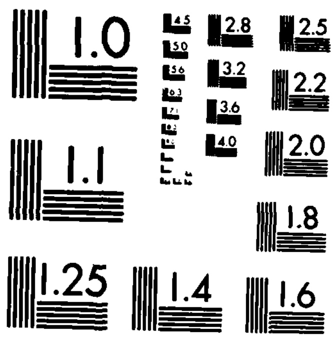
AD-A125 575 A FIELD VISIBILITY COMPARISON BETWEEN ELECTROLUMINESCENT SOURCES AND STAN..(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA J R THACKER OCT 82 1/1

UNCLASSIFIED F/G 13/1 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD A125575

NAVAL POSTGRADUATE SCHOOL

Monterey, California

DTIC
ELECTE
MAR 14 1983
S H D

THESIS

A FIELD VISIBILITY COMPARISON BETWEEN
ELECTROLUMINESCENT SOURCES AND STANDARD
U.S. COAST GUARD INCANDESCENT AIDS-TO-
NAVIGATION SOURCES

by

John Richard Thacker
October 1982

Thesis Advisor: S. H. Kalmbach

Approved for public release, distribution unlimited

DTIC FILE COPY

83 03 14 048

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A125 575	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Field Visibility Comparison Between Electroluminescent Sources and Standard U.S. Coast Guard Incandescent Aids-to-Navigation Sources		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis October 1982
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John Richard Thacker		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 October 1982
		13. NUMBER OF PAGES 88
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		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)

electroluminescent	incandescent	intensity
aids-to-navigation	contrast	luminance
illuminance	field test	zinc sulfide
Lambertian		

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

The U.S. Coast Guard has traditionally relied on incandescent sources for lighted aids-to-navigation. However, incandescent sources suffer from scintillation, halo effects, catastrophic failure, and other problems. Electroluminescence (EL) may offer some advantages in overcoming these difficulties.

From approximately 1.3 miles distant, sixteen observers made simultaneous brightness comparisons between EL and selected standard incandescent aids-to-

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

navigation sources for both red and green colors. In addition, a test was conducted to determine if any of several spatial arrangements of EL panels were perceived as brighter. Green EL sources seemed to perform better than predicted, consistently brighter than their incandescent counterparts. The spatial arrangement test indicated that no statistically discernable difference existed in perceived EL brightness in any of the tested panel arrangements.

Accession For	
NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	

DTIC COPY INSPECTED 2

Approved for public release; distribution unlimited.

A Field Visibility Comparison Between Electroluminescent Sources and Standard U.S. Coast Guard Incandescent Aids-to-Navigation Sources

by

John Richard Thacker
Lieutenant, United States Coast Guard
B.S., U.S. Coast Guard Academy, 1976

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
October 1982

Author: ______________________________

Approved by: ______________________________
Thesis Advisor

____
Second Reader

____
Chairman, Department of Physics

____
Dean of Science and Engineering

ABSTRACT

The U.S. Coast Guard has traditionally relied on incandescent sources for lighted aids-to-navigation. However, incandescent sources suffer from scintillation, halo effects, catastrophic failure, and other problems. Electroluminescence (EL) may offer some advantages in overcoming these difficulties.

From approximately 1.3 miles distant, sixteen observers made simultaneous brightness comparisons between EL and selected standard incandescent aids-to-navigation sources for both red and green colors. In addition, a test was conducted to determine if any of several spatial arrangements of EL panels were perceived as brighter. Green EL sources seemed to perform better than predicted, consistently brighter than their incandescent counterparts. The spatial arrangement test indicated that no statistically discernable difference existed in perceived EL brightness in any of the tested panel arrangements.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. COAST GUARD INTEREST IN EL

The United States Coast Guard's responsibilities in the area of maritime aids-to-navigation are defined in Title 14, U.S. Code. This nation enjoys an exemplary maritime commercial accident record partly due to a well maintained, functional aids-to-navigation system. The principal component of this system is the lighted aid which exists in many forms, from the wind and wave buffetted buoy to the massive lighthouse. Though these lighted aids are very different in their design, function, and use, nearly all share a common ingredient. That common ingredient is the incandescent light source. Incandescent sources are widely used for a number of reasons: (a) low cost; (b) installation ease; (c) dependability; (d) well known operating capabilities, and (e) lack of suitable alternative. Despite these advantages, incandescent sources are not without fault. Imagine the following scenario.

At 2. a.m. a Coast Guard duty officer is informed by a vessel pilot via radio that a certain range light is entinguished. The duty officer then notifies appropriate response personnel of the discrepancy. The two or three response personnel report to the pier, gather the needed equipment and get underway in a small boat. The transit time may be well over two hours. On scene, the response team discovers that the light has been vandalized with firearms and repair takes about one hour. Total time for this critical range light to be extinguished is four hours. When this is combined with foul weather and a fatigued master who is unfamiliar with the passage, the potential for disaster is readily apparent. Besides catastrophic failure, there are other problems with incandescent sources which warrant a search for a suitable alternative. This alternative should be rugged, easy to maintain, long lived, inexpensive, energy efficient, and of comparable brightness to standard incandescent sources. In short, these requirements demand a source quite unlike anything tried before.

The generation of light can be categorized into two general methods, incandescence and luminescence. Incandescence can be described as a molecular, indirect process wherein a filament is heated by the action of an applied electrical current resulting in the emission of photons. The photon emission then is indirectly related to the applied electrical energy.

Luminescense, however, is a direct process. There are several categories of luminescence including photoluminescence, cathodoluminescence, and electroluminescence. The distinguishing feature of each type of luminescence is the excitation mechanism. In electroluminescence (EL), the excitation process is directly accomplished by application of electrical energy. Briefly, EL may be defined as the direct conversion of electrical energy to light.

The usefulness of EL in cockpit lighting schemes has already been demonstrated (Pieroway, 1981). Whether or not EL has a useful place as a supplement to or a replacement for the currently used incandescent sources as aids-to-navigation is the subject of this thesis. Before presenting a detailed description of the problem, various fundamentals are provided as review to aid the reader in gaining an appreciation of the various aspects of the problem which must be considered.

B. THE PHYSICS OF INCANDESCENT SOURCES

A review of incandescence begins with the discussion of a blackbody radiator. Two quantities are important. The first is the total radiant power emitted and the second is the distribution of this power with wavelength. A true blackbody is one that absorbs all radiation (of all frequencies) incident upon it. A true blackbody then does not reflect but it does emit radiation as a consequence of its temperature. A non-blackbody at a temperature, T, will absorb a fraction, b, of the radiation incident upon it. The amount of radiation flux subsequently emitted by the non-blackbody is b times the emission of a true blackbody, at that T, where absorptivity, b, equals emissivity, ε, at thermal equilibrium.

The law that connects the total radiant energy flux from a blackbody to the temperature of that body is the Stefan-Boltzmann Law:

$$M = \sigma T^4 \tag{1}$$

where σ is the Stefan-Boltzman constant with the value 5.670×10^{-8} W M^{-2} K^{-4}. Of interest here is how the energy considered in the Stefan-Boltzmann relation is partitioned among the possible emitting frequencies. Planck proposed what is now known as the Planck theory of thermal radiation given by:

$$M_\lambda(T) = (2\pi c\ h/\lambda)\ \{[\exp\ (hc/\lambda kT)]\}\ -1 \quad W\ M^{-2}\ \mu M^{-1} \tag{2}$$

The wavelength distribution of the emitted thermal radiation for a typical tungsten filament lamp (Cotton, 1951) is shown in Figure 1.

