and has more widely accepted units.

2. Allard's Law and the Blondel-Rey Law

In order to adequately discuss aids-to-navigation it is necessary to be aware of the physical laws affecting light signals. An understandng of Allard's Law and the Blondel-Rey Law is critical to understanding flashing light phenomena. Allard's Law states that $I=ED^2/T^D$ where:

I = fixed intensity (candlepower)

E = observer's threshold illumination (foot-candles)

T = transmissivity of the atmosphere = $\exp(-\mu)$

D = distance (feet)

Allard's Law then provides the necessary intensity of a fixed light for a given luminous range. Usually aids-to-navigation signals are flashing to enhance their conspicuity. Therefore, a fixed-intensity-equivalent is necessary for a flashing light. In 1912 Blondel and Rey developed the relationship between fixed and flashing lights when viewed at threshold. Using square pulses they arrived at:

$$I_e = \frac{It}{a + t}$$

where

I_e = equivalent intensity (candlepower)

t = time of the flash (seconds)

I = intensity of the flash (candlepower)

a = constant (0.21 sec at threshold)

The value of "a" has been found to be constant under a given set of conditions. It is normally used only with threshold conditions when it is equal to 0.21 sec. If supra-threshold conditions are applied the value of "a" is generally found to be smaller. However, its value at conditions other than threshold, where I and I_e are clearly defined, depends on how the values of I and I_e are defined or matched.

If the wave form was not a square wave, then their law is modified to

$$I_e = \frac{\int_{t_1}^{t_2} I dt}{a + (t_2 - t_1)}$$

where the limits of integration are not the times of onset and offset, except with a square wave, but rather t_1 and t_2 are the times which will maximize the integral; they occur when the intensity (I) equals the effective intensity (I_e). Figure 3 illustrates this integration graphically.

Operating at threshold allows the interchanging of illumination and intensity and the Blondel-Rey Law can be expressed as

$$aE_e = \int_{t_1}^{t_2} (E - E_e) dt$$

and effective illumination can be determined for any pulse shape (Schmidt-Clausen, 1971).

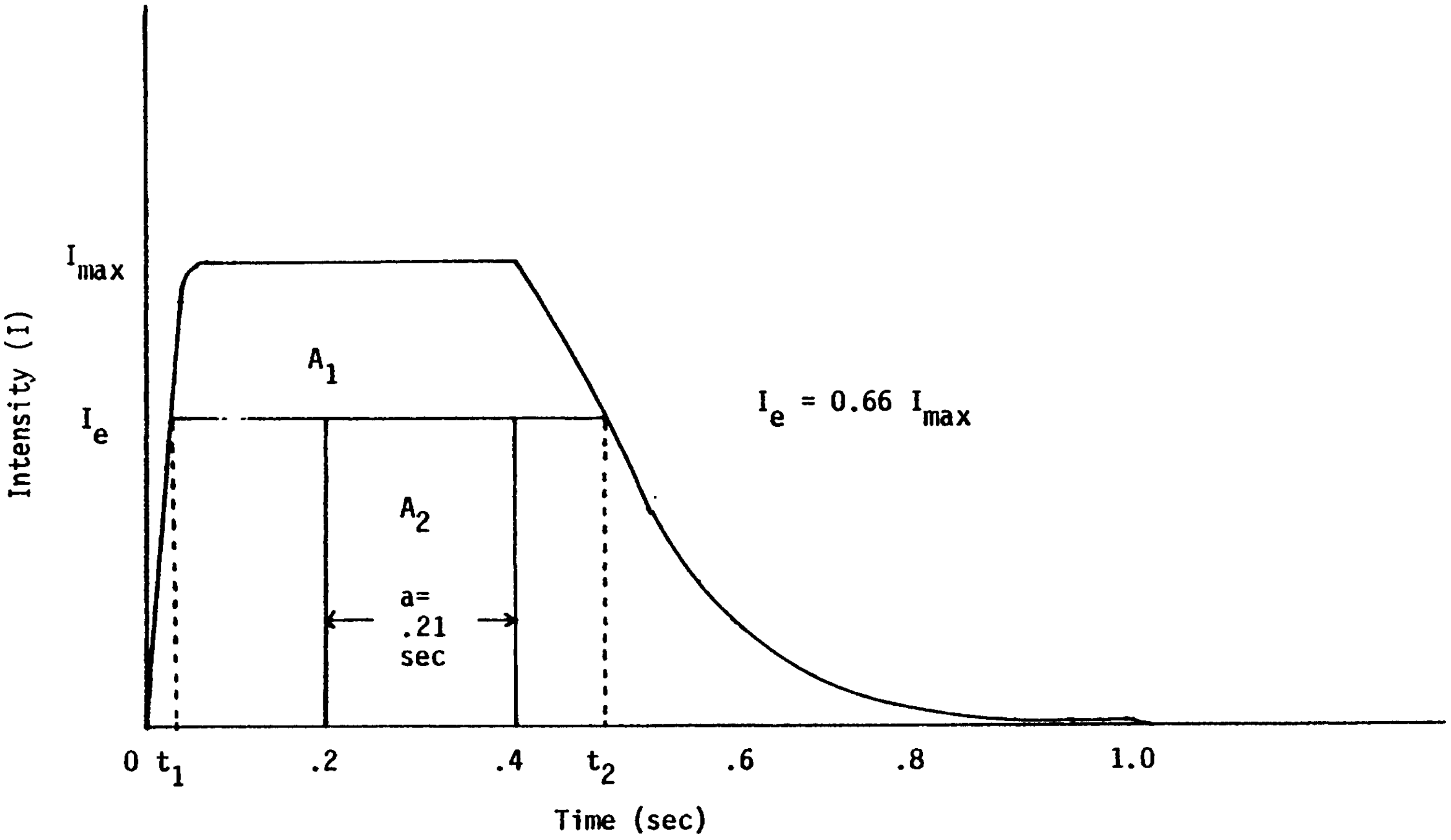

Figure 3. INTENSITY vs TIME CURVE OF FLASHING INCANDESCENT SOURCE WITH GRAPHICAL SOLUTION OF THE BLONDEL-REY FACTOR

From the first form of the Blondel-Rey equation the advantage in effective intensity of the short flash is apparent. For a given expenditure of energy (It), particularly below the critical duration, the greatest effective intensity is obtained from the flash with high intensity and short duration. The xenon flashtube takes advantage of this effect, which is not the same as the Broca Sulzer Effect or enhancement.

3. Broca Sulzer Effect

The Broca Sulzer Effect occurs with single flashes (flash duration 0.03 to 0.1 sec), at supra threshold levels. The apparent brightness of a flashing light, shortly after the onset of the flash, is greater than that of a fixed light of the same intensity (Holmes, 1974). The Broca Sulzer Effect has been explained by suggesting that initial response of the eye overshoots the final equilibrium level. The effect has been confirmed to occur with white and colored light, in the periphery and the fovea, with different sized stimuli, monocularly and binocularly (Katz, 1964).

Enhancement is similar to the Broca Sulzer Effect, but applies to rapidly repeated flashes. Also the flashes must be viewed at a moderate to high illumination level. The apparent brightness of the flashes is greater than that of a steady light of the same maximum intensity.

4. Critical Duration and Bloch's Law

Much experimental work has been done on the critical duration effect. Critical duration is defined as the time period "during which the retinal image typically moves through an angle less than that of the separation between adjacent single central cones" (Graham, 1965). The movement of the image is due to the involuntary movements of the eye. This means that if two separate light flicks were presented during the critical duration period they would both impact on the same cone receptor and consequently, the illumination would be summed by the eye. The period or duration of this temporal summation by the eye is approximately 0.1 seconds. This is an average value obtained by comparing several experimental works referenced in Graham, 1965 and Cornsweet, 1970.

Critical duration is directly related to Bloch's Law which states that "For short flashes near the threshold, only the quantity of light (the product of luminance or flux and time) is effective" (Holmes, 1971). This says that for short flashes the effect on the eye will be a constant if the product of luminance (L) and time (t) equals a constant. Bloch's Law is applicable with increasing time, up to critical duration, beyond which a given effect is achieved with a given level of luminance (Figure 4).

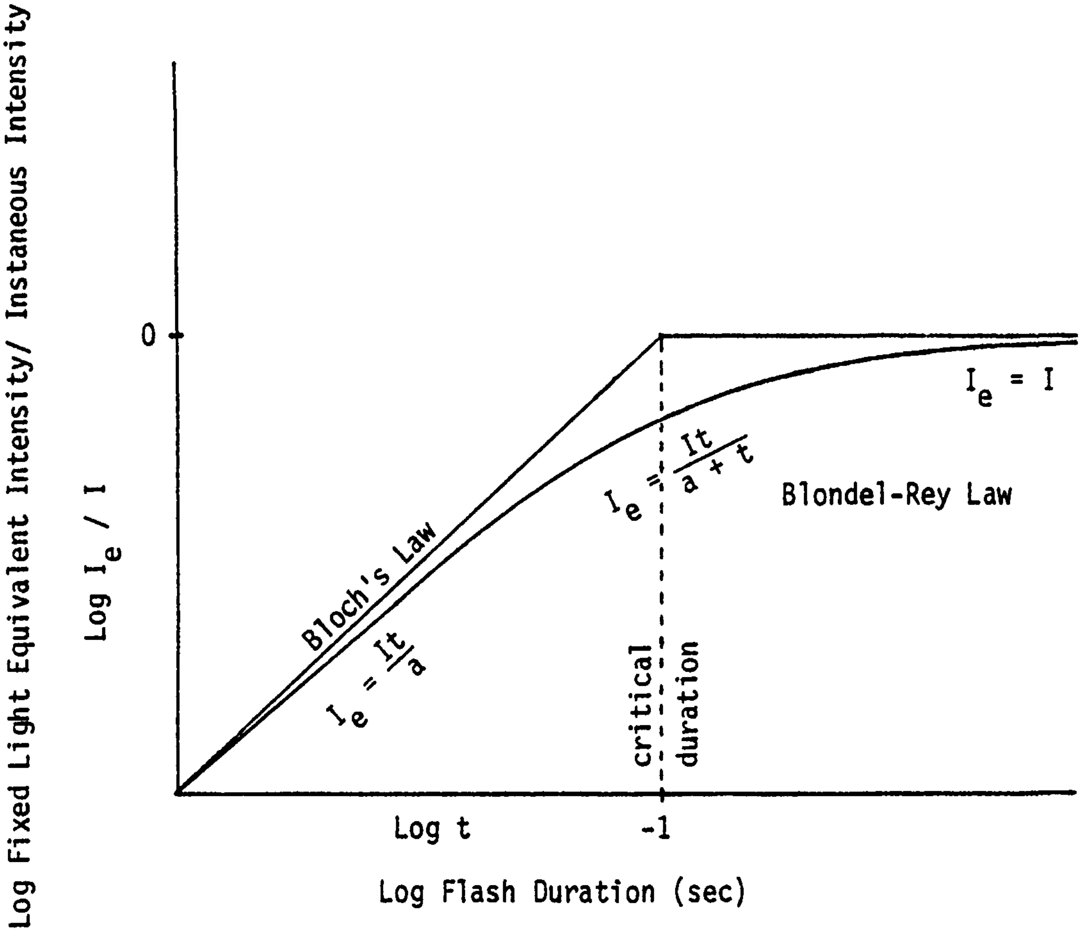

Figure 4. FACTORS AFFECTING APPARENT BRIGHTNESS OF A FLASH (SQUARE PULSE)

5. Flicker Fusion Frequency

Flicker fusion frequency (FFF) is another factor that has an important bearing on the use of a multiflick flashtube for an aids-to-navigation signal. FFF is the frequency at which separate pulses of light appear to be fused to the observer. This is also commonly called critical flicker frequency (CFF).

The frequency at which the signals fuse depends on several variables. A partial list of stimulus variables effecting CFF would include the contrast between the flicker stimulus and the surrounding area, the size of the stimulus, the color of the stimulus and the number of flashes presented. Characteristics of the observer such as age, visual acuity and state of dark adaptation also effect FFF. Additionally, there can be interactions between stimuli and observer's characteristics which have an effect on CFF. Graham presented work by Berger in 1953 on FFF in number of flashes per second. From this work it appears that for an aid-to-navigation viewed at a distance with no background illumination, FFF would be approximately 11.5-14 Hz. (Graham, 1965). This disregards any variations in the observers, and assumes it is for two flicks. Lindsley and Lansing in 1956 found that under conditions where CFF was 40 Hz. for a series of continuous flashes, in order for just two flashes to be seen as separate it was necessary to present them at a time interval corresponding to 14 Hz. This indicates that CFF is also dependent on time of exposure, and that the eye is more sensitive to temporal inhomogenieties for a series of flashes than for two flashes.

6. Light-Dark Ratio

Light-dark ratio (also called light-time fraction) also has an impact on flashing light theory. CFF was found to vary with the duration of exposure, which also is a change in light-dark ratio. Work by Williams and Allen (1971) dealt with thresholds as a function of pulse length and null period, or light-dark ratio. They used five null periods ranging from 0.025 sec to 3.20 sec and nine pulse lengths ranging from 0.01 sec to 1.60 sec. Only for their two longest null perids 0.40 sec and 3.2 sec did the Blondel-Rey constant approach the 1912 value of 0.21 sec.

E. DEPTH PERCEPTION REVIEW

Visual depth perception is an important function in navigating a ship through a channel, even with the radar in use. A great deal of navigation is done by "seaman's eye" with the captain, pilot, or conning officer making his own judgements of the time or distance to turn and the course to steer based on the positions of the buoys and other aids. If no depth information can be obtained from a buoy because its flick is too short, this compounds the mariner's problem of navigating the channel safely.

1. Depth Cues

Graham lists 9 cues that are used to determine depth. These are divided into the two catagories, monocular and binocular, summarized below:

1) Monocular Vision

   a. Relative size. An object of known size produces a retinal image whose size depends on its distance. We then perceive this object, a football for example, as either near or distant.

   b. Interposition. An overlapping object is perceived to be closer than the overlapped object.

   c. Linear perspective. A constant distance between points subtends a smaller and smaller angle as the points move away from the observer. A single row of telephone poles is a good example.

   d. Aerial perspective. The surface details of an object provide a clue to its distance. An absence of these details indicates the object is distant.

   e. Monocular movement parallax. As an observer moves his eyes with respect to his surroundings, a differential angular velocity will exist between the line of sight to a fixated object and any other object in the visible field. Near objects appear to move against the direction of movement, and distant objects move with the direction of movement, thus providing a depth cue.

   f. Light and shade. Different combinations of shadow and highlight are reported for objects lying at different distances.

   g. Accommodation. Accommodation (focusing) is only of consequence at distances of a few yards.

2) Binocular Vision

a. Convergence. As an object gets closer and closer the eyes are turned in a coordinated manner so that the lines of fixation converge on the object. Convergence is effective out to a distance of several yards.

b. Stereoscopic vision (stereopsis). When viewing an object in the surroundings the retinal image on the right eye is in a different position from the retinal image on the left eye. This retinal disparity is the basis for making spatial discriminations (Graham, 1965). Stereoscopic vision is effective to 135 meters (Haber, 1973).

A mariner in transitting a harbor or channel at night would use, principally, interposition, movement parallax, light (and shade), and stereoscopic vision to determine distances of navigational lights. All of these cues require fixation of the eye on the light signal.

2. Howard's Experiment

In 1919 Howard, who was concerned about real depth perception of naval aviators, devised an experiment to test depth perception. Howard's apparatus differed from other apparati then in use in that he measured real depth perception, providing only cues of stereoscopic vision and size. Other apparati utilized a stereoscope to present different images to each eye. Howard's apparatus, which is referred to as a Howard-Dolman Box, required that the observers view two objects in space and determine which was closer.

Howard's observers sat 6 meters in front of the box, which had an opening 12 cm high and 20 cm wide. Two vertical sticks, 1 cm in diameter and horizontally separated by 6 cm, were visible. One stick could be moved toward the observer, the other was fixed. The back of the box was flooded with white light so the sticks appeared dark. Howard then used the method of limits to determine the threshold angle of retinal disparity. He placed the movable stick at 0.5 cm increments of distance greater than or less than the fixed stick. By means of a shutter, he gave the observer a brief glance of the two sticks. The observers then reported which stick was nearer.

Howard's apparatus provided only two depth cues. These were stereoscopic vision and size. Howard (1919) determined by a monocular-binocular comparison that the size cue was 1/20 of the stereoscopic vision cue. Howard found a wide variation in the depth perception abilities of his subjects, who were mostly naval aviators.

F. STATEMENT OF THE PROBLEM

The flash provided by one flick of a xenon flashtube is typically about 100 μ seconds in duration. This duration is too short to permit the human eye to fixate on it. Although the flick is too short for fixation, it is produced for a given luminous range with about a 50% savings in energy over tne standard incandescent flash for this same range. So while the flashtube flick is more efficient to produce, it may not be as usable as the standard incandescent flash.

G. GOAL

The goal of this evaluation was to determine through laboratory experiment the flick rate and the number of flicks of a multi-flick xenon flashtube, with a 4 second duty cycle, which will provide depth perception comparable to that of a 0.4 second flash from an incandescent lamp, with a 4 second duty cycle.

1. Choice of a 4 Second Duty Cycle

The selection of a presently employed aid-to-navigation with which to compare the flashtube was relatively easy. An involved characteristic such as the Morse Alpha (- ---), would be difficult to reproduce in the flashtube controller. An equal interval characteristic (on and off times are equal) might get involved with some complex light-dark ratio relationships. The flashing 4 second incandescent is the most widely used aid-to-navigation signal the Coast Guard employs. Consequently, if flashtube use did appear feasible, sites for field testing would be numerous without changing the buoy's characteristic. Also, with the popularity of the 4 second duty cycle light, any possible small energy saving per unit might have a significant impact economically.

2. Choice of Flashtube Signal Selection

The flashtube signals selected were a single flick and three multi-flick bursts at 12 Hz. The latter three were 3 flicks (0.25 sec duration), 4 flicks (0.33 sec), and 5 flicks (0.42 sec). One flick was not an acceptable aids-to-navigation signal due to its short duration. While 5 flicks should have been acceptable because the duration approximates that of the acceptable incandescent source, the 3 and 4 flick signals were tested to help provide information as to the threshold time duration for fixation on a flashtube burst.

H. HYPOTHESES

Two sets of hypotheses were developed. The reason for two sets was that the duration of the signal that would allow adequate depth perception was not known. However, it was expected that the duration lay between 100 μ sec (1 flick) and 0.25 sec (3 flicks), or between 0.25 sec (3 flicks) and 0.33 sec (4 flicks). These suppositions were based largely on the fact that the 2.5 second duty cycle, 0.3 sec flash incandescent lamp is considered a satisfactory signal by the mariner. This gives some evidence that the fixation time for these light sources is less than 0.3 seconds.

In each set of hypotheses, the first hypothesis was to be tested first. If it was rejected, the second hypothesis, although the data may support it, was meaningless in attempting to determine the fixation time. In this case the second set should be considered. Likewise, with the second set, if the first was rejected, the second hypothesis, although it may be supported, was meaningless from the standpoint of this evaluation.

1. Set I
   a. Hypothesis--The mean positioning error value for the 1 flick signal is significantly greater than the mean error for the 3 flick signal.
   b. Hypothesis--The mean positioning error value for the 3 flick signal is not significantly different from the means of the errors for the 4 flick, 5 flick, and incandescent signal.
2. Set II
   a. Hypothesis--The mean positioning error value for the 3 flick signal is significantly greater than the mean from the 4 flick signal.
   b. Hypothesis--The mean positioning error value for the 4 flick signal is not significantly different from the means of the errors for the 5 flick and incandescent signal.

Figure 5 is a diagram of the expected paths the results might follow.

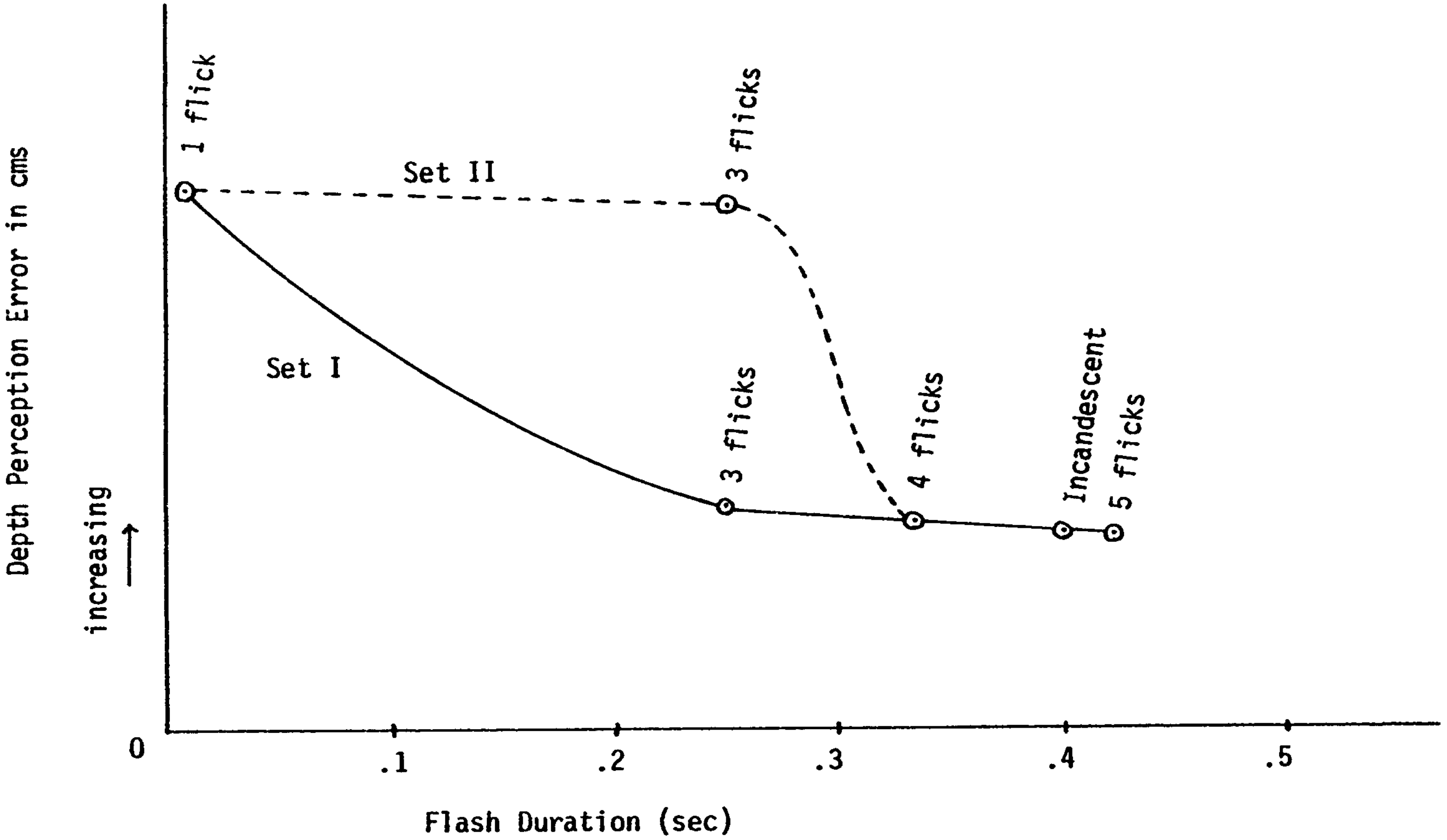

Figure 5. GRAPH OF EXPECTED RESULTS SHOWING THE TWO POSSIBLE DATA PATHS

II. METHODOLOGY

A. LAB EXPERIMENT VERSUS FIELD TEST--LIMITATIONS AND ASSUMPTIONS

Considerable thought was given to conducting a field test to judge the depth perception of an observer viewing various aids-to-navigation signals. However, field tests yielding quantitative results were deemed impractical due to the inability to control environmental factors such as sea state, ambient lighting, etc. A test range for taking suitable measurements would have been needed and additional funding and available operating units would also have been necessary. Additionally, Montonye and Clark (USCG, 1970) had already conducted a very thorough qualitative field study. Working flashtube buoys had been placed in several geographic locations and mariners' comments were solicited. The negative aspect of the short flash was documented and Montoyne and Clark concluded that one flick was too short for the eye to fixate on.

Qualitative results were necessary to determine at what time duration the mariner no longer would perceive the flick or burst as being too short. Such results were most easily obtainable in the lab. The depth information perceived in the lab was based solely on two cues, size and stereopsis, while in the real world situation the mariner has several usable depth cues. All of these cues require fixation on the object (light) to be effective and it was assumed that the use of different cues did not require different fixation times.

Different conditions in the surroundings do effect fixation time, as shown by White (1965). With a reference point, fixation time will be shorter than in the case where the light appears in a completely black background. Unless he is steaming out of a port and has a single buoy left between himself and open water, the mariner would normally have several references available. The worst case situation that could be modelled in the lab was this situation, with only one reference available. As described below under "Apparatus," the flashing light models the buoy while the lighted stick models a reference point that enables the observer's estimated line of sight to the buoy to be very close to where the buoy light would appear. The goal of this experiment was to measure the ability of an observer to match a stick position with a simulated buoy light. The absolute worst case of a single flash appearing against a totally black background would not be useful in the lab. Nothing could be co-located with the light source to provide measurements.

B. APPARATUS

The apparatus for the experiment consisted of a Howard-Dolman Box (used for measuring depth perception) with two signal sources. One source was a flashtube and controller and the other was a flashing incandescent lamp. Scaling and transmission of the light signals to a position where they could be viewed by the subjects was accomplished by filters and a fiber optic bundle.

1. The Howard-Dolman Box

The apparatus used to present the light signals to the observers was a Howard-Dolman Box. The box was 60 cm high, 40 cm wide, and 120 cm deep. The oox frame was 1" by 2" furring strips which were covered by black cloth and flat black poster board. A horizontal opening 12 cm high and 27 cm wide was centered and cut out of the front end of the box. The horizontal centerline of the opening was located 137 cm above the floor. The box was on a movable table which had shelves underneath the top surface. The opening could be covered and exposed by the testor with a horizontally mounted, left opening shutter (Figure 6).

Running perpendicular to the opening and 5 cm to the left of the center of the opening was an optical bench with three lens supports (optical bench riders) fastened together which acted as a sliding cart (Figure 7), after the bench was lubricated. A system of pullies and strings enabled an