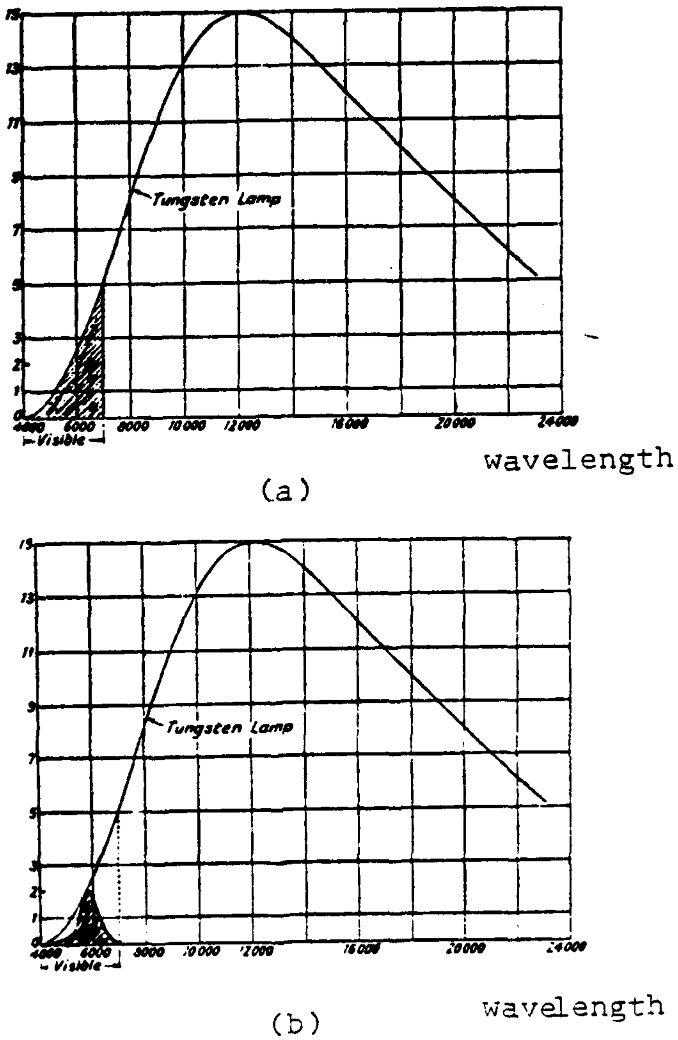


Figure 1. Wavelength Distribution of a Typical Tungsten Lamp

Note that the visible portion of the emitted spectrum is relatively small. Further, the power delivered in that portion of the spectrum is much less than the power of the total radiated energy. The shaded portion of Figure 1a is proportional to the power of the radiated energy in the visible portion of the curve while the total area under the curve is proportional to the total power of all the radiated energy. The ratio of this shaded area to the total area might be defined as the radiant efficacy of the source. But the various wavelengths are not equally effective in producing a sensation at the eye. Hence, when the radiant power in the visible spectrum is multiplied by the relative luminosity efficiency factor from the CIE Standard Observer Curve, a new distribution is arrived at. The shaded portion of Figure 1b illustrates the light output perceived by the observer. The ratio of this shaded region to that of the area of the entire curve is the luminous efficacy of radiant flux expressed as lumens per radiated watt (Cotton, 1951).

As noted, the Planck distribution of thermal radiation is highly temperature dependent. A filament operating at 3000 K will have a different distribution than a filament operating at 2200 K. This is why the operating voltage of a lighted aid is always specified when discussing its output. Refer to Figure 2 (Grum, 1971).

Often it is assumed that the relative spectral distribution of an incandescent source is equivalent to the relative spectral distribution of a blackbody operating at a particular temperature. As Figure 3 depicts, this is not generally the case. The ratio of the emittance of the non-blackbody to that of the blackbody is known as the (spectral) emissivity. The emissivity may vary with wavelength and temperature.

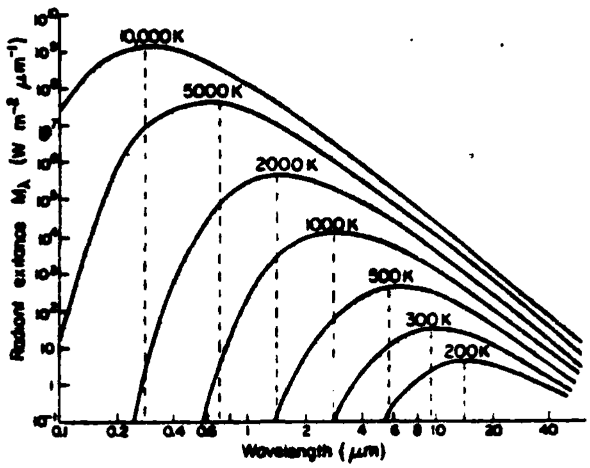


Figure 2. Radiant Exitance of a Blackbody as a Function of Wavelength

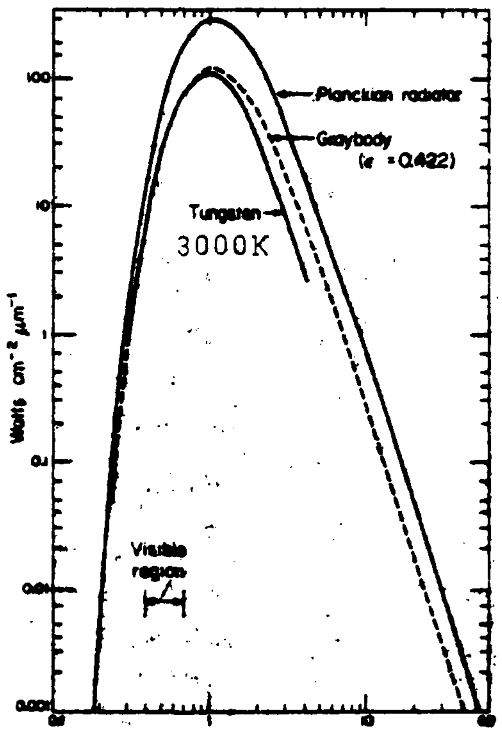


Figure 3. Relative Spectral Distribution of a Blackbody Radiator

It is often of interest to lighting engineers to determine the in-band flux density (W/Cm^2) of a radiator. For example, assuming a tungsten filament operating at a particular temperature closely approximates a blackbody, what portion of its radiant flux lies in the visible region? Programs for use with desk top calculators are available for the solution of this problem (Evans, 1978).

C. ELECTROLUMINESCENT SOURCES

EL lighting sources can be divided basically into four categories (Lehmann, 1980): (1) AC excited powder screens; (2) DC excited powder screens; (3) AC excited thin film screens, and (4) DC excited thin film screens. Thin film electroluminescence (TFEL) has enjoyed vigorous research efforts in the last five to ten years. Essentially, the thin film device (also known as a light emitting film or l.e.f.) is capacitor structured. The substrate is typically indium-tin oxide coated Corning glass. The transparent conductor is then followed by a layer of Y_2O_3. The next layer is the maganese doped ZnS host (ZnS:Mn) followed by another layer of Y_2O_3 and the final conduction layer (typically aluminum). The vacuum deposition system is usually microprocessor controlled and the critical film thicknesses are laser monitored. Refer to Figure 4.

The differences between the newer technology TFEL and the older powder screen EL lamps is substantial. TFEL is typically brighter (1000 foot-lamberts is advertised) and has higher efficiency at high brightness levels. But TFEL is also heavier, smaller, less rugged, and much more expensive than the powder screen technology. TFEL efforts have

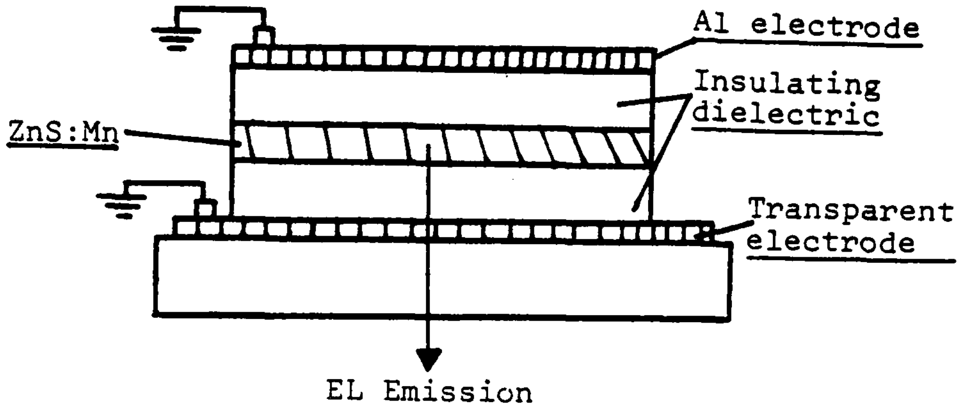


Figure 4. Thin Film EL Device

been concentrated in the area of displays, particularly flat panel color television matrix displays for military applications.