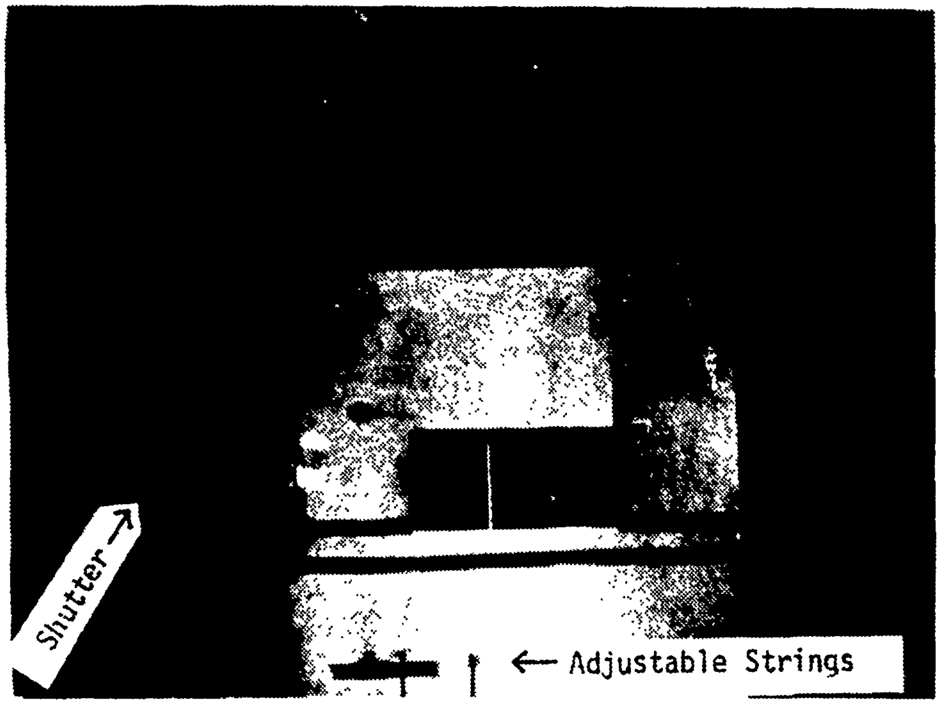

Figure 6. FRONT VIEW OF THE HOWARD-DOLMAN BOX

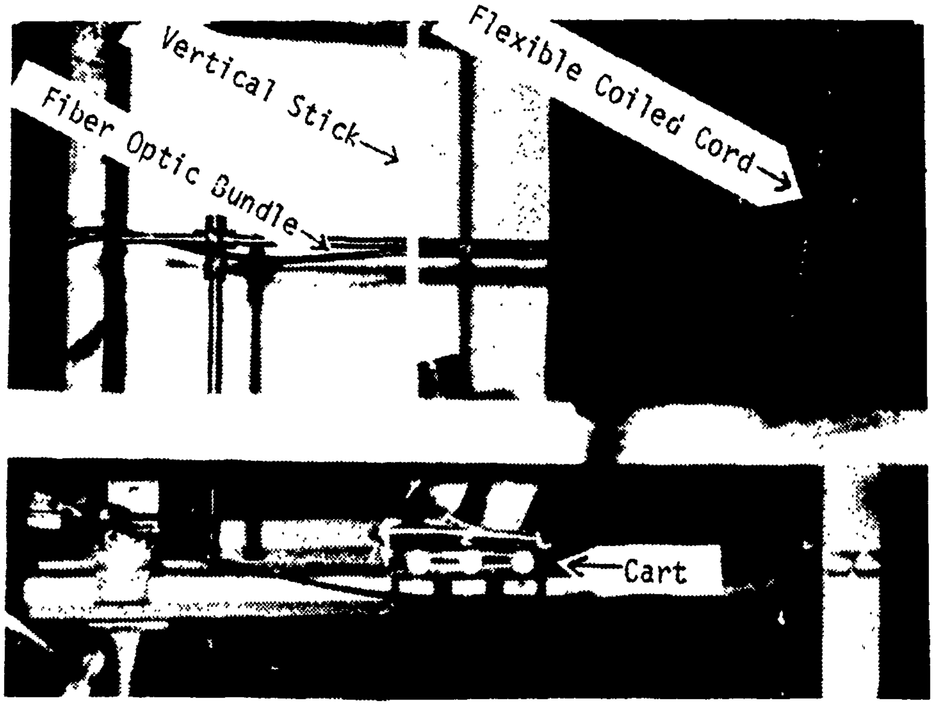

Figure 7. SIDE VIEW OF THE TRAVELING CART WITH ITS VERTICAL STICK IN FRONT OF THE FIBER OPTIC

observer in front of the box to move the cart. The lens support comprising the back end of the cart supported a one cm diameter hardwood dowl, 42 cm in length, positioned vertically. Only the center 1/3 of this stick was visible to the observer. The pointer on its lens support was used to take readings to the nearest 0.1 cm from the horizontal scale on the side of the optical bench. The cart's range of travel on the optical bench was 70 cm. The two front supports of the cart held the flashlight that illuminated the stick. The flashlight was wired to a DC power source through a flexible microphone cord terminating at the top edge of the box, and spliced to 20 gauge wire leading to the power source. The flexible microphone cord was not visible to the observer.

Training with the Dolman Box for the tasks was found to be essential as will be discussed in "Subjects" later in this chapter. During the training session two sticks were used. The second stick was identical to the first, but was stationary, and they were placed 14 cm apart. A similar light operated by the second channel on the power source illuminated the second stick. Therefore, using the DC power source, constant nearly equal luminance of the stick(s) was maintained at a value of 1-2 millilamberts (mL). In 1948, Mueller and Lloyd demonstrated that the threshold angle for stereopsis decreased as illumination of the objects being viewed increased. Threshold angle becomes a minimum and then levels out at luminance levels of one millilambert, and greater (Graham, 1965). Therefore, keeping the luminance levels greater than one millilambert assisted the subjects in making more accurate depth measurements.

2. The Signal Sources

The flashtube signal controller (Figure 8) was located on the shelves under the table directly in front of the tester who was seated on a stool. Also on the shelves were: a frequency counter, the DC power source for the flashlights, and the DC power source for the incandescent lamp. The flashtube itself, along with the incandescent lamp was mounted on the back of the table. The flashtube was placed in a cylinder which was closed at both ends. The incandescent lamp was mounted in a 6 place lampchanger on top of the solid state flasher and was located in the base of a 155 mm navigational lantern. Both sources and the shelf area were covered with black cloth, and the flashtube container was also covered with acoustical packing to prevent the observer from "hearing" the flicks.

A 3.2 mm diameter, 120 cm length fiber optic bundle was used to transmit the signals into the box. When the flashtube signal was used, the pick-up end of the fiber optic was placed through a hole in the surrounding cylinder. The fiber optic bundle was passed through the side of the cylinder and positioned in the center of the reflective shield approximately 3 cm from the flashtube envelope. For the incandescent source the fiber optic bundle was located 1.5 cm from the bulb in line with the vertical filiment. The fiber optic then transmitted the signal up and into the back of the box where the fiber optic was attached to a horizontal rod. The rod was mounted on a stand and extended into the box in the direction of the observer at his eye height. An artifical pupil of 1.44 mm diameter was placed over the finished end of the fiber optic (Figure 9). This diameter subtended an arc of 1.0 min at the observer's position and was, therefore, equivalent to a point source (Kisto, 1969).

The horizontal rod could be adjusted front and back in the box for a distance of about 15 cm. Therefore, the light source was not always in the same position in space. It could be moved along the observer's line of sight.

3. Room Layout

The observer was seated on a stool at a desk, 5.0 meters from the center position of the pupil on the fiber optic. This distance minimized the cues of accommodation and convergence and still provided good visual acuity of the stick. The observer placed his head in a set of blinders that permitted approximately +/- 30 degrees of vertical viewing and +/- 20 degrees of horizontal viewing, while

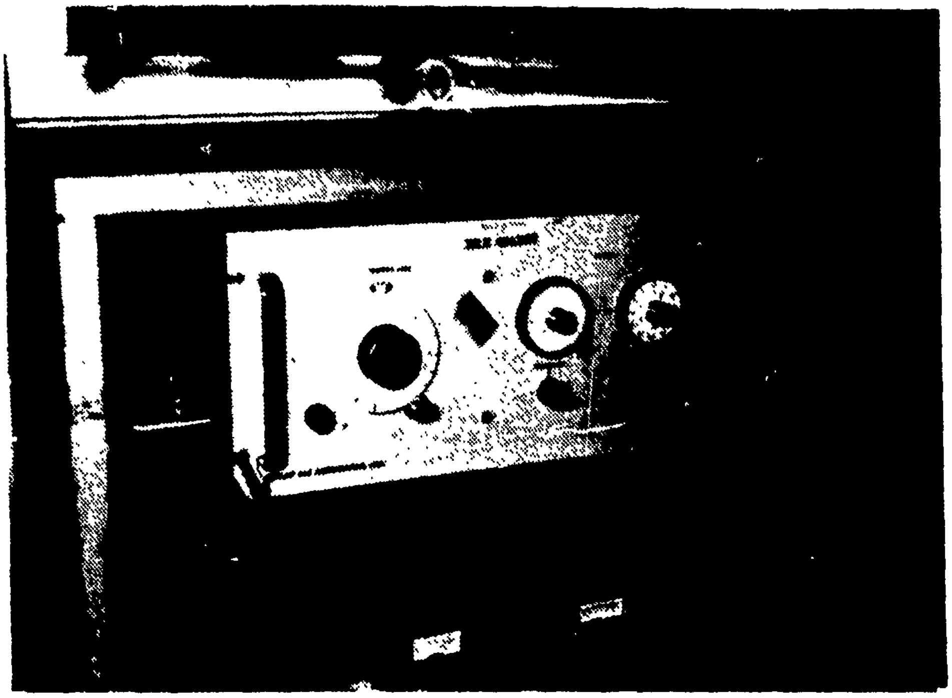

Figure 8. THE FLASHTUBE CONTROLLER ON THE SHELF UNDER THE TABLE

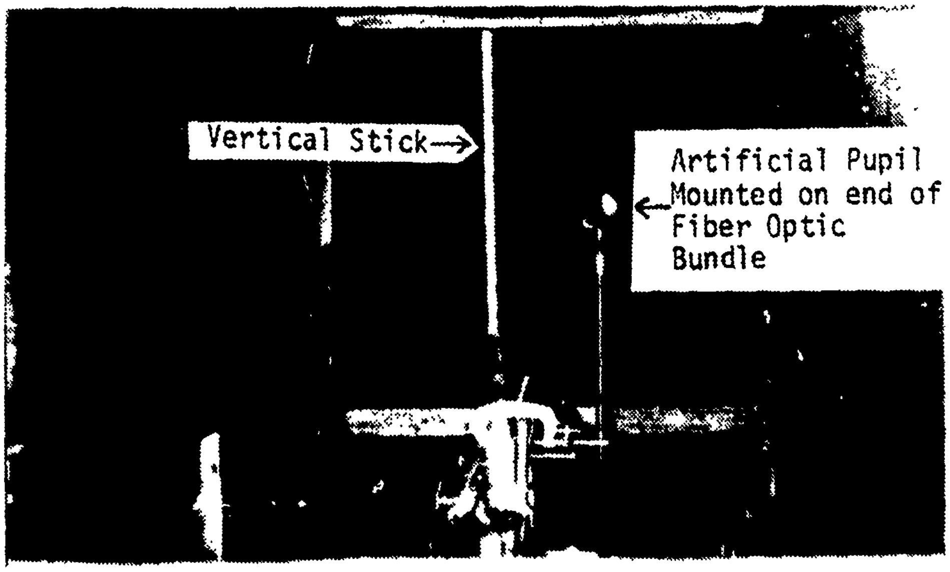

Figure 9. OBSERVER'S VIEW OF THE MOVABLE STICK AND FIBER OPTIC, WITH THE OCCLUDING MATERIAL REMOVED FOR ILLUSTRATIVE PURPOSES

positioning his line of sight at approximately 137 cm, the height of the fiber optic above the floor. Some variation was possible from this position depending on the observer's seat to eye height distance. The blinders were raised and lowered several cm to accommodate this dimension. This still permitted the light source to be viewed in the horizontal center of the opening.

Located 80 cm in front of the observer, at an angle of depression of 20 degrees to his line of sight to the box opening, was a red lighted 8 1/2" by 11" piece of off-white paper (Figure 10). This paper provided an average luminance level of 0.8 - 1.0 foot-lamberts (fL), which was within the requirements of MIL-STD 1472B (1974). This DOD standard states that red floodlighted navigational bridge luminance for chart reading should not exceed 1.0 fL. In addition to simulating a chart being illuminated by the mariner, this luminance served another purpose. It prevented any observer from getting totally dark adapted and maintained all observers at a given state of dark adaptation.

4. The Flashtube Source

The flashtube signals were produced by a unit called the Hi-Con for "high conspicuity." It was built for the Coast Guard about 12 years ago by Dunlap and Associates from General Radio components. The principal components are a timer, oscillator, and the xenon flashtube. The flashtube

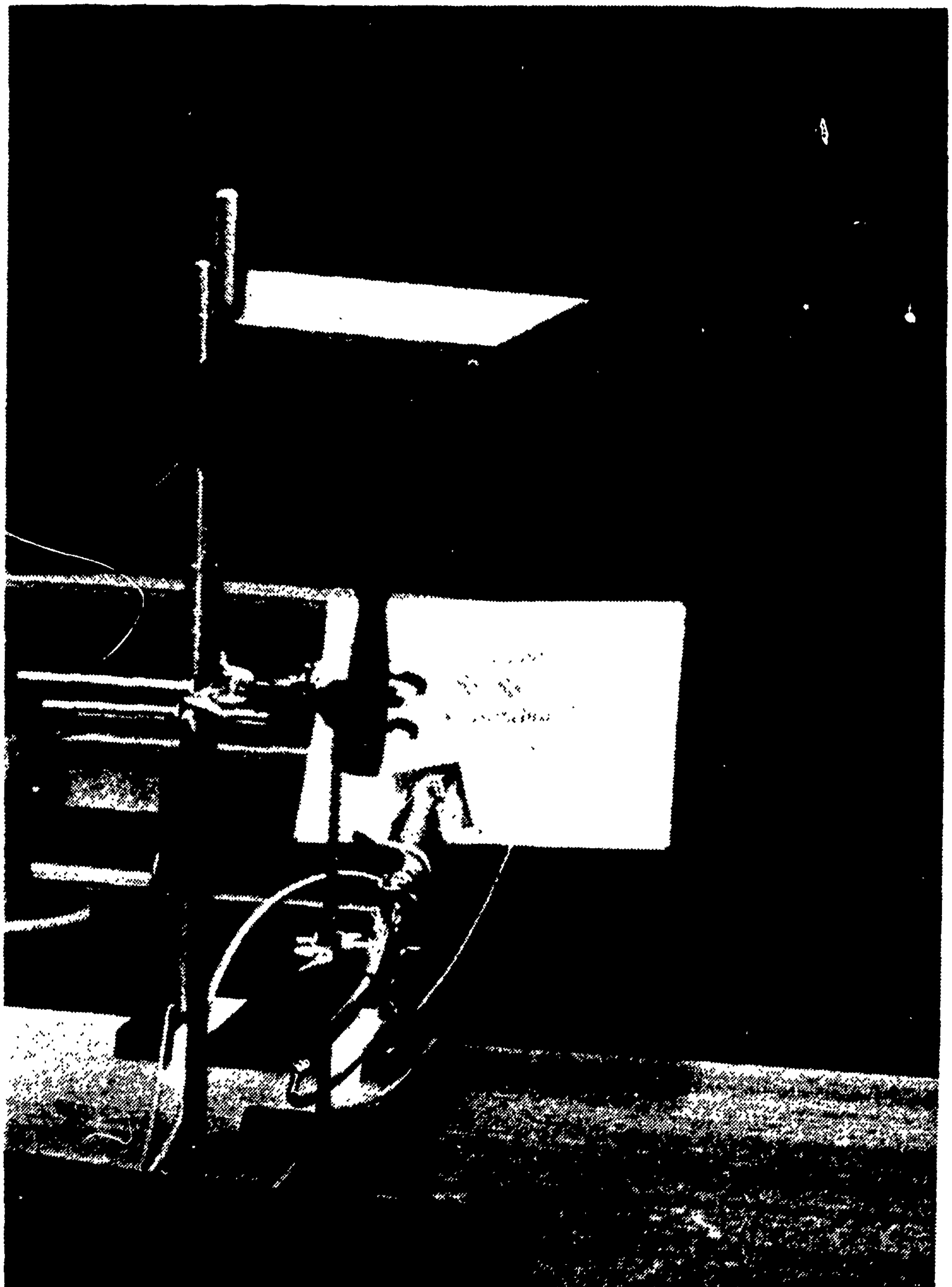

Figure 10. TEST APPARATI AS VIEWED FROM BEHIND THE THE SUBJECT'S TEST POSITION

itself was a General Radio Stroboslave stroboscopic light source capable of 25,000 flashes per minute. The Hi-Con in its present condition could produce continuous flicks up to a frequency of at least 100 Hz. Additionally, its light-dark ratio could be controlled from 0.1 sec to 10 sec for both the pulse and the eclipse time. Finally, a burst of a given number of flicks (1,2,3,4,5,8,9,16,17...) could be obtained at a given frequency while the eclipse time was controlled at 4.0 sec. It was in this final mode of operation that the tests were made.