The AC excited powder screens (also known as Destriau type or thick film) available today are of two varieties, ceramic and plastic. This report deals with the more common plastic type powder screen as shown in Figure 5. The powder screen or panel consists basically of a thin uniform layer of phosphor (typically ZnS:Cu) embedded in a dielectric and sandwiched between two electrodes. The flexible panel is then coated in a moisture resistant plastic to reduce moisture breakdown and to provide rugged packaging. The EL devices tested in this investigation used a ZnS phosphor powder and were the plastic type of panel. They were not microencapsulated.

Microencapsulation is a relatively new process (Alinikov, 1978) developed to protect the phosphor from moisture hazard as well as heat

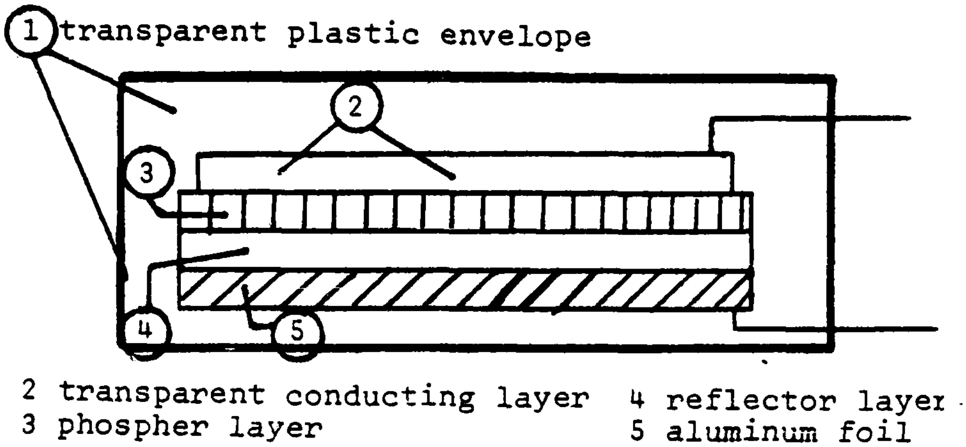


Figure 5. Plastic EL Panel

generated by the phosphor, particularly at high voltage and high frequencies. This process coats the phosphors with a liquid crystal mixture. There is, unfortunately, a brightness degradation when this process is used. The average lamp life curve for these panels is shown in Figure 6 (EL Products Brochure).

EL brightness varies with the exciting voltage, frequency, and age as well as other factors external to the panel itself. Figure 7 (Grimes Division brochure) below represents typical curves for constant frequency and constant voltages.

Two models are presented briefly in Appendix A to explain EL emission. The complexities involved with inhomogeneous, polycrystalline phosphor particles makes verification of any model a staggering problem.

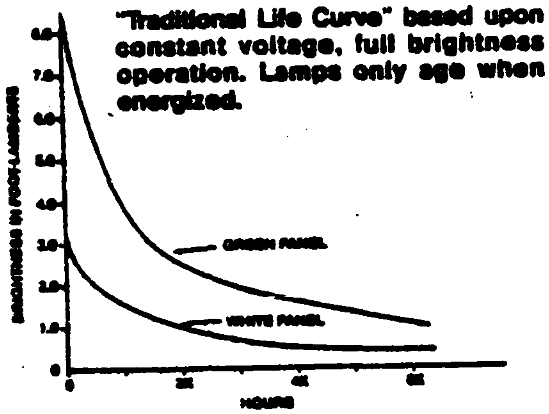


Figure 6. Typical Lamp Life Curves

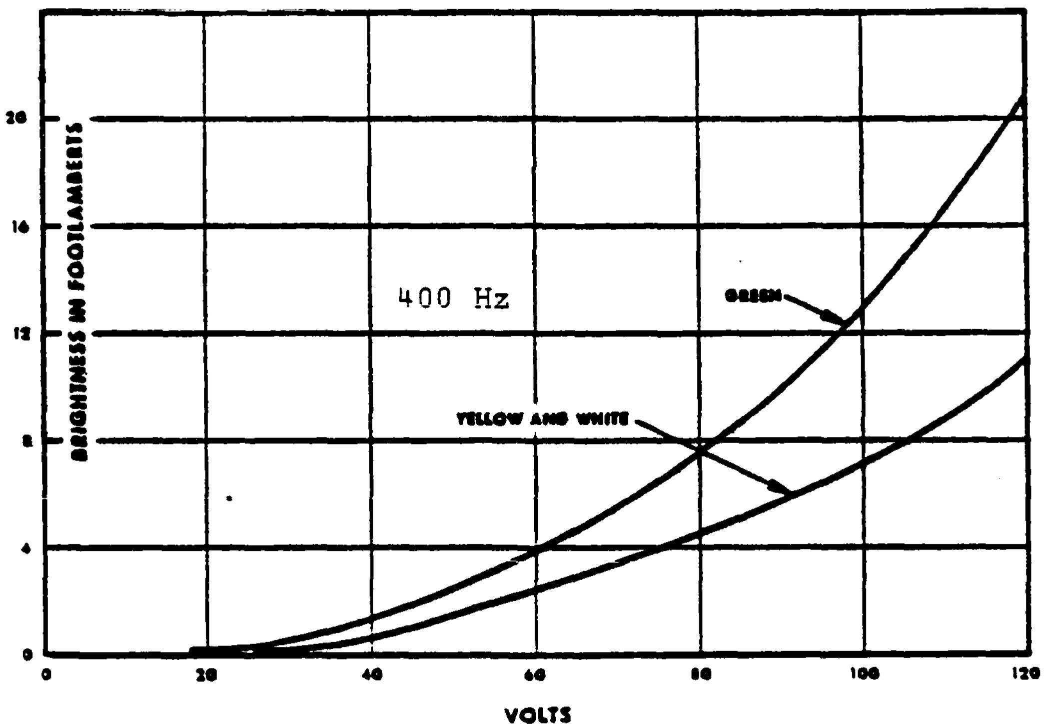
The approach to designing the model has been to identify the different observable aspects of the emission and then to attempt to construct a model that explains what is observed. The exact mechanism is still in question. This lack of full understanding has been a hindrance in the development of EL.

D. HUMAN VISION AND PHOTOMETRY

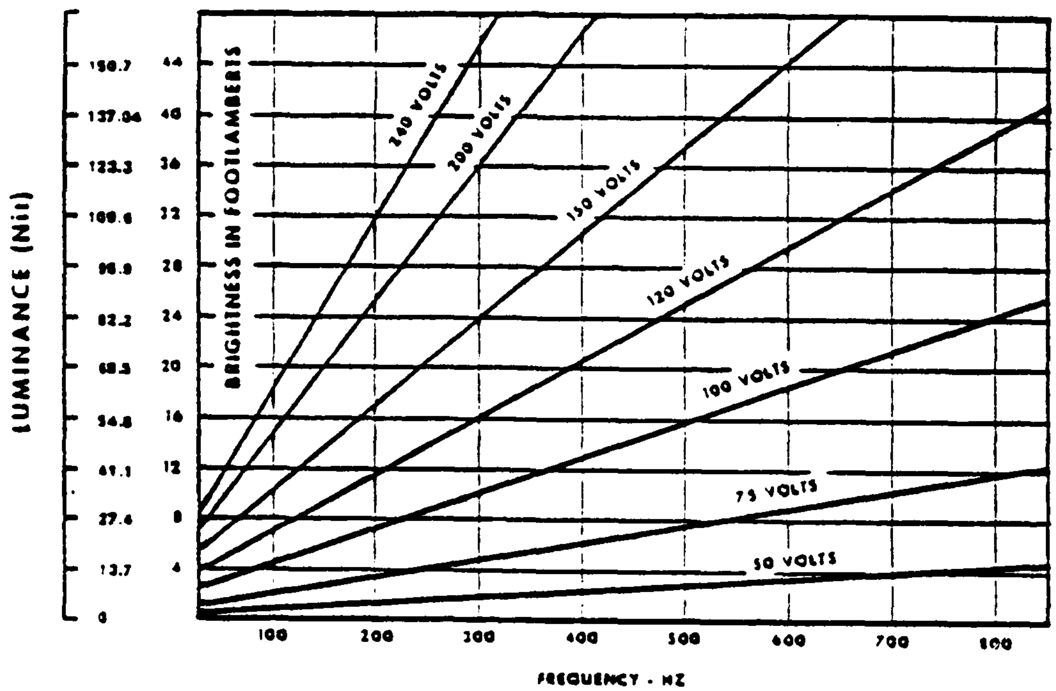
1. Spectral Luminous Efficiency

The electromagnetic spectrum is pictured below in Figure 8. Note that the visible portion of the spectrum is roughly from 390 nm to 770 nm.

The various wavelengths in this range are not equally effective in producing visual sensation in the eye. The wavelength effectiveness varies somewhat from observer to observer. Further, the wavelength



(a)



(b)

Figure 7. Typical EL Output as a Function of Voltage and Frequency: (a) Constant Frequency (b) Constant Voltage

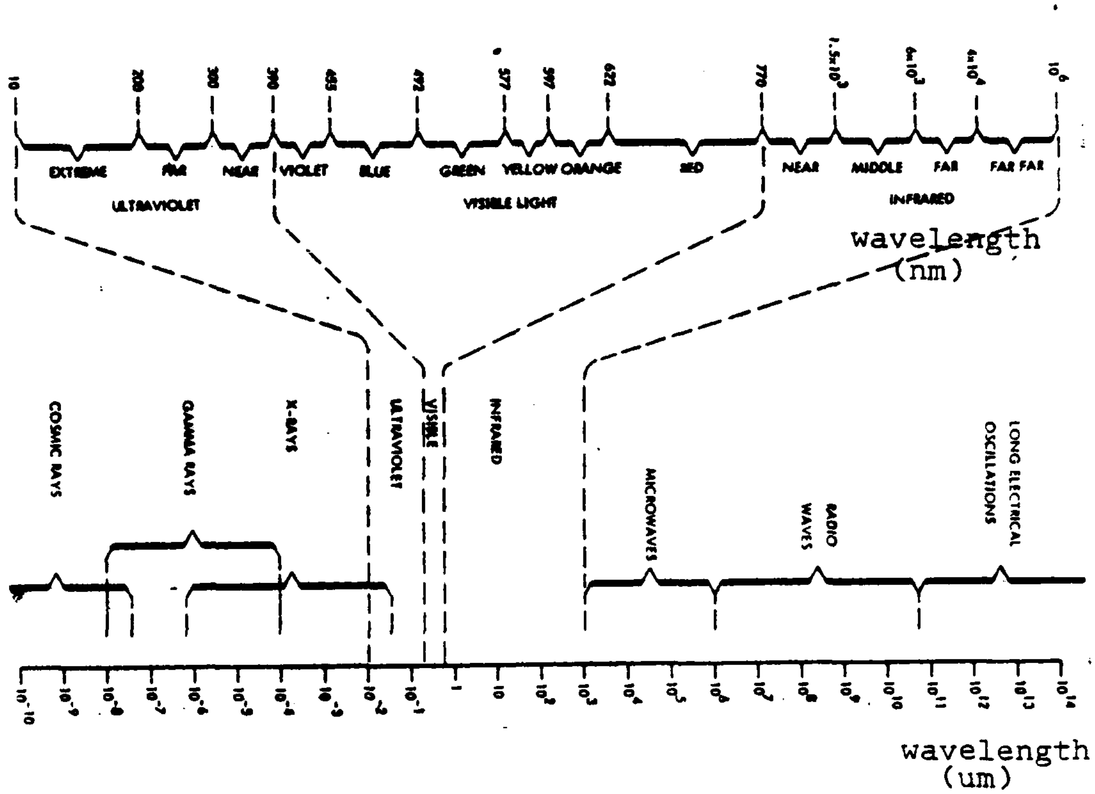


Figure 8. The Electromagnetic Spectrum

effectiveness depends on whether the eye is a photopic (cone vision/daylight conditions), scotopic (rod vision/night conditions), or mesopic (in between) state. This wavelength dependence is known as the spectral luminous efficiency, where the dimensionless efficiency factor is unity at the wavelength of maximum luminous efficacy. Tabulated values for a standard observer are well known (IES Lighting Handbook, 1981). Figure 9 is a graphical representation. The lower threshold for photopic vision is a field luminance of about 3 cd/m^2, while the scotopic upper

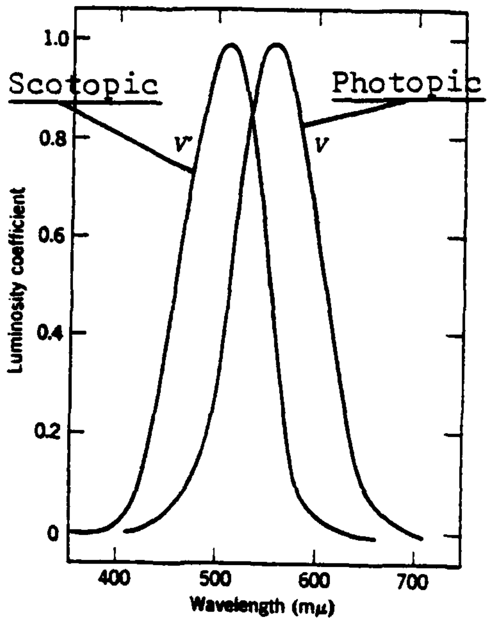


Figure 9. Spectral Luminous Efficiency for the Standard Observer

threshold is about 3 x 10^{-5} cd/m^2. In the mesopic region (in between) the spectral luminous efficiencies gradually shift depending on whether the field luminance is nearer the scotopic or photopic threshold.

2. Psychophysical Aspects

Some relevant general conclusions from research are presented here.

(1) The visual system doesn't perform as well at very low contrast levels (Stone, 1980).

(2) Smaller contrast differences can be detected with higher levels of luminance (Guth; McNeilis, 1968).

(3) A small lighted square such as an EL panel will appear to change in brightness if another source of different brightness is brought close to it. As the second source increases in luminance, the apparent brightness of the first source decreases (Diamond, 1953).

(4) Different visual tasks require different levels of illumination. A recognition task requires more light than a detection task (Blackwell, 1952).

(5) Varying the size of retinal image is similar in effect to varying the intensity of the source (Beitel, 1952).

(6) There is an inverse relationship between the intensity of a light source and its area required to yield a detection threshold response. The intensity threshold decreases to a limiting value as the area increases (Graham, 1939).

(8) In a recognition task with high contrast, ideal viewing conditions, and knowledge of target characteristics, a minimum visual angle of 12-20 minutes of arc is required to maintain constant search time and error rate (Steedman; Baker, 1960).

(9) The critical visual angle is the maximum angle at which a source may be regarded as a point. The critical angle is highly dependent on the background brightness (Blackwell, 1946).

3. Visual Acuity

Visual acuity is the ability to discriminate the fine details of an object. It is often expressed as the reciprocal of the visual angle of the target in minutes of arc. Some factors which affect visual acuity are: pupil size, source intensity, source contrast, observation time, state of dark adaptation, and source or eye movement. Visual acuity depends on the task. A recognition task places higher demands on visual acuity than a detection task. In a detection task, intensity discrimination is the basis for visual acuity (Graham, 1965). Finally, visual acuity increases with increased illumination.

E. CONTRAST THEORY

Contrast detection is the method the eye uses to visually distinguish objects. Generally, the greater the contrast, the more easily the object will be seen. The apparent luminance of a source is governed by two processes: (1) light emitted from the source is attenuated by the atmospere, and (2) background lighting is scattered along the observation path to the observer. The defining equation for contrast is (Duntley, 1948):

$$C = \frac{L - L'}{L'} \tag{3}$$

where C = contrast; L = the luminance of the object; L' = the background luminance.