5. The Incandescent Source

The incandescent source was the standard Coast Guard incandescent buoy signal flashing every 4.0 sec with a 0.4 sec flash duration. The signal was controlled by a CG-181 solid state flasher which provided the 4 second duty cycle and the 0.4 sec contact closure time. The signal, powered by a 12V DC power source, was produced by a 0.25 amp 12V lamp with a 6.0 mm vertical tungsten filament. The color temperature of the lamp approximated 2700 degrees K. The intensity versus time curve of the flashing lamp is shown in Figure 3 in Chapter I, as well as the graphical calculation of its Blondel-Rey factor.

6. Calibration and Scaling of the Light Sources

The method selected to determine whether or not a flashtube would make a suitable aid-to-navigation was to compare it to that of a signal of a presently employed navigational aid, as discussed in Chapter I. The incandescent aid selected had a 4 second duty cycle so the flashtube signal was adjusted to match it. Every aid has a luminous range at which it has some probability of detection and it was necessary to match the luminous range of the flashtube to that of the incandescent source. Otherwise the comparison would not be valid. The perceptual effect of the flashtube might be very different if it modelled an 8 mile buoy while the incandescent source modelled a 3 mile buoy.

Scaling the light sources so that both sources had equal luminous ranges was facilitated by several assumptions.

1. The transmissivity of the atmosphere was assumed to be 1.
2. Critical duration was not considered. Only the single flick flashtube signal and not a multi-flick was considered.
3. No attempt was made to make any calculation for enhancement.
4. The only attenuation to the signal was provided by the $1/D^2$ spreading.

The goal of the scaling was to have the observer receive equal "photopic energy" from both sources.

The scaling was achieved by using a photometer with a silicon sensor and an integration time of approximately 100 milliseconds. The photometer also had a band pass filter approximating the CIE photopic curve. The photometer itself was more suited for practical engineering work than lab work. Full details of scaling are contained in Appendix B.

Illumination (E) measurements were made at a distance of 1 foot from the end of the fiber optic. The flashtube source was measured with the signal operating continuously at 100 Hz. This measurement was an average illumination (E_a) value because of the time constant of the photometer. It was converted to average intensity (I_a). An intensity scale for the I vs t curve was then developed using graphical methods. Assuming that the shape of the I vs t curve remains constant at any distance (T=1), and using the Blondel-Rey Law, the fixed light equivalent intensity was then calculated at threshold using E = 0.2 μ lux. The integration to obtain I_e was performed over the entire duration of the flash and the value of I (when it was less than I_e) was neglected (Bates, 1971).

With the photometer placed 1 foot from the incandescent source burning steadily, neutral filters (NF) were placed immediately in front of the source until the correct value of I_e was reached. Thus the incandescent source, when energized continuously and filtered, had the equivalent fixed light intensity for the flashtube. When the flashing incandescent source was utilized for testing, a .62 NF was removed from the set of filters to approximate the I for a flashing incandescent lamp. The Blondel-Rey factor for a flashing 4 sec, 0.4 sec flash, 12 volt, 0.25 amp, lamp is approximately .63 (USCG, 1972). Graphical calculation of this value using the photographed I vs t curve resulted in a factor of .66 (Figure 3). Thus the incandescent lamp burning steadily was the equivalent fixed intensity for both sources, and the luminous distances should be equal.

Due to enhancement, and the advantage gained by the short flash (Chapter I), the flashtube should appear brighter if both sources have equal luminous distances. Indeed, all observers did report that the flashtube appeared brighter.

The observer's distance of 5.0 m represents a particular range for each luminous range (Table I).

Table I. LUMINOUS BUOY RANGE AND CORRESPONDING OBSERVER DISTANCE

Luminous Range of the Aid-to-Navigation	Observer's Scaled Distance
4 nmi	900 yds or 0.45 nmi
5 nmi	1100 yds or 0.55 nmi
7 nmi	1550 yds or 0.78 nmi

C. PILOT STUDY

1. Subjects

In order to determine the frequency at which to present flashtube signals, a pilot study was conducted using three subjects. Subjects were trained and qualified in a manner similar to that used for the experiment. Four different flashing signals were presented to each subject. For each signal the subject was required to place the illuminated stick and the point source signal being emitted from the fiber optic side by side. Ten matches were made with each signal.

2. Signal Selection

The signals used were the 0.4 second flash incandescent lamp with a 4 second duty cycle and three flashtube signals. The flashtube signals were selected on two bases:

1. The relationship of the frequency to CFF.
2. The desire to provide a signal of similar duration to the incandescent signal.

With a point source of light and a contrast with the surrounding area approaching zero. CFF was determined by Berger to be 12 Hz (Graham, p. 257, 1965). Based on these criteria, three flashtube signals were selected. The 7 Hz, 3 flick signal of 0.43 sec duration was below CFF. The 12 Hz, 5 flick signal of 0.42 sec duration was at CFF, and the 19 Hz, 8 flick signal of 0.42 sec duration was above CFF.

3. Signal Separation

The horizontal distance separating the signals was also considered during the pilot study. It was desired that the entire experiment by a foveal task. Initially the two sources (stick and light) were separated by 24.0 cm or 2.7 degrees at the observer's position. This should have been a marginally foveal task. The source separation was then reduced to 14.5 cm or 1.7 degrees to the observer. All three observers indicated that the task of putting the signals side by side seemed much easier with the closer separation. Matsubayashi's work in 1937 (Graham, 1965) pointed this out in a more quantitative manner. Therefore, a signal separation that was as small as mechanically possible without allowing the stick illumination to illuminate the fiber optic and rod was selected--10.5 cm or 1.2 degrees, at the observer's position.

4. The Pilot Experiment

Each subject upon entering the lab went through a 20-30 minute training session with the two illuminated sticks. The fiber optic bundle was then substituted for the second stick. Each subject was then required to place the movable stick side by side with the flashing light from his position. He was given ten trials with each of the three flashtube signals and the one incandescent signal. The light signals were presented in a randomized order with the ten trials being performed with each signal prior to the presentation of the next signal. Positioning error for each trial was recorded and a mean positioning error value and standard deviation was determined for each light source and each subject.

5. Results and Conclusions of the Pilot Study

After the testing the results were analyzed on the basis of mean positioning error and standard deviation. The results from observer #2 were discounted due to his demonstrated poor depth perception on previous tests and his minimized variability of performance regardless of the light source presented. It can be seen from Table II that 5 flicks at 12 Hz every 4 seconds provides depth perception that appears to be better than that of the incandescent source for this small population. Based on these data, 12 Hz was selected as the frequency for further testing.

Table II. RANKING OF THE SIGNALS* USED IN THE PILOT STUDY

	Observer			
	#1		#3	
Signal	$\bar{X}$	σ	$\bar{X}$	σ
Incandescent	4	4	2	3
7 Hz, 3 flicks	3	3	4	4
12 Hz, 5 flicks	1	2	1	1
19 Hz, 8 flicks	2	1	3	2

*Signal rank was determined by the distance the sample mean was from a correct match, and the magnitude of the standard deviation; lower values indicate closer matches.

D. SUBJECTS

All subjects were volunteers between the ages of 28 and 37. Nine were Navy or Coast Guard male officers and one was an adult female. Three subjects were considered lab experienced based on their participation in the earlier pilot study.

Although difficult to quantify, motivation was believed to be a very important factor in performance. As with any group of volunteers, some seemed more interested in the experiment than others. All, except two, were selected on the basis that they had had real world exposure to flashing marine aids, or to flashtubes as aircraft collision avoidance signals. The other two were a Navy Flight Officer (non-pilot), and the adult female. At least one volunteer was motivated by the fact that he had heard that a peer had been unable to match the stick and the lights.

All subjects were initially screened on a Bausch-Lomb Master Ortho-Rater. They were given test F-3 for distant visual acuity and test F-6 for depth perception. All scored 20/30 distant visual acuity or better, and the average was 7.5 out of 9 correct on the depth perception test. Two subjects, one who scored 8 out of 9 and the other 9 out of 9 on the depth perception test, were disqualified because of their inability to match signals in the Dolman Box while the female subject, who scored 4 out of 9 on the same test, was a satisfactory performer on the experiment.

All subjects were given verbal or taped instructions for each training and testing session. Instructions are contained in Appendix C. Training for the subjects was considered very necessary. Langlands in his work on measuring retinal disparity stated, "I have no doubt that with improved apparatus and greater practice finer binocular acuities could be reached" (Graham, 1965). Initial training, similar to Howards, was with two sticks of nearly equal luminance. The observers were coached in placing the sticks side by side. Once the sticks could be placed side by side the observers were coached on placing the stick at equidistance with a non-point source (8.0 minutes of arc) light burning steadily. Both of these coaching or training sessions lasted 5 to 10 minutes depending on the observer.

Matching the stick to the steady, non-point source light was then used as a qualifying test. Ten depth matches were made. With no performance guidelines to follow, three factors were considered in this qualifying test:

1. The distance the mean position of the stick was in front or behind the position of the light.
2. The standard deviation of the stick positions.
3. The sujects comments on how he was performing the task.

A goal of a mean stick position value of +/- 6.0 cm in relation to the light was initially established as a criterium for continuing the tests. However, due to the different luminances of the light and stick, values greater than that were accepted if the standard deviation of the readings was less than 8 cm. Two subjects who were considered marginal were allowed to continue and then disqualified because of their inability to match the signals in the test. An observer who stated that he was only watching the stick and was returning it to its center position, was disqualified.

E. EXPERIMENTAL DESIGN

Three independent variables were incorporated in the experimental design.

1. Signal type: a xenon flashtube and an incandescent lamp were used.
2. Number of flicks per flashtube burst: 1, 3, 4 and 5 flicks were presented (can be considered as flash duration).
3. Starting position: the movable stick was started in different positions relative to the light source.

The dependent variable of the experiment was depth perception. Depth perception was measured in cm in front of (+), or behind (-), the fixed position of the light source.

The ten qualified subjects viewed each of the 5 different flashing signals in a sequence determined by a 5 x 5 Latin square. No attempt was made to assign certain subjects a particular signal sequence. The starting position of the stick was also randomized with 15 different starting postions selected. Different random starting positions were drawn for each signal, but not for each subject.

Assuming that a 5 mile buoy had been modelled, the observer's station corresponds to a distance of .55 nmi. This is a reasonable situation. If the mariner is travelling at 15 knots and has a buoy .55 nmi ahead, he will pass that buoy in 2.2 minutes. Therefore, he should be making some judgements about the buoy distance in anticipation of turning or adjusting course when it is abeam.

F. TESTING PROCEDURE

Several iterations of a testing sequence were considered and tried before a final form was arrived at. The amount of training, the number of sources, the number of trials with each source, and the number of sessions per subject all underwent revisions. Figure 11 is a nominal time-line diagram depicting the final testing sequence.

All testing sessions were held in the evening in the optics laboratory after sunset, to minimize ambient light in the laboratory. The optical lab did have room darkening shades, but the windows which they covered faced west, precluding afternoon and evening testing. When the subject entered the lab, he was shown the Howard-Dolman Box and the string and pulley arrangement for controlling the movable stick. He was also shown both the fixed position stick and the signal presentation end of the fiber optic and the point

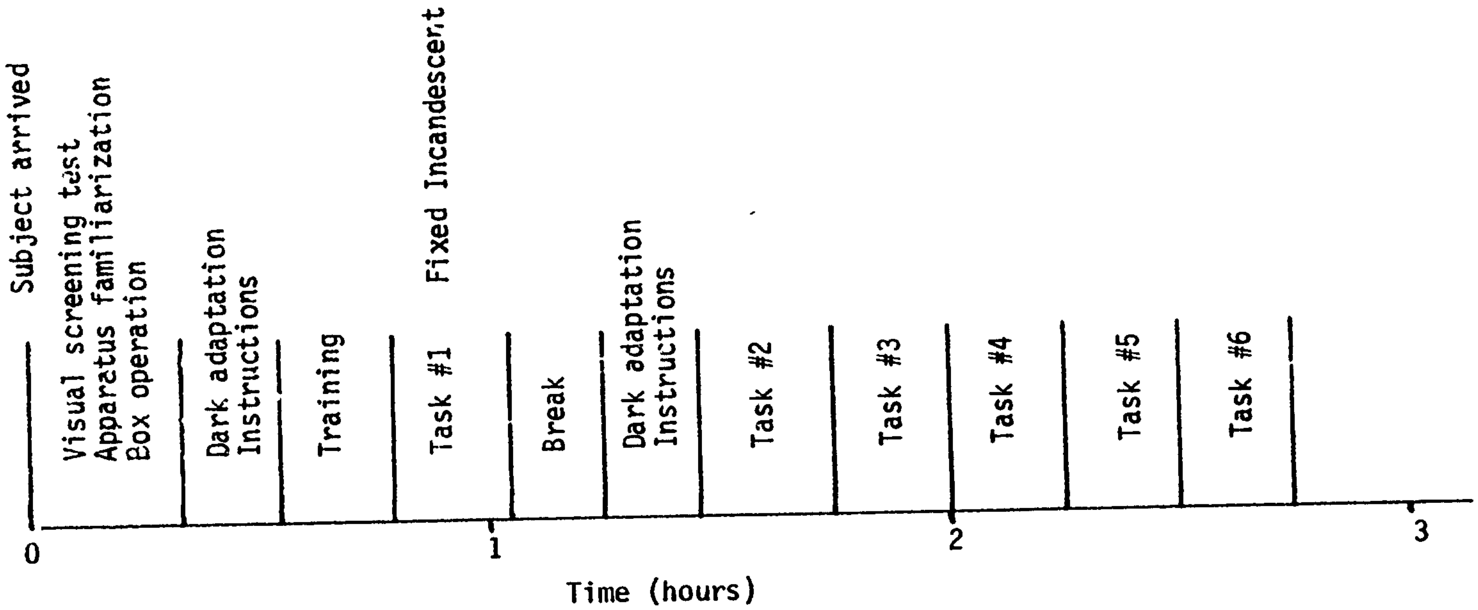

Figure 11. TIME-LINE DIAGRAM OF TESTING PROCEDURE

from which the light sources would emminate. Illumination in the lab was then reduced to a level of about 5 fc and the subject was tested on the Bausch-Lomb Master Ortho-Rater. The results of the distant visual acuity test and the depth perception test were discussed with the subject. No subject was disqualified at this point. All lights were then secured and the observer took his position on the stool 5 meters from the center of the box. Ambient lighting in the vicinity of the box at this point was about 0.0010 fc. The simulated chart lighting was then energized, the two sticks illuminated, and the subject was encouraged to move the stick and get the feel of the apparatus. When that was accomplished, he was instructed (Appendix C) on matching the positions of the two sticks. He matched their positions 10-12 times and was given feedback concerning his error. He was also shown the correct alignment. When he felt comfortable with the task, he was asked to make three matches with no immediate feedback, within the one minute time limit imposed on each match. Upon completion, these results were discussed with the observer.