Consider a certain sky background with luminance L', and let there be an empty dark hole in this sky. The amount of luminance required of a source placed into this hole to cause the hole to "disappear" (i.e., have the same luminance as its background) will be L'. But since there is no contrast there will be no light signal perceived. The observer would perceive a consistent background of luminance L' and thus zero contrast. The zero of intensity then of the light source in the hole will be at L' (Middleton, 1952).

Therefore, the defining equation for the intensity of the source is:

$$I = (L - L')A \tag{4}$$

where I = intensity; L = luminance of the source; A = area of the source. Substituting the contrast equation into the intensity equation:

$$I = L'AC \tag{5}$$

The illuminance is the amount of luminous flux per unit area arriving at the detector. The illuminance is proportional to the intensity by the inverse square law:

$$E = \frac{I\ T^R}{R^2} \tag{6}$$

where E = illuminance in lumens per unit area

T = transmissivity of atmosphere, and

R = distance from source to observer.

After substitution, the relation between the illuminance at the observer's eye and the area of the source is:

$$E = \frac{(L'AC)T^R}{R^2} \tag{7}$$

The size of a source may be expressed in terms of the angle it subtends at the eye. The "critical angle" is that subtended angle which separates point sources from extended sources. Any source that subtends an angle at the eye less than the critical angle may be considered a point source. This critical angle, however, is a function of the background luminance as Figure 10 shows. Ricco's Law states that the product of the threshold luminance and the solid angle subtended by that source is a constant. Stated another way, all combinations of area and contrast that have the same product are equivalent sources. But the apparent contrast is reduced by the atmospheric absorption and scattering. Thus, the visible range of a source may be predicted only if account is taken of the atmospheric contrast reduction. This is the purpose of nomographic visibility charts.

The connection between contrast and illuminance is straightforward. When dealing with large area sources, contrast is the meaningful quantity to measure. When dealing with point sources, which stimulate the

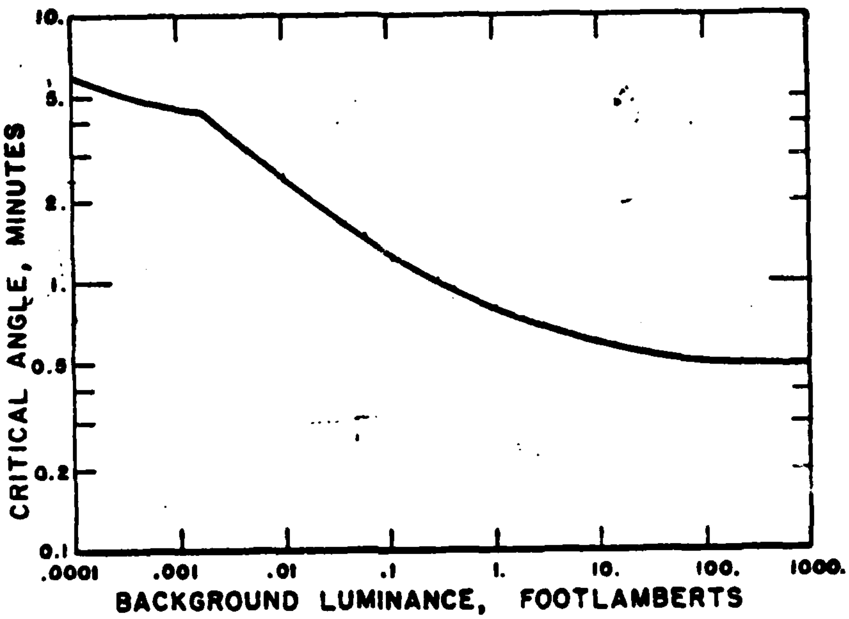


Figure 10. Critical Angle as a Function of Background Luminance

eye only in proportion to their intensity, it becomes convenient to consider the illuminance produced at the eye by the source.

F. VISION IN THE ATMOSPHERE

The topic of vision in the atmosphere is an extremely complex one and therefore only the fundamentals will be touched on here. There are many factors which affect the ability of one to see in the atmosphere (Middleton, 1952):

(1) The optical properties of the atmosphere, such as transmissivity; this general category also includes meteorological and oceanographic variables;

(2) The amount and distribution of the light;

(3) The characteristics of the source itself;

(4) The properties of the eye, and

(5) The psychological factors affecting the observer.

Absorption and scattering are the primary causes of atmospheric light extinction. Beyond these, atmospheric turbulence may be considered to play an important role. A turbulent atmosphere leads to erratic intensity distributions known as scintillation. A familiar example of this effect is "twinkling stars." Scintillation distortion or disruption can be crucial to truly coherent sources such as laser target designators. But this can also be important for the incandescent source such as the aid-to-navigation source. At near threshold levels when the mariner isn't even sure of the exact location of the source he is trying to detect, this optical disruption may render the aid undetectable.

As stated above, absorption and scattering are two processes which tend to extinguish a distant source. When the scattering particle is small compared to the transmitted wavelength, Rayleigh scattering results. This phenomenon is important in the visible region. In terms of nearly monochromatic radiation, Beer's Law indicates that the intensity is exponentially attenuated:

$$I(z) = I(0)\, e^{-\mu z} \tag{8}$$

where μ is the linear extinction coefficient for the horizontal path of length z of uniform atmospheric composition. This coefficient is the sum of absorption and scattering effects. Aerosol and molecular scattering are dominant processes in the visible band. The ratio $I(z)/I(0)$ is known as the transmittance, T, of the path length z. This transmittance is a function of the wavelength.

Visibility (or meterological range) is the horizontal distance required to reduce the contrast transmission of an object to 5%. It should be noted that most of the literature defines the contrast reduction as 2%, largely due to historical reasons. The current international standard, however, is now 5%. Thus,

$$.05 = e^{-\sigma V} \tag{9}$$

and

$$\sigma = 2.996/V \tag{10}$$

where σ is the average attenuation coefficient for the visible spectrum and V is the meterological range. Figure 11 (RCA, 1974) indicates the relation between the extinction coefficient and the daylight visibility range, using the past definition of .02 for the contrast.

The above information has been used to develop useful nomographic visibility charts using parameters such as contrast, target size, meterological range, and target distance (Duntley, 1948).

G. STATEMENT OF THE PROBLEM

Approximately 99% of Coast Guard aids-to-navigation light sources are incandescent (USCG, 1971), acting as point sources. There are various difficulties: (a) when we treat the light as one narrow beam of photons from source to detector (the eye), it is easy to see how atmospheric turbulence might deflect the beam, causing the detector to register intermittently or not at all, producing scintillation. A twinkling or flickering source isn't a fully efficient aid-to-navigation; (b) Due to halo effects, incandescent sources may look larger the