The method of adjustment (Woodworth and Schlosberg, 1954) using the string and pulley arrangement was used for all trials. This method, unlike those that force single judgements, permitted the subject to move the cart up and down the scale at will. He was free to make as many readjustments as he wished within the one minute time limit. When the subject indicated that he had placed the two sticks side by side, or the one minute had elapsed, the position of the cart (movable stick) was recorded. It was compared with the position of the light or the second stick, whichever was being used, and the positioning error in centimeters was determined.

The second stick was then removed from the box and the non-point source light was swung into place on the end of the fiber optic. Again the observer was coached for about 8-10 matches, and provided with his results. He was then asked through written instructions to make 10 matches, with no assistance, as a qualifying test. These results were recorded and not discussed with the observer, other than to indicate the approximate absolute value of his error and whether or not he would be allowed to continue. Two observers were disqualified at this point. The subject then took a ten minute break while signals were changed.

After the break the room lights were secured, except for the simulated chart lighting, and a 12 minute period of dark adaptation began. During this period the instructions for matching the stick to the flashing light signals were read to the subject. Testing with the first flashing light source then began immediately after the 12 minute period.

The subject was asked to match the stick with each of the 5 signals 10 times. The events occurred in the following order:

1. The cart and stick were positioned at the randomized starting point for that trial.
2. The shutter was opened and the observer was told to "put the stick and the flashing light side by side."
3. The observer adjusted the strings until he was satisfied with the side by side positioning. He indicated that the sources were matched.
4. The shutter was closed, the position reading was taken and recorded, and the sequence was started again.

The observer was given 1 minute to make each match and a 15 second warning prior to the end of this time. After matching each source 10 times his comments were solicited concerning his method for accomplishing the task, the visibility of the lights, and the characteristics of the lights.

After presentation of some sources, the testor randomly moved the end of the fiber optic to eliminate any cues that the subject might have accumulated as to its position. Such displacements were 4-8 cm toward or away from the observer. The new position of the light source was measured using a carpenter's square on the optical bench, and was recorded in the data as the light position.

G. DATA ANALYSIS

The ten trials for each of the five sources were averaged. The mean value was then compared to the light position and the depth perception error was determined and assigned a plus value (in front of the light source) or a minus value if it was behind the light source. This value was $\bar{x}$, and was determined to the nearest 0.1 cm. A standard deviation was also determined. Absolute mean error was used in all subsequent calculations except the reliability tests.

1. Grouping the Subjects

An attempt was made to group the ten subjects using different criteria, particularly background and experience. Three subjects could be identified as having recent navigational experience. One had just reported to the Naval Postgraduate School from an assignment as executive officer on a buoy tender. The other two had reported to the school from earlier at-sea tours, but had kept involved in sailing and recreational boating. No other subjects had recent real world experience in viewing and using lighted aids to navigation.

Other groupings of the subjects were considered. Subjects #2 and #6 were both pilots, while subjects #9 and #10 had both participated in the pilot study and, therefore, had lab experience. Both of these groups were too small to provide any significant data.

2. Statistical Testing Performed

An analyis of variance using repeated measures was performed on the data. Since this evaluation was the first of its kind, the 0.10 alpha level was selected. The subjects were grouped by recent navigational experience (n=3), and no recent navigational experience (n=7).

A set of planned comparisons between the sources were also done. The comparisons considered were the mean values of positioning error for the signals as follows:

1. 1 flick > 3 flicks, 4, 5, Incandescent, and Fixed
2. 3 flicks > 4, 5, I, Fixed
3. 4 flicks > 5, I, Fixed
4. 5 flicks > I, Fixed
5. Incandescent > Fixed

These comparisons were tested for significance at the .10 level.

An F test for variability (alpha = 0.10) was also performed. Correlations between test conditions were also obtained and split-half reliability was determined.

III. RESULTS AND DISCUSSION

A. DESCRIPTIVE ANALYSIS

A mean positioning error value ($\bar{x}$) and a standard deviation were determined for each source, for each subject. Table III contains these values, while Figure 12 provides a graphical presentation of both the mean and the standard deviations. It is apparent from this graph alone that there may be no significant differences in the light sources.

The results of the separation of the ten subjects into two groups, one with recent practical experience (n=3), and the group without recent practical experience (n=7) are depicted graphically in Figures 13 and 14. Comparing the two figures it appears that the group with recent experience (subjects #1, 5, and 9) performed differently than the other group. Their position errors were smaller with the longer duration sources, and their standard deviations were smaller than those of the other group, except under the 1 flick signal condition.

B. STATISTICAL TESTING

A two way analysis of variance (ANOVA) was used to test for differences among the mean position error for the light signals. The subjects were grouped into their two

Table III. MEAN POSITION ERROR AND STANDARD DEVIATION IN cm FOR ALL SUBJECTS UNDER ALL CONDITIONS

Subjects	SIGNALS											
	Flashtube Flicks								Incandescent			
	1		3		4		5		Flashing		Fixed	
	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ
#1	-21.4	7.67	-6.2	5.27	-9.1	6.16	-9.2	4.62	1.4	5.36	-3.5	1.93
#2	-1.2	4.74	0.6	2.99	-8.0	3.69	-6.4	3.81	-1.1	6.33	-1.0	2.49
#3	0.9	9.12	-10.4	8.94	-8.1	6.50	-7.0	4.87	3.1	6.31	-16.8	3.62
#4	-4.7	5.97	-5.8	2.94	-6.1	3.77	-3.7	5.29	-4.2	4.22	-2.5	2.70
#5	-6.7	11.93	-7.6	11.33	-11.3	5.61	-9.8	4.55	3.5	5.59	-7.6	3.81
#6	-4.7	9.02	-7.4	14.58	16.0	10.14	-3.5	11.30	-0.6	12.23	-5.9	3.08
#7	-8.3	8.08	-0.8	8.73	-3.5	10.39	-21.0	7.19	-21.0	10.71	-12.0	7.96
#8	-21.6	5.30	-15.8	5.32	-17.8	4.42	-21.7	5.47	-13.2	4.41	-2.9	2.04
#9	-3.6	6.77	-3.0	4.71	-4.6	4.92	-5.1	5.04	-5.0	3.84	-5.4	2.16
#10	-16.1	8.55	-14.3	7.21	-10.0	6.45	-10.3	9.52	-10.8	7.57	-7.8	3.94
Overall	*8.6	7.97	7.1	8.03	9.5	6.60	9.7	6.58	6.5	7.16	6.5	3.77

*Overall values are absolute.

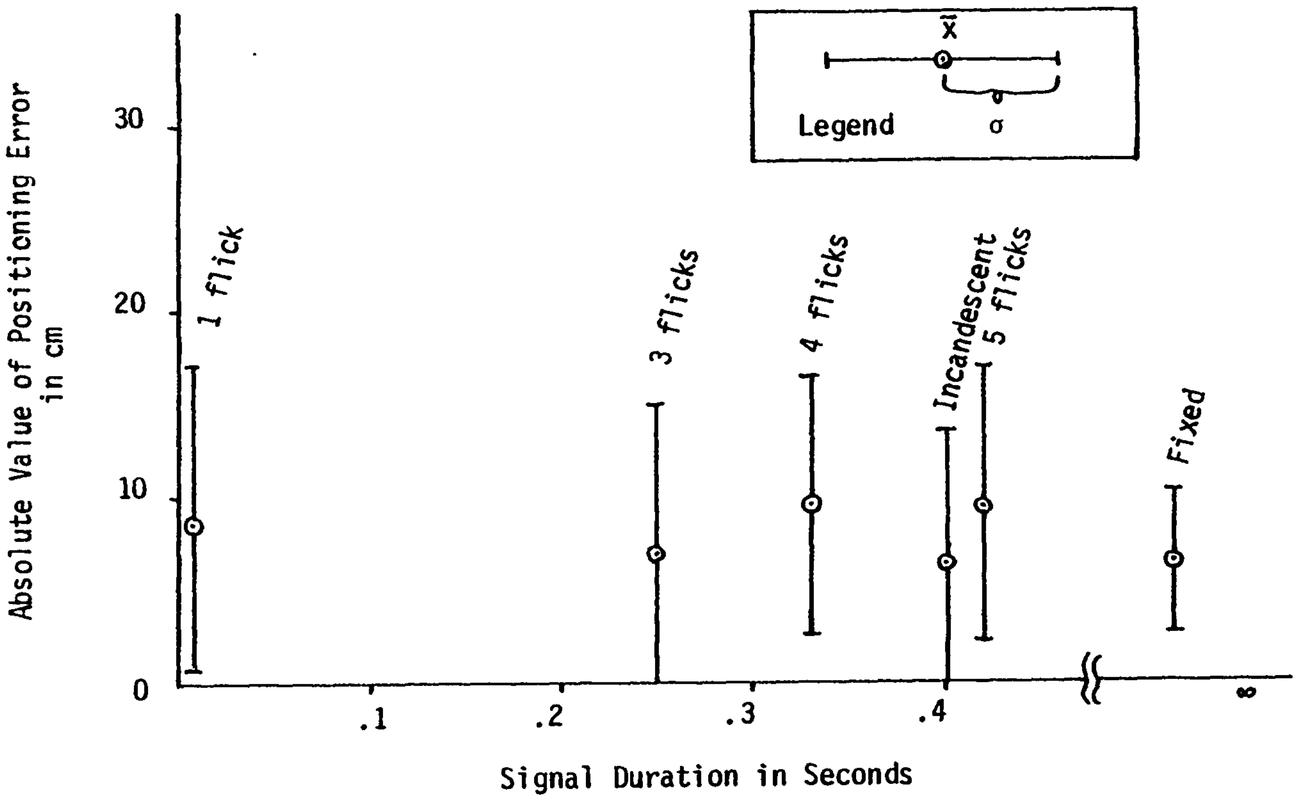

Figure 12. POSITIONING ERROR vs SIGNAL DURATION BY SIGNAL CONDITION FOR ALL SUBJECTS (n=10)

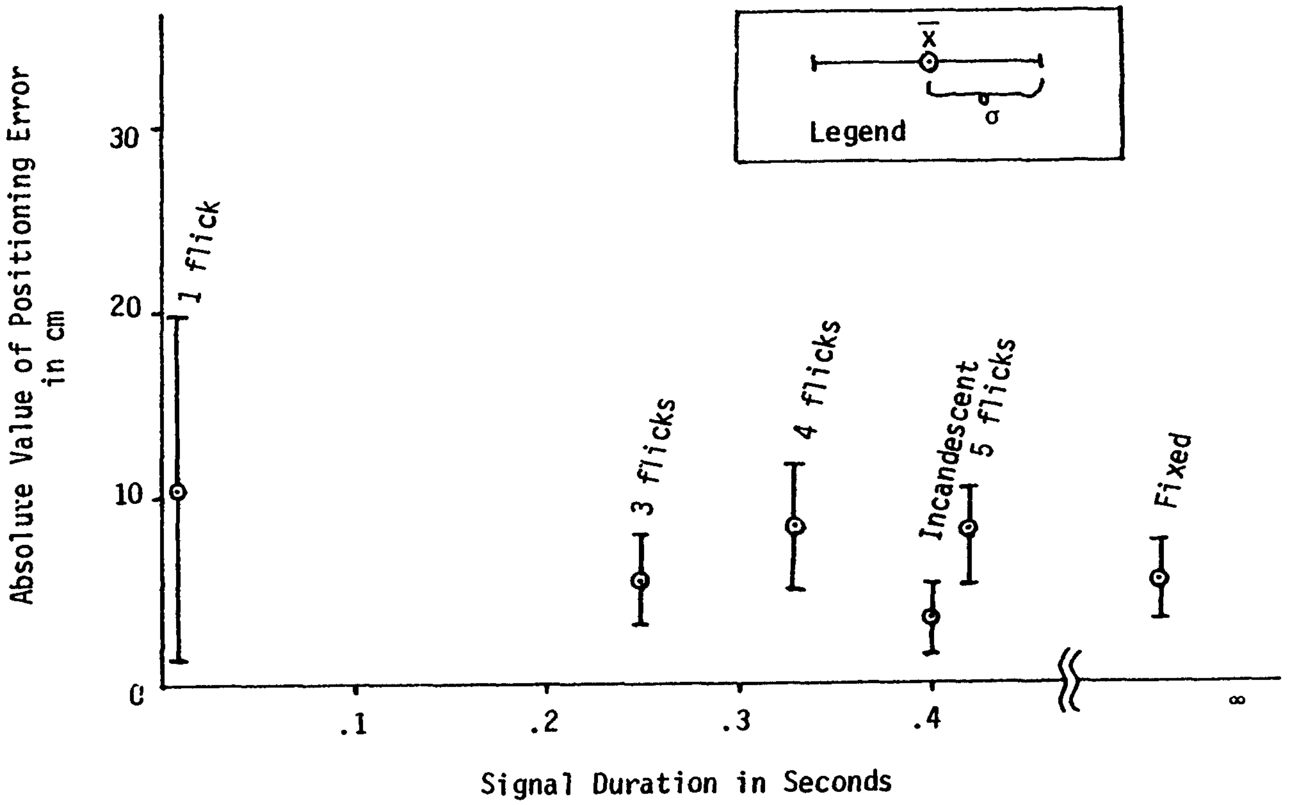

Figure 13. POSITIONING ERROR vs SIGNAL DURATION BY SIGNAL CONDITION FOR SUBJECTS WITH RECENT NAVIGATIONAL EXPERIENCE (n=3)