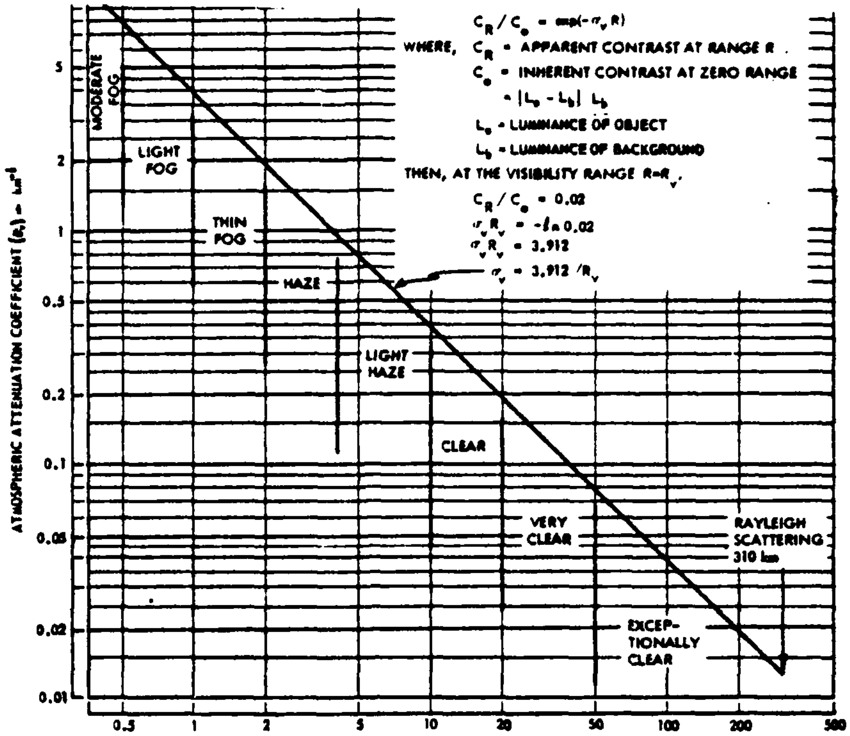


Figure 11. Extinction Coefficient and the Visibility Range

further away that they are. This has lead to depth perception problems; (c) Also, an incandescent source emits over a very wide band with most of the radiant energy delivered to the infrared portion of the spectrum. But the most serious drawback to an incandescent source is (d) catastrophic failure. When the tungsten filament breaks, the source no longer emits. In terms of aids-to-navigation, this is critical. All buoy and many shore based systems employ back-up systems. In the case of buoys, when a lamp fails to emit, a new lamp is rotated into place and the aid continues to function. Regular service intervals by aids-to-navigation personnel then replace non-working lamps with new ones. Some systems, including some critical range lights, do not have back-up sources. Typically, when such an aid becomes extinguished it remains nonworking until either the public reports the malfunction or until its failure is discovered by servicing personnel on routine checks. The time for correction of the discrepancy can range from minutes to several hours.

In some situations an EL source might have some advantages: (a) At distances where an incandescent source suffers from scintillation, the EL may not. This is particularly true if the distance is such that advantage may be taken of the EL source area; (b) There is improved depth perception since the closer an EL source is to the observer, the larger it looks; (c) the EL emits over a narrow band all in the visible; (d) Finally, the EL panel doesn't suffer from catastrophic failure.

From the above, the possibility of employing EL sources as aids-to-navigation should be investigated. The purpose of the work described in this thesis is twofold:

(1) To collect data on subjective brightness comparisons between incandescent sources and EL sources in a field test environment, and

(2) In the same environment, to investigate the importance of the spatial arrangement of lighted EL panels.

H. GOALS

The average intensities of the various 155 mm standard incandescent buoy lantern configurations are published (USCG, 1972), and the intensities for the various EL configurations may be calculated. The first goal was to determine if the EL panels are actually perceived as their intensities indicate that they should. That is, when the incandescent source and the EL source are theoretically of the same intensity, do the observers agree that the sources are of equal brightness?

The second goal was to determine if the various EL lighting patterns are statistically perceived as different in brightness. Is it better to close pack EL panels or separate them spatially for maximum perceived brightness?

II. METHODOLOGY

A. A BRIEF SUMMARY OF EXPERIMENTAL SET UP

In order to gain information on how the electroluminescent panels compared in brightness to standard Coast Guard incandescent sources, a series of direct comparison observations was made. A large EL source was fabricated from 15 smaller panels and set up 143 feet away from a standard incandescent 155 mm buoy lantern assembly. Both sources were adjusted to direct their highest intensity at the observation point, 1.3 miles distant. The observer, viewing the sources simultaneously, was then asked to decide which of the two sources was brighter. This portion of the experiment was termed the "brightness equivalence test."

In the second portion of the experiment, the buoy lantern assembly was replaced by a controllable intensity spotlight. The observer was again asked to observe the lights simultaneously and render a judgement as to which source, if either, was brighter. For this part of the experiment, only eight of the fifteen EL panels were lighted. Various patterns of these panels were then compared to the spotlight source, in an attempt to determine if the spatial arrangement of the EL panels had any effect on the perceived brightness. This portion of the experiment was termed the "spatial arrangement test."

B. REASONS FOR A FIELD TEST

The lack of control over many variables makes a field evaluation complex. However, at this point a field test of EL seemed desirable to provide concrete data on just how well EL compares to standard Coast Guard incandescent sources in various circumstances. Of course, the primary uncontrolled variable is the atmosphere but there are other factors such as the moon's contribution to background lighting. A new moon contributes much less to background luminance than does a full moon. The experiment was designed to measure comparative brightness for each observer at each observation time. Hence, within each observation the uncontrollable variables will be constant. The only difficulties that might arise would be those comparing observations made at different times. However, by collecting data in groups of approximately equal background luminances and visibility, correlation between background observational days was felt to be feasible. Then at this point, the variables of primary concern must be:

(1) Visual acuity of observer;

(2) Contrast (background luminance enters here), and

(3) Visibility of distant objects.

The assumptions are: (1) that the observation is essentially horizontal with a homogeneous atmosphere of some constant transmissivity; (2) that the output of the EL source and the incandescent sources was constant for the various test configurations over the entire period of the observation; and (3) that the various psychological and physiological factors effecting the observers (motivation, comfort, etc.) did not significantly affect the data.

C. EXPERIMENTAL SET UP

From a practical standpoint the test range selected was excellent. The sources were located 143 feet apart, atop Spanagel Hall at the Naval Postgraduate School, Monterey, California. The observer was located at the end of the Coast Guard pier in Monterey, a distance of 6937 feet from the sources. The elevation of the sources above the plane of the observer was approximately 125 feet. The background for the sources was a large, densely-wooded hill which is part of a state park. There were no artificial light sources in this background. The observer then was looking over approximately three quarters of a mile of water at a light source located another half mile inland. The observer contended with the usual shore and harbor lighting. This was a very realistic setting and closely approximated a harbor pilot making his way up a channel using the channel range lights to aid in navigating. The Monterey bay area provides a formidable test for the EL source. This area in the late summer months is notorious for its cold, wet fog that comes rolling in after sunset and typically remains until the later morning hours. Successful visibility in fog would be crucial to the acceptance of EL as an aid to navigation.

The brightness equivalent portion of the experiment was carried out as related in Pilot Study I. The EL spatial arrangement portion of the experiment was basically carried out as described in Pilot Study II. Using the results of Pilot Study II, the means of adjusting the intensity of the spotlight test source used in the spatial arrangement test was as follows. Heavy matte board filters were constructed which had circular holes cut in them with diameters varying from 1.75 inches to

5.00 inches. The incremental change in the hole diameter from filter to successive filter was 1/8 inch. As the hole diameter of successive filters increased, the effective intensity of the spotlight was also increased accordingly.

D. EQUIPMENT

1. The Incandescent Sources

Figure 12 below is a sketch of the 155 mm lantern which is the standard incandescent source used on buoys and the equipment used in this investigation (USCG, 1979). In this case, the lantern assembly consists of a red or green colored acrylic fresnel lens resting upon a polyester-resin base. The lantern base contains the components necessary to interrupt or flash the source. The fresnel lens has a specific focal plane and the lantern base is designed to allow the incandescent

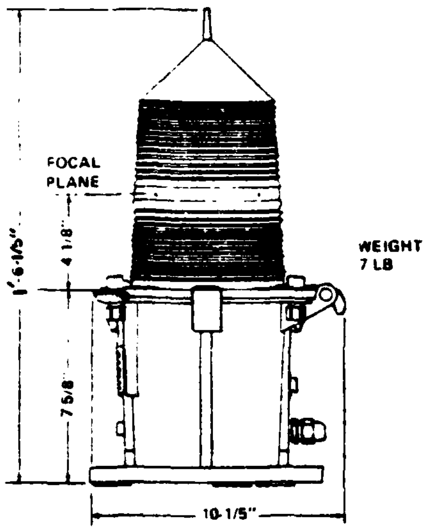


Figure 12. 155 mm Buoy Lantern

filament to rest squarely in the middle of this plane, thus automatically being focused. The lens provides the familiar fan beam as indicated in Figure 13. The intensity in the beam is 10 to 40 times greater in the horizontal plane than is the case for the bare incandescent lamp.

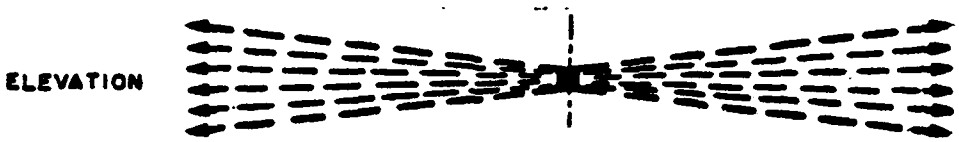


Figure 13. Fan Beam From 155 mm Source

Table 1 shows the various sized incandescent sources used at 12 volts. Note that the size is distinguished by its current rating in amperes. The incandescent sources used were powered by a Kepco, 0 - 36 volts, 0 - 5 amp, voltage regulated, power supply.

Table 1. Incandescent Source Table of Information

		Size	Intensity
155 mm 12 volts	RED LENS	0.25A	14 cd
		0.55A	35 cd
		0.77A	52 cd
		1.15A	75 cd
		2.03A	145 cd
	GREEN LENS	0.15A	23 cd
		0.55A	55 cd
		0.77A	83 cd
		1.15A	120 cd
		2.03A	230 cd

2. The EL Source

The EL source was made up of a 3 x 5 matrix of EL panels. Each of the 15 panels had lighted dimensions of 13.44 in. x 6.63 in. The maximum lighted area (all 15 panels lighted) of the source was 9.27 square feet. Each panel was attached to the 3/4 in. plywood support backing with two-sided carpet tape. This technique was used to allow for easy removal of the panels if required. The panels were mounted side by side in a close-packed arrangement three panels across and five panels high. To insure protection from exposure to the very moist and very windy source site, the EL source matrix was covered with a sheet of 1/8 in. plastic sheeting similar to Plexiglas. The assumption was made that the plastic had a negligible effect on source luminance.

In the case of the red EL source, a similar 1/8 in. filtered plastic covering was fabricated with manufacturer supplied red filter material on the inside of the protective plastic.

Each panel was connected to the "hot side" of the power supply with a 6 ampere, SPDT switch. The 15 switches allowed different panels to be lighted independently. The entire EL source was powered by a 415 hz, 220 volt, 3 phase generator. Figure 14 represents a schematic of this arrangement.

E. SUBJECTS

No attempt was made to gather subjects to represent a wide population. In fact, all observers were military personnel. All seemed highly motivated. A Bausch & Lomb Ortho-Rater was used to measure each subject for far acuity for both eyes. Ortho-Rater Test F-3 was administered. A table of pertinent information is provided below.

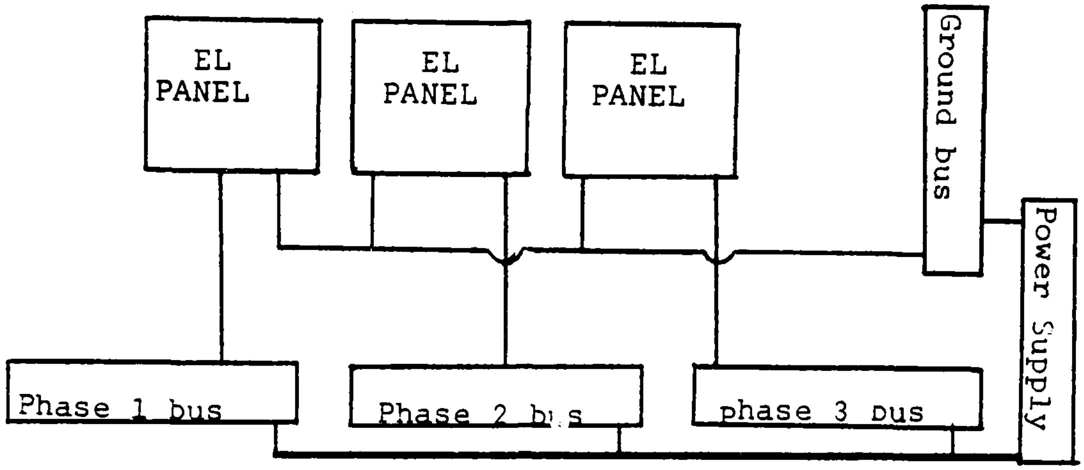


Figure 14. Schematic of EL Source

Table 2. Background Information on Subjects

	AGE	VISION	SEX	ED.	EXPERIENCE	PAY GRADE
1	31	20/20	M	BS	recent/extensive	0-3
2	29	20/20	M	BS	2 yrs nonrecent	0-3
3	28	20/17	M	BS	aviator	0-3
4	23	20/20	M	14 yr	recent/smallboats	E-4
5	19	20/20	F	HS	recent/smallboats	E-2
6	27	20/20	M	HS	recent/smallboats	E-5
7	35	20/18	M	BS	recent	0-2
8	32	20/17	M	BS	recent/buoytender	0-4
9	29	20/20	M	BS	2 yrs/nonrecent	0-3
10	36	20/18	M	BS	recent/extensive	0-3
11	31	20/20	M	MS	recent/buoytender	0-3
12	27	20/17	M	BS	2 yrs/nonrecent	0-2
13	36	20/20	M	BS	recent/sub	0-4
14	33	20/18	M	BS	none	0-3
15	28	20/22	M	BS	2 yrs/nonrecent	0-3
16	28	20/22	F	BS	none	0-3

F. PILOT STUDY I

The purpose of the initial pilot study was twofold: (1) to gain an approximate understanding of how the various EL configurations compared to the available incandescent sources (EL/IC brightness equivalency test); (2) to determine if observers could detect a brightness difference when different EL patterns were displayed even though they had the same emitting areas (spatial arrangement test). The brightness equivalency portion of the experiment concerned brightness matching of from 1 to 15 EL panels to each of 5 incandescent sources. The maximum number of observations required would then be 75.

The incandescent source (IC) was located at the western point of the Spanagel Hall roof. The EL panel matrix was set up 143 feet away, also on Spanagel Hall roof. The observer was located 6937 feet distant, at the Coast Guard pier in Monterey. At this distance, the EL panel matrix subtended less than 1.5 minutes of arc. Assuming full moon conditions, the background luminance would be of the order of .01 ft-L. Referring to Figure 10, this is equivalent to a critical angle of nearly 2.5 minutes of arc. Thus, the assumption that the EL source may be treated as a point source (and therefore affecting the eye in proportion to its intensity) is justified. This observation distance required the proctor to communicate with the observer via two-way radios.

1. Test Plan

a. Brightness Equivalency Test

An incandescent (IC) source was selected. The EL panels were switched on one at a time noting when the observer reported equal brightness. Another incandescent source was selected and the process repeated until all five incandescent souces had been tested.

As initially arranged, the proctor met with the subject at the intended observation point (Coast Guard pier, Monterey) approximately thirty minutes prior to onset of observations. This thirty minute period had a three-fold purpose. First, and foremost, it provided the necessary time for the subject to adapt to the ambient nighttime luminance. Second, a portion of the time was spent giving instructions to the subject. Finally, this time allowed the proctor to return to the source site for the start of the observations. Besides verbal instruction, the subject was left with a plastic laminated card and a red filtered penlight. The card contained the comparative brightness rating scale that the subject was to use. The card was designed to help the subject be more precise in his reported evaluation by eliminating any doubt as to what number should be reported.

The subjective brightness comparisons were made by the observer who rated the EL source (the observer's left source) in comparison to the incandescent source (the observer's right source) on a numerical scale from one to seven. The numerical observation was defined as follows:

1.....Left source much brighter than the right source

2.....Left source moderately brighter than the right source

3.....Left source slightly brighter than the right source

4.....Left source of equal brightness with the right source

5.....Right source slightly brighter than the left source

6.....Right source moderately brighter than the left source

7.....Right source much brighter than the left source.

The subjects were not told which source was the EL source. In fact, the observers were told nothing about the sources except that they would observe two sources and make a brightness judgement.

b. Spatial Arrangement Test

The purpose of this portion of the experiment was to investigate the effect on perceived brightness due to different spacial arrangements of the EL panels. A 155 mm incandescent source was selected and various arrangements of the equivalent 8 EL panel source was tested against it. The test patterns are shown in Figure 15. These test patterns could not be resolved by the observers.

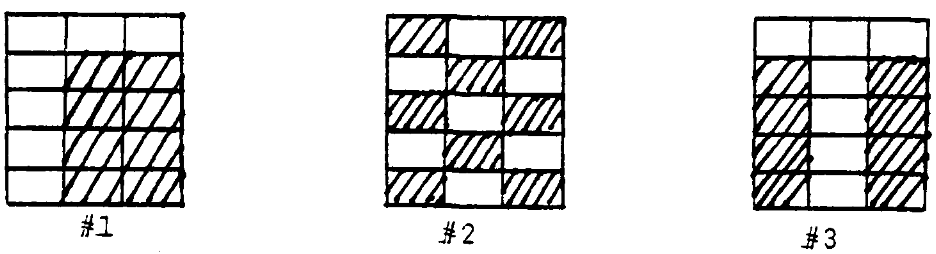


Figure 15. EL Test Patterns

Each test pattern was tested at least twice against the observer in a random fashion.

2. Pilot Study I Results

Four subjects were selected and the two part experiment carried out. The results of the brightness equivalency test provided approximate information on which incandescent source matched 8 close-packed (pattern #1) EL panels.

The results of the spatial arrangement test were inconclusive. It was felt that the experimental technique devised was inadequate due to its lack of sensitivity. A technique was required that would provide a sensitive means of adjusting a test source until it matched in brightness a particular pattern of 8 EL panels. A statistical comparison of the intensity matches would then indicate if there was indeed a difference in perceived brightness of different spatial arrangements of the EL panels. Upon consideration, the intensity adjustable spotlight was selected to carry out this portion of the experiment since it could provide the requisite "fine tuning" possibly required to match the various EL patterns.

3. Directions to Observers

"The purpose of this experiment is to ascertain the relative brightness of two different sources. Your task as an observer is to report which of two sources, left or right, is brighter and to describe qualitatively how much brighter one source is. The proctor will now go through the seven point rating scale on the card in front of you.

"Observe the two green sources in the distance noting there is indeed a 'left source' and a 'right source' as you face the sources. Practice rating these sources.

"The value of your observations cannot be underestimated. Your brightness evaluations are important. Therefore, try to be as accurate as possible, reporting in an unbiased manner exactly what you see. If the two sources seem of equal brightness, so state that. However, should one source be brighter than the other, report that, remembering to use your reference card if need be. Do not attempt to judge your performance by any inflections you may perceive in my voice while we are communicating. Remember, unbiased reporting is essential.

"You will be asked to avert your eyes from these sources from time to time to allow for source adjustment. Please do so since it does matter how the sources are presented to you. Remember also not to look toward any high intensity lights in your observation area (such as pier lighting). This too could affect your observations.

"Finally, we will be communicating on channel 21 VHF. We will obtain a radio check once before I leave the pier area and then once more in the vicinity of the source site. If at any time during the test you have a question feel free to ask. Remember, there is no time limit on your observations. Do you have any questions at this time?"

G. PILOT STUDY II

One of the areas explored in this investigation was the importance of the spatial arrangement of the EL panels which were lighted. From the observation distance, the patterns were indistinguishable and were point sources. The question to be addressed was whether or not an observer perceived one pattern to be brighter than another through both patterns had identical emitting areas.

The results of Pilot Study I indicated a different method be employed then merely comparing different EL patterns to one fixed 155 mm incandescent buoy lantern. The means used to address this question was as follows. A certain source, the spotlight test source, was set up and a means devised to accurately, incrementally adjust its intensity. The test source was then allowed to emit at some level of brightness obviously different than that of the EL source. The test source was then intensity adjusted until the observer reported equal brightness between the two sources. This process was repeated for several EL patterns. Evaluation of the data would determine if there was a statistically discernable difference in perceived brightness between patterns.

In order to carry out the proposed test, a pilot study was conducted to determine some preliminary results. A photo enlarger shell fitted with a 150 watt, commercial, outdoor spotlight was set up on a stable tripod approximately 140 feet from the EL source. Approximately 14 inches in front of the lamp was fitted a large diffusing plate and directly in front of the diffusing plate was fitted a filter holder. The filter holder not only held the colored filters but also plates of various sized openings used to control the effective intensity of the light.

A volunteer observer was selected and the tests were conducted. (The visibility at the time of the observations was 4 miles in fog.) The red filtered EL source was lighted in a close-packed 8 panel pattern. A number of red acetate filters was placed in front of the spotlight test source until the observer reported that both sources were the same color. Then aluminum flat stock plates with 1 inch increment holes cut in them were used to restrict the effective intensity to any desired level. From the reports of the observer, a region was determined wherein smaller increments would be desirable to carry out the main experiment. The observations were then repeated for the green EL source. Again, results were obtained for the intensity region of interest. However, during the course of the main experiment, it became necessary to drop the green EL spatial arrangement test and do the test only with the red EL. This necessity was due to the excessive time required for the observations.

H. SPECTRAL MEASUREMENTS OF EL

The electroluminescent source was set up in a darkroom laboratory. The exposed portion of the EL panel measured 4.0 inches in diameter. The remaining panel and a large area of the background was covered with a flat black matte surface. An EG&G model 585 spectroradiometer was used to make measurements of the source from 380 nm to 800 nm. The results are indicated in Figure 16. Note the peak emission at 520 nm. The CIE curve for the average observer is overlaid on this emission curve to point out the relative photometric efficiency of EL.

I. LUMINANCE/INTENSITY OF EL

1. Experimental Measurement of EL Luminance

An experiment was carried out to determine the luminance of the EL source. A black matte surface with a 1 inch diameter hole in it was placed over the EL source. This one inch diameter emitting area was used to measure the luminance of the EL panel, assuming the panel is of uniform exitance.

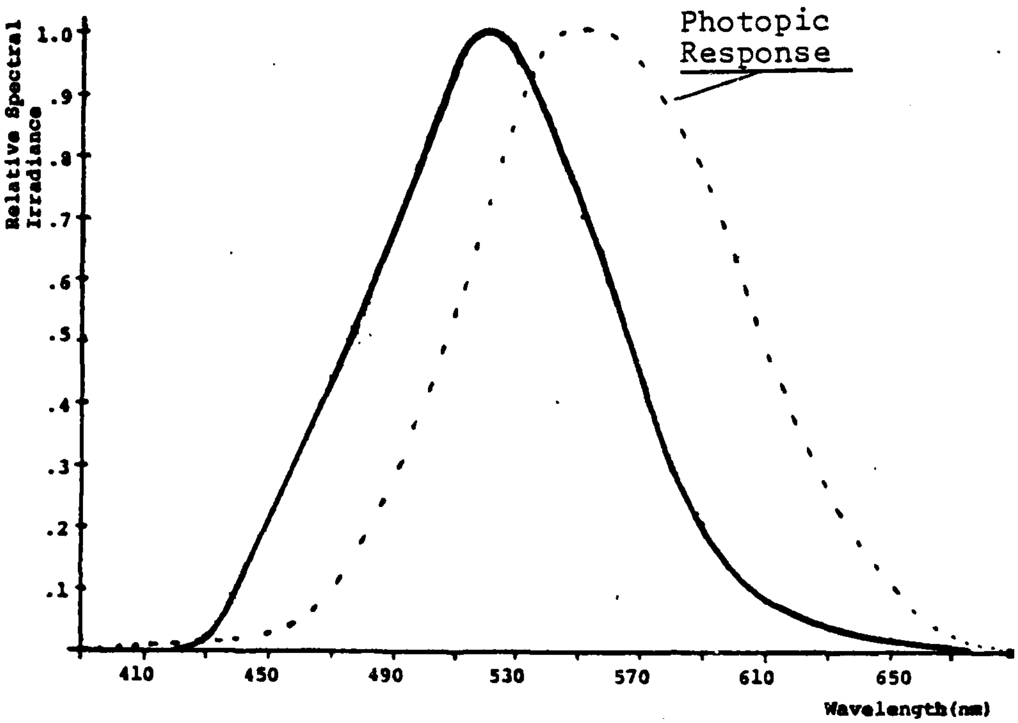


Figure 16. Spectral Emission of EL

In a darkroom laboratory with essentially no ambient light, the EL source was powered by a 12 volt DC source via an inverter supplied by the EL manufacturer. This inverter converted the 12 volt DC source to a

400 HZ AC source at approximately 90 volts. The entire EL panel, including that portion covered by the black matte surface, drew approximately 1.93 amperes at 12 volts