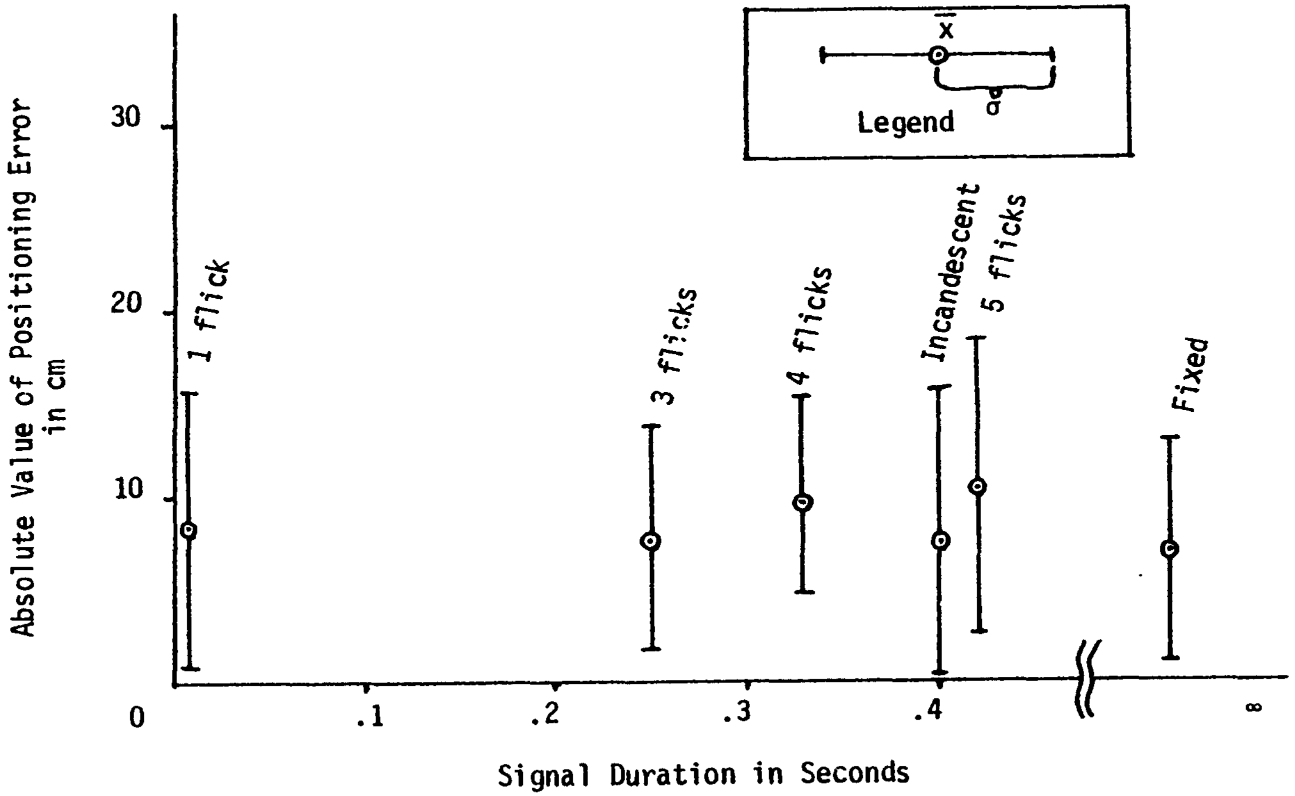

Figure 14. POSITIONING ERROR vs SIGNAL DURATION BY SIGNAL CONDITION FOR SUBJECTS WITHOUT RECENT NAVIGATIONAL EXPERIENCE (n=7)

subgroups based on recent experience and an ANOVA with repeated measures was completed. The ANOVA considered the signals, the subject's experience level and the interaction between signals and experience level. In addition to the interaction term and an error term within subjects, an error term between subjects was also calculated. The results of this ANOVA appear in Table IV, where no significant differences in the light sources are noted.

The planned comparisons were made as outlined in "Data Analysis," Chapter II. No significant differences between the light sources were noted at the 0.10 level. However, the error for the 5 flick signal was significantly greater than for both incandescent signals at the 0.20 level.

An F test for variability was performed to compare the overall variances of the experienced (n=3) group with that of the non-experienced (n=7) group. No significant difference was found.

In an effort to further analyze the unexpected results, the correlations between the signals were examined. Each subject's data were first rank ordered from the smallest to largest mean positioning error (Table V). Then the Spearman Rank Order Correlation (rho) between ranked subject performance under each possible pair of light signals was calculated (Table VI). A "t" test for significance was performed at the 0.05 level with a

Table IV. SUMMARY OF ANALYSIS OF VARIANCE (ANOVA) BETWEEN AND WITHIN SUBJECTS

Source	SS	df	ms	F	p
Total	2094	59			
Between Subjects	785	9	87.22	3.36	<.01
Experience Level	34	1	34.0	0.36	n.s.
Error_b	751	8	93.9		
Within Subjects	1309	50			
Signal	114	5	22.80	0.88	n.s.
Experience X Signals	52	5	10.4	0.36	n.s.
Error_w	1143	40	28.6		

SS = sum of the squares
df = degrees of freedom
ms = mean squares (SS/df)
F = calculated F ratio (ms/ms of Error_w)
p = probability
n.s. = not significant

Table V. RANKING OF SUBJECT PERFORMANCE BY SIGNAL CONDITION*

	Signal					
	Flashtube Flicks				Incandescent	
	1	3	4	5	Flashing	Fixed
1	6	3	4	5	1	2
2	4	1	6	5	3	2
3	1	5	4	3	2	6
4	4	5	6	2	3	1
5	2	3.5	6	5	1	3.5
6	3	5	6	2	1	4
7	3	1	2	5.5	5.5	4
8	5	3	4	6	2	1
9	2	1	3	5	4	6
10	6	5	2	3	4	1

*Ranking determined by positioning error
lowest = 1, highest = 6

Table VI. CORRELATION COEFFICIENT (rho) BETWEEN RANKED SUBJECT PERFORMANCE UNDER SIGNAL CONDITIONS

	Signal					
	Flashtube Flicks				Incandescent	
Signal	1	3	4	5	Flash.	Fixed
1 flick		.69*	.61*	.73*	.66*	.30
3 flicks			.70*	.44	.56*	.56*
4 flicks				.65*	.38	.50
5 flicks					.66*	.60*
Flashing						.70*
Fixed						

*Significant at the .05 level with a 1 tail t test one-tailed test being used, since a positive relationship was expected to exist between all signal pairs.

Using the split-halves method of forming pairs of scores, the data for each light signal were divided into two equal groups. For each light signal the odd-numbered trials for each subject were correlated with the even-numbered trials. This essentially correlated two identical signals viewed by the same observer under the same conditions. The Pearson Product Moment (r) was then calculated as a step in determing the reliability (Table VII).

Table VII. PEARSON PRODUCT MOMENT CORRELATION (r) BY LIGHT SIGNAL

SIGNALS					
Flashtube Flicks				Incandescent	
1	3	4	5	Flashing	Fixed
.54	.27	.36	.63	.48	.47

The "r" values were then used to compute a true reliability. Reliability is the degree to which the test repeatedly measures the same parameter. The method of calculating the reliability when the split-half reliability technique is used is:

$$\text{reliability} = \frac{r \times 2}{r + 1}$$ (Bruning and Kintz, 1968)

Table VIII shows the reliability for each signal.

Table VIII. RELIABILITY FOR EACH LIGHT SIGNAL

SIGNAL					
Flashtube Flicks				Incandescent	
1	3	4	5	Flashing	Fixed
.70	.43	.53	.77	.64	.73

These values yield an average reliability of 0.63.

B. DISCUSSION

1. Signals

The "Hypotheses" in Chapter 1 stated that the positioning error using the 1 flick or the 3 flick flashtube signal would be significantly greater than the signals of longer duration. Several methods were used in attempting to identify significant differences in subject's positioning error under different light sources.

Table IV shows no difference between the light signals. The more powerful planned comparison test confirmed this finding. However, significant differences were noted between the subjects. The differences among the subjects had been expected, but the lack of any significant differences between the light sources surprised the investigator.

It is interesting to note the results of the correlations performed between each set of signals. The 1 flick signal correlates well with each of the other flashing signals. This means that the positioning error with the 1 flick signal is a reasonable predictor of the positioning error of each of the other flashing signals. That is, there is good positive correlation. Also, each flashing signal correlates well with the signal of the next longest duration. Furthermore, the incandescent signals, both flashing and fixed, are good predictors of each other. These positive correlations lead one to believe the cues that subjects use for one test signal are being used for other similar test signals, i.e., the tasks that correlate well are accomplished in a similar manner.

During the course of the experiment, several persons in the visual perception field were contacted and the experiment was discussed with them. None were able to recommend a better method for measuring real depth perception as opposed to two separate image (stereoscopic) depth perception. However, one of these people did comment on what he termed the "unreliability" of the Howard-Dolman

Box. The results of the reliability test provide strong evidence of the unreliability of the Howard-Dolman Box, at least as it was used in this experiment. The reliability was developed from the correlation value (r) which measured the correlation of the two identical signals viewed by the same subject. Correlation should have approached 1.0 under such conditions and, likewise, the reliability should also have approached 1.0 and not have been in the 0.43-0.77 range.

2. Subjects

It was concluded that none of the signals provide a significant advantage over another in depth perception, that is all were equally good or equally poor. Some factors which help to explain the results may be more closely linked to the subjects than the signals. The mariners dislike of the short flashtube signal could be prompted by characteristics of the signal not readily recognizable to the mariner. The spectrum of the xenon flashtube (Figure 2) has an appreciable quantity of energy on the lower wavelength limit of the eye's photopic response (viz. blue). This may seem, to the mariner, to be an adverse effect that he is unable to quantify, so his immediate reaction is that the flash duration is too short.

In addition, it appears that the subjects knew when the cart was approaching the front end or the back end of the box. This was evidenced by the fact that the limit stops were hit only 9 times out of 600 trials. It may be that the subjects could tell when they were in the last 10-15 cm of travel of the cart in the front end or back end. This grouped the data toward the center of the optical bench, and may explain why the error for the one flick signal is not significantly larger than the other signals.

The small sample size had some impact on the results. The depth perception error was measured only 100 times for each light source. More trials per subject would have provided a larger, and hopefully more reliable, data base. Additionally, perhaps more training to a certain criterion, such as mean positioning error with the fixed light, might have been considered. The training sequence for the subjects went through several iterations. The final sequence of training, on the evening of testing, used sources that progressively became more difficult (two sticks, then one stick, and finally a non-point source fixed light). Training with an incandescent flashing light would have been desirable but may have biased the results in favor of the incandescent flashing signal.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. EXAMINATION OF THE HYPOTHESES

The Hypotheses listed in Chapter I were divided into two sets which will be discussed here based on the results of the experiment.

Set I

a. Hypothesis--The mean positioning error value for the 1 flick signal is significantly greater than the mean error for the 3 flick signal.

b. Hypothesis--The mean positioning error value for the 3 flick signal is not significantly different from the means of the errors for the 4 flick, 5 flick, and incandescent signal.

The first Hypothesis was not supported by the data and is rejected. The second Hypothesis, although supported statistically, may lead to erroneous conclusions. One must consider the strong evidence presented in Chapter III concerning the unreliability of the test.

Set II

a. Hypothesis--The mean positioning error value for the 3 flick signal is significantly greater than the mean error for the 4 flick signal.

b. Hypothesis--The mean positioning error value for the 4 flick signal is not significantly different from the means of the errors for the 5 flick and incandescent signal.

Again, the first Hypothesis was not supported by the data and is rejected, while the second Hypothesis was supported by the data. However, although the second hypothesis was supported statistically, it may lead to erroneous conclusions, again considering the evidence presented in Chapter III concerning the unreliability of the test.

B. CONCLUSIONS

In my opinion, there are several reasons why the hypotheses were not reliably confirmed.

The main reason that the hypotheses were not confirmed is the unreliability of the test. As listed in Table VIII, Chapter III, the reliability values are very low in the split-halves test. Comparing odd-numbered trials against even-numbered trials with the same light source for the same subject should result in a reliability approaching 1.0 instead of 0.63.

However, despite this lack of reliability, the correlation between signals followed a pattern. Each signal correlated well with the signal of the next longer duration, but not with all signals of longer or shorter duration. This indicates that there is a relationship between the way some pairs of signals are perceived. Both incandescent signals are perceived or viewed in a similar manner. Subjects use similar cues when making matches with these signals. The least relationship exists, as one might expect, between the 1 flick flashtube signal and the fixed incandescent signal.

C. RECOMMENDATIONS

Several recommendations can be made based on the results and the experience gained in conducting this experiment. These recommendations include modifications to the testing procedure to improve reliability, and changes to the visual signals. Finally, a proposed pilot study for continuing work is presented.

1. Box Reliability Improvements

The results obtained from the Howard-Dolman Box proved to be somewhat unreliable. It should be possible to improve the reliability of the depth perception measurements by using the method of limits and by careful selection and training of subjects as proposed below:

a. Use of Method of Limits

Howard (1919) used a method of limits in his testing for real depth. In this test method the relative position of the two sticks is set by the experimenter. The subject does not move the sticks. Howard's observers had to state whether one stick was in front of, or behind, the other immediately after a brief viewing. After a number of trials in which the relative positions of the sticks were changed, the experimenter can determine the minimum depth perception perceived by the subject. Several subjects in the current experiment commented that they nearly always knew the direction of the first move after the shutter was opened, but after making that move they found the task more difficult. Several variations on the method of limits are available, but another consideration is that the method used should account for guesses, as Howard's did. A major drawback to the method of adjustment is now apparent, in that there may have been many guesses accumulated in the data. The present device is well suited for use with the method of limits.

b. Use Trained, Experienced Subjects

Chapters II and III provided much discussion on the training of subjects and on the performance of a small subgroup who had recent navigational experience. The data indicate, however, that there is no difference between experience levels (Table IV). Based on previous work, cited earlier, training is also an important factor in depth perception. It is my opinion, therefore, that experienced subjects should be selected and then trained to a pre-established criterion with a fixed light. Table III might be of some help in establishing that criterion. I believe reliability will improve with added experience and training. This experience and training would make the results less generalizable to the population as a whole and would limit the applicability to that section of the population using buoys at night. Fortunately, it is not necessary to generalize the performance of such a specific task to the population as a whole. I would hope that the training would not impact excessively on performance and that it would not yield a task that could be accomplished only in the lab and not in the real world.

2. Signal Changes

Three recommendations concerning the output of the multi-flick flashtube are presented in this section.

a. Increase the Frequency of the Flashtube Signal

The frequency at which the flashtube signal is presented should be raised, while keeping the duration of the longest flashtube burst constant (0.40 sec). 12 Hz could have been considered to be a marginal CFF. The pilot study indicated by visual inspection of the data that 5 flicks at 12 Hz was the best signal of the four tested for depth perception. However, 8 flicks at 19 Hz was the second best and 19 Hz was well above CFF. Observers' comments on how many flicks they saw from the 5 flick signal varied widely. Some saw only one, while others saw "three or four." Several subjects saw all five flicks, and one claimed that he saw six.

b. Disregard Power Considerations

This recommendation is tied directly to the previous one. Any future work should disregard any power considerations until an effective signal is obtained. Experimentation should not be restricted to the lower frequencies because they will take less battery power to produce. An effective signal should be one where the flicks are temporally summed and do not appear individually. Six flicks at 15 Hz (.40 sec duration) should be considered.

c. Spectral Output Considerations

Assuming that these recommendations lead to productive work in determining the time duration of a multi-flick burst from a xenon flashtube that would lead to fixation, then the signal spectrum should be considered. As mentioned in Chapter I, "Positive Aspects of a Xenon Flashtube," different gases and other elements can be added to the xenon to change the spectral output. If a burst needed several flicks before fixation could be achieved, then the spectral output could be changed to more closely approximate photopic response. Then, even with a multi-flick burst the efficacy of a xenon flashtube may exceed the efficacy of an incandescent lamp with a comparable duty cycle. However, additional work is necessary to determine the duration of the signal that is necessary for fixation.

3. Proposed Pilot Study

The first step in any additional work should be to test well trained subjects with a temporally-fused flashtube burst of 0.40 sec. This could be accomplished with 12 flicks at 30 Hz or 20 flicks at 50 Hz, for example.

The threshold value of each subject's depth perception with this source should be compared with his threshold value with the 0.40 sec flashing incandescent source. The data should then be tested for significant differences between the two signals. A significant difference would then indicate that there are factors other than duration involved in perceiving depth from a flashing point source light.

D. THE IMPORTANCE OF CONTINUING THIS EFFORT

The question regarding the usability of a xenon flashtube signal as a suitable aid-to-navigation has not been resolved. A flashtube signal

> is a more reliable light source which for the same luminous range is more conspicuous and more economical (longer service periods for both batteries and lamps). (USCG, 1970).

Such advantages could save thousands of dollars annually. With 4000 lighted buoys and an annual battery cost of $500 per buoy, a 50 percent increase in battery life would save one million dollars annually. However, the disadvantages--inability to fixate on the signal and interference with normal photopic and scotopic vision at short range need to be addressed.

Continued research on the perception of flashtube signals, despite the disappointing findings of this evaluation, is essential in light of the potential economic savings and signal advantages of the flashtube. A reliable technique for measuring depth perception is needed to continue work. Assuming such a technique is developed, a more definitive answer could be obtained regarding the optimal characteristics of the flashtube signal as an aid-to-navigation.

APPENDIX A

FLASHTUBE OPERATION

A flashtube lamp is a gaseous discharge lamp which produces very short, high intensity bursts of luminous energy. These lamps are used in photography, for viewing and timing rotating parts (stroboscopes or strobes), as airport approach lights, and as navigational lights.

A flashtube consists of a tubular envelope of glass or quartz which contains very pure xenon gas at a pressure of about 0.5 atmospheres below atmospheric pressure. Other gases can be used for discharge lamps and metal halides may be added to the gases to obtain a change in spectral output (Bamburg, 1981).

The two discharge electrodes are located in the envelope along with a third external electrode (Figure A1). With voltage applied across the electrodes the tube appears as an open circuit. When the xenon gas is ionized by a trigger pulse applied to the third electrode, the xenon gas then becomes conductive and a several hundred volt discharge occurs between the main electrodes, and the gas becomes highly emitting.

The duration of the flash depends on the path length of the discharge as well as the voltage potential. Typical

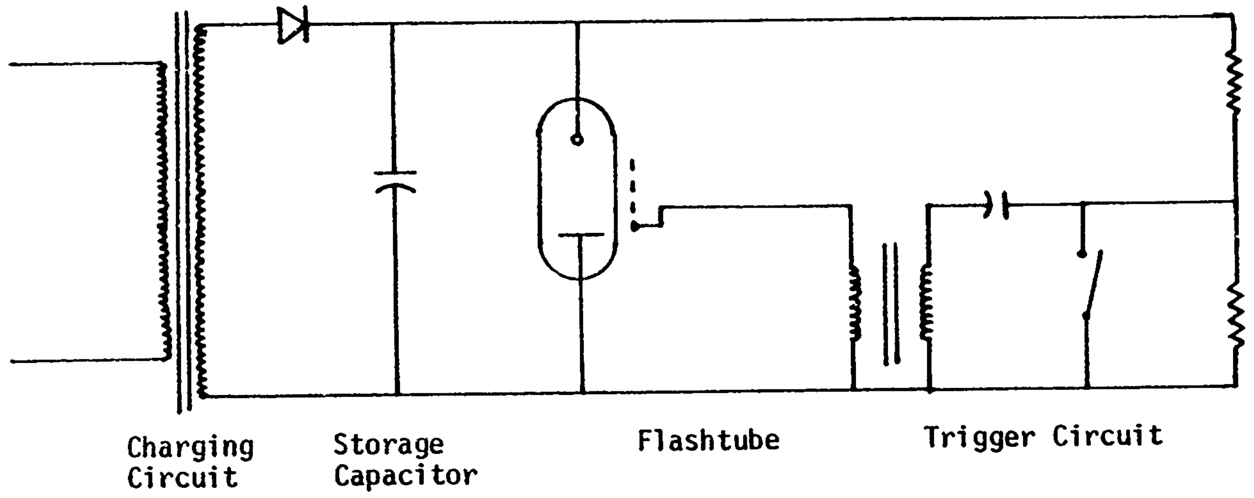

Figure A1. ELEMENTS OF A FLASHTUBE (IES, 1981) values of flash duration range from 3 µsec to 100 µsec. The luminous flux produced during a flash depends on the voltage, the stored energy in the capacitor, and the type of ionized gas. Thermal shock of the envelope and cooling pose problems for larger flashtubes. With higher energy tubes the quartz envelope is used instead of glass to prevent shattering. The flashtubes that are utilized for short range aids-to-navigation signals have discharge potentials of about 300-500 volts and energy storage loading up to 10 Joules. Energy storage can be described by

$$E = \frac{CV^2}{2}$$

where C is capacitance in farads, and V is potential across the flashtube in volts.

Halide selection for spectral enhancement would be made depending on the desired radiation characteristics. For example, a xenon lamp with a cadmium additive would have a different spectral output from a pure xenon lamp (Figure 2). Rather than having a spectrum with a spike in the blue wavelengths, the cadmium additive would produce a flat visible spectrum with very intense spikes at 480 nm and 510 nm (Bamburg, 1981). Such additives may increase the efficacy of flashtubes which now approximate 30-60 lumen-sec/joule (IES, 1981).

APPENDIX B

SCALING THE LIGHT SOURCES

As stated in Chapter I, the goal of scaling the experiment was to provide equal photopic energy from both the incandescent and the flashtube sources when 1 flash (flick) was provided. The first step was to photograph both wave forms as they were presented to the observer. To do this a silicon PIN diode was used as a detector and the signal was displayed on the Techtronix 541A Oscilliscope using a type L plug-in unit (Figures 3 and B1). No filter was utilized except that which is inherent in the spectral response of the silicon photo diode.

The photometer used was a Techtronix J16 Digital Photometer with a J6501 Illuminance Probe. The photometer was equipped with a multilayered glass filter to model the CIE photopic curve (Figure 2), i.e., the spectral response of the fovea of the average human eye. The time constant of integration was 100 ms, and up-dated readings were provided about 5 times per second. The sensor was a silicon photodiode which had a time constant of about 200 ns (Wolfe, 1978). The photometer had a measurement range of 0.0001 to 1999 fc, and a light acceptance angle that diminished to 50% sensitivity at 48 degrees off axis.

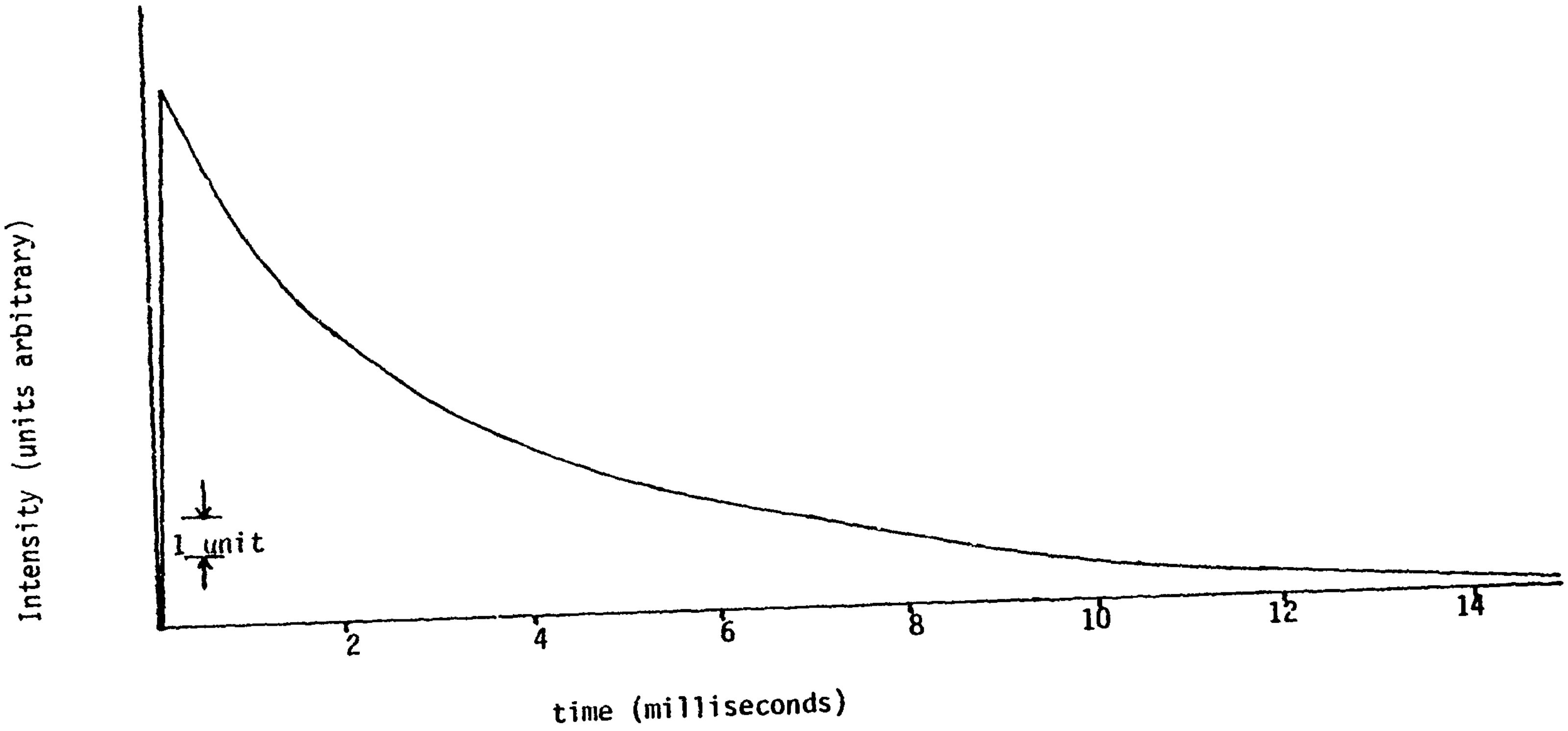

Figure B1. INTENSITY vs TIME CURVE OF THE XENON FLASHTUBE SIGNAL USED FOR TESTING

Because the photometer did not have a very high sensitivity, all readings for the observer were taken at a distance of 1 foot and converted to readings that the observer would see at 5 meters, by assuming only $1/D^2$ spreading.

Because the responsivity of the photometer was not fast enough to measure the illuminance of either the incandescent or flashtube flashes, another method had to be devised. This method entailed establishing the linearity of the photometer and verifying that it was "seeing" all the luminous flux (luminance) in its acceptance angle. Then it was necessary to assign values to the illuminance units on the E versus t curve of the flashtube. This was done by reading the average illuminance value with the photometer and determining its position on the curve graphically. This average illuminance, E_a, could not be converted to intensity at the source because the source was not omnidirectional. The beam of light from the fiber optic filled approximately a steradian but no exact measurements of it were made. E_a was directly related to a value of I_a, and E_a was the average illuminance that would be measured, if E from one flick could be measured. Then using the Blondel-Rey Law, I_e, equivalent fixed light intensity, was calculated and plotted and its relation to I_a was obtained. Then using Allard's Law the modelled distance from the source could be determined using a 4 nmi luminous range and the average illumination reading, E_a, at any distance.

This was accomplished by locating the photometer 1 cm from the fiber optic producing the light source. A plot was made of illuminance versus frequency with the flashtube operated continuously over the range from 2 Hz to 100 Hz. The illuminance reading at 50 Hz was 0.265 fc with the readings remaining constant. At 100 Hz illuminance read 0.485 fc, again with constant readings. Assuming the silicon photo diode was sensing all the photons, the 100 Hz reading should have been twice the 50 Hz reading. However, at 100 Hz about 6% of the tail of each pulse was cut off by the succeeding pulse (Figure B2). Therefore, the expected value at 100 Hz was 0.498 fc while the actual value was 0.485 fc or a 3% difference, which was considered insignificant for this calculation. The photometer reading was then called average illuminance (E_a). Figure B2 depicts this graphically with the solution for E_a occurring when $A_T = A_{B1} + A_{B2}$.

A luminous range for the buoy was assumed to be 4 nautical miles (nmi), and Allard's Law

$$I = ED^2/T^D$$

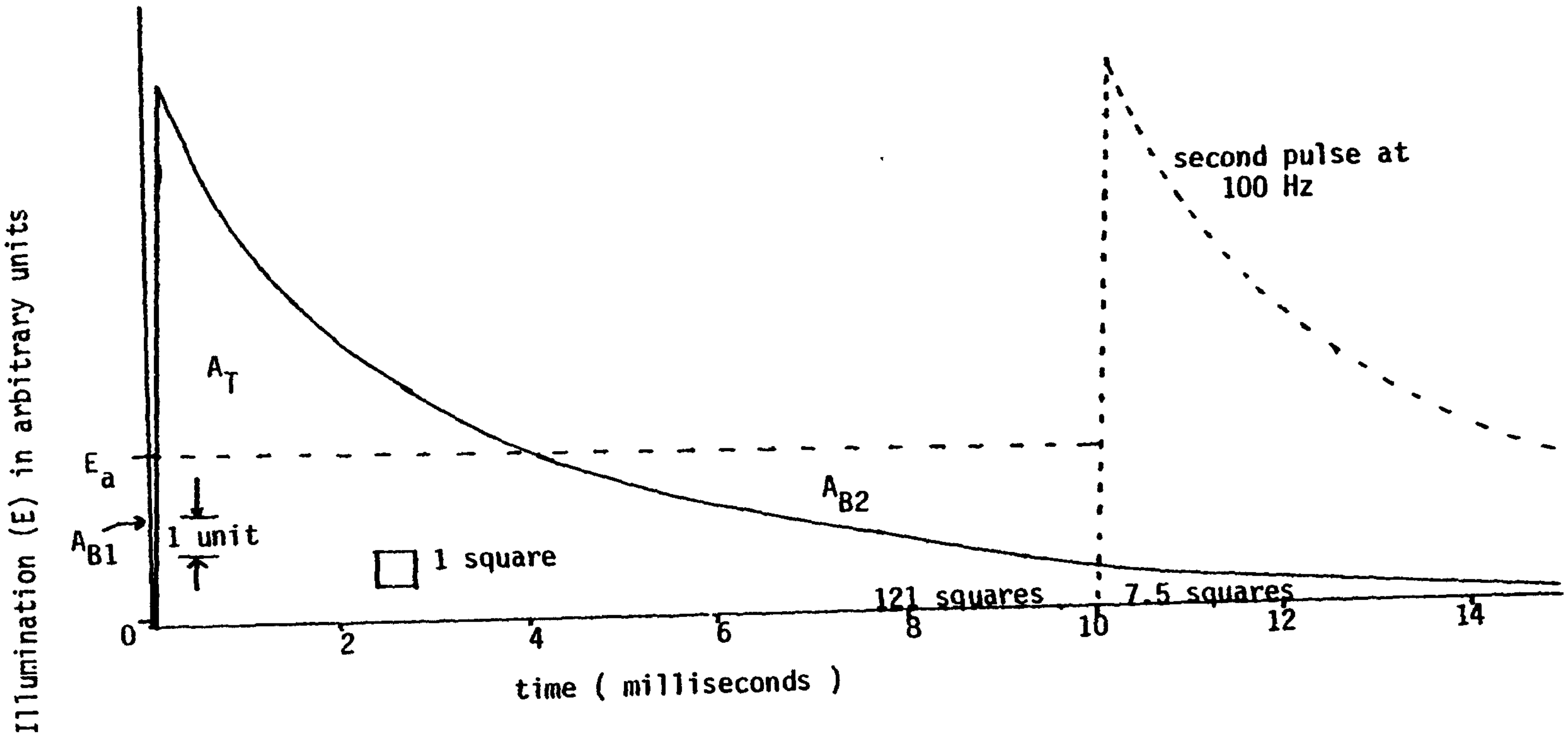

Figure B2. ILLUMINATION vs TIME CURVE OF THE FLASHTUBE SIGNAL GRAPHICALLY DEPICTING THE SOLUTION FOR E_a

was used with a threshold illumination (E_t) of 0.2 μ lux to determine the fixed intensity that would produce a 4 nmi buoy. A fixed light intensity of 10.7 cp was necessary to establish that range, so it was necessary to equate both flashing lights to a fixed light intensity of 10.7 cp.

Conversion from a flashing light to a fixed light equivalent is only meaningful at some threshold level. With transmissivity equal to 1 both the incandescent and the flashtube forms are affected by only the $1/D^2$ spreading and at threshold each I versus t (or E versus t) curve would appear the same as at any distance.

It is necessary to apply the Blondel-Rey Law to convert from a flashing light to a fixed light equivalent. This can be done using Blondel-Rey in the form

$$aI_e = \int_{t_1}^{t_2} I dt$$

Since an I_e of 10.7 cp was necessary for a 4 nmi buoy, and with the assumption that the Blondel-Rey Equation and threshold constant "a" were valid for short flicks (Bates, 1971), the intensity scale for the I versus t curve for the flashtube could be defined.

$(.21\ s)(I_e)$ = area under the curve for the entire flash duration, minus $(I_e)(t_2 - t_1)$, assuming that $I_e(t_2 - t_1)$ is very small and can be neglected (Clark, 1971). By iteration a value of $I_e = 0.25$ units was selected, thereby yielding

$$(.21\ \text{s})(.25\ \text{units}) = (128.5\ \text{units})\ (.4\ \text{ms}) \quad \text{(Figure B3)}$$

$$0.0525\ \text{s-units} \approx 0.0514\ \text{s-units}$$

However, the photometer will not measure I but will only measure E_a which occurred at 4.85 units on the E versus t curve. Therefore, with E_a corresponding to I_a and

$$I_a = 19.4\ I_e$$

Using Allard's Law for any distance:

$$E_a = I_a\ /\ D^2$$

$$E_a = (19.4)\ (10.7)\ /\ D^2$$

where E_a was measured by photometer at 1 foot and equals 0.078×10^{-1} fc, and converts to $E_a = 2.98 \times 10^{-5}$ fc at 5 meters. Therefore, the distance corresponding to the illumination provided by the flashtube is

$$D = \frac{(19.4)(10.7)}{29.8} \times 10^3\ \text{ft}$$

$$D = 2640\ \text{ft}$$

Then it was necessary to scale the incandescent light burning steady to correspond to a D of 2640 feet. At 5 meters E should be:

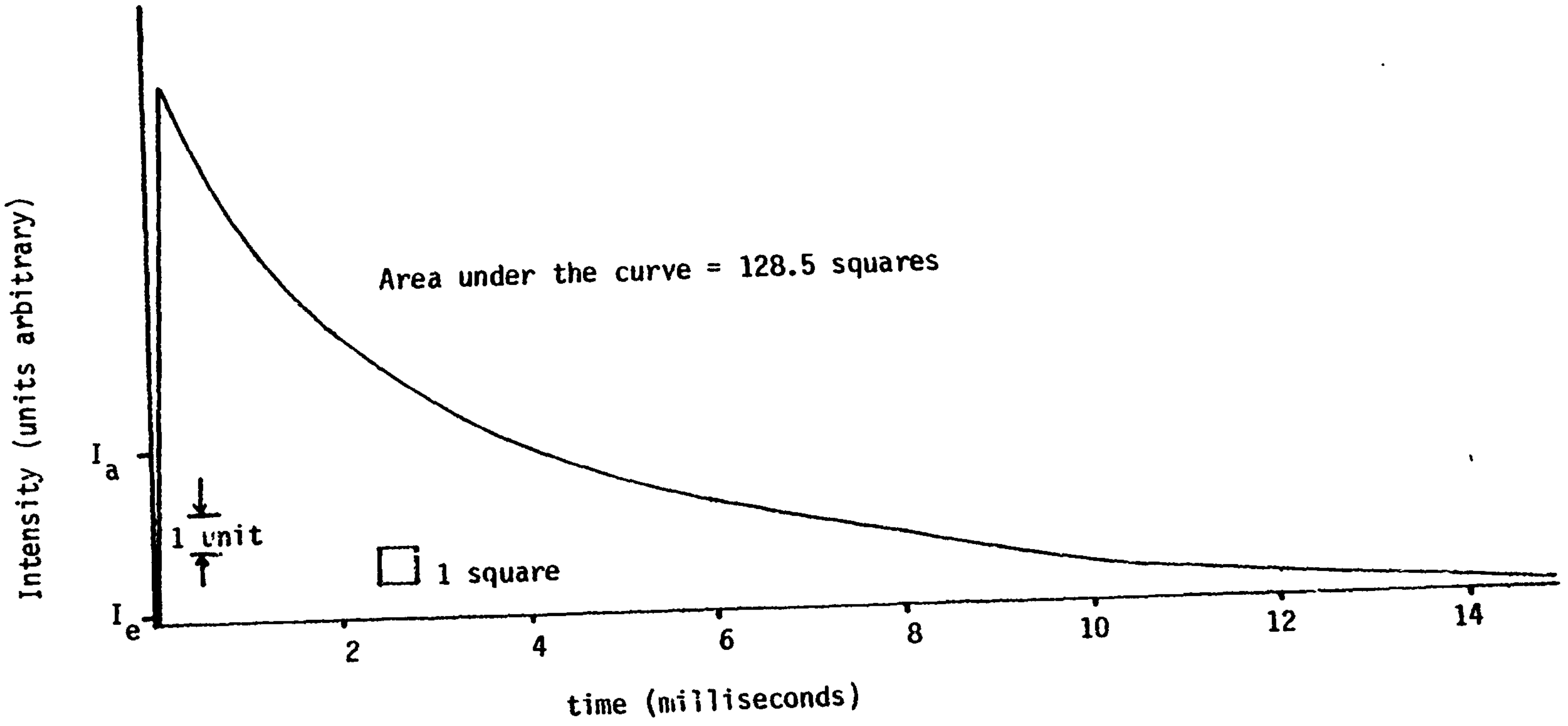

Figure B3. INTENSITY vs TIME CURVE FOR THE FLASHTUBE SIGNAL DEPICTING THE RELATIVE VALUES OF I_a AND I_e

$$E = \frac{10.7\ cp}{6.96 \times 10^6}\ ft$$

$$E = 1.54 \times 10^{-6}\ fc$$

or at 1 foot

$$E = 0.402 \times 10^{-3}\ fc$$

so E from the steady incandescent source should be 0.004×10^{-1} fc above ambient illumination.

Ambient illumination measured 0.013×10^{-1} fc. With 3 neutral filters of transmittance 20%, 25%, and 62% in front of the pick-up end of the fiber optic, an illumination reading at 1 foot of 0.017×10^{-1} fc was obtained with the incandescent lamp on steady. With the three NFs in place, the steady incandescent lamp was the fixed light equivalent of the 1 flick flashtube.

It was then necessary to equate the flashing incandescent light to the same fixed light source. The Blondel-Rey factor for a flashing every 4 seconds, 0.4 second flash, with a 12 volt, 0.25 amp lamp is 0.63 (USCG, 1972). The factor was calculated graphically from the wave form as 0.66 (Figure 3). Therefore, when the .62 transmissivity neutral filter was removed, the steady incandescent light became the fixed light equivalent for both flashing sources, and an observers range of 900 yards on a 4 nmi buoy was approximated.

APPENDIX C

INSTRUCTIONS TO SUBJECTS

Shortly after entering the lab the subject was shown the apparatus and the mechanics of the stick motion. He did not see the signal sources, that is the incandescent lamp and the Hi-Con, but did see that the signal was presented by a fiber optic.

"Shortly, I will illuminate the movable stick in the box. At that time I want you to take the strings that control the stick's motion and move the stick back and forth. By pulling with your left hand you can pull the stick away from you. By pulling with your right hand you can pull it towards you. Please keep your head in the blinders and both eyes open, because I am testing binocular vision. The red light in front of you is there to maintain a constant level of dark adaptation. It should not distract you or interfere with these trials.

After you become comfortable moving the stick, I will then illuminate an identical stick about 6 inches to the right of the first stick. I will then ask you to position the sticks so that they are equidistant from you, or side by side.

Once you feel that the distances match, tell me and I will then tell you how accurately you matched the sticks. I will then show you the correct alignment. We will do this several times, until you feel confident of your ability to match the sticks."

TRAINING WITH STICKS

"Now that you are familiar with the motion of the stick and the matching position of the sticks I am going to change the signal on the right from a stick to a steady light source. We will conduct training similar to what we did with the sticks. After you have matched the stick with the light source, I will again tell you your error and show you the correct alignment."

TRAINING WITH STICK AND STEADY LIGHT

"Now that you are familiar with the motion of the stick and matching position of the stick and steady light I am going to test you on your ability to match these signals without my help.

I will randomly position the movable stick at various distances in front or in back of the light source. I will then open the shutter and tell you to 'pick up the strings, and position the stick beside the light signal'. After you have positioned the stick, tell me 'positions matched' and release the strings. I will then close the shutter and start the process again. We will match the stick with the steady light source 10 times."

QUALIFYING TEST--MATCHING STICK WITH STEADY LIGHT

BREAK 10 minutes

"Now that you are familiar with and have demonstrated an ability to use the apparatus, I am going to change the manner in which the light signal is presented. The new light source will be flashing also. The flashes may number one to five or the light may appear to flicker.

Again, I will randomly position the stick at various distances in front or in back of the light source. I will then open the shutter and tell you to 'pick up the strings and position the stick beside the flashing light'. After you have matched the two, tell me 'positions matched' and release the strings. I will close the shutter, record the data, reposition the stick, open the shutter and start the process over again. You will make 10 different matches with each of 5 different light sources.

Remember, try to be as accurate as possible and remember there is no time limit."

TEST--MATCHING STICK WITH FIVE FLASHING LIGHT SOURCES

COMMENTS

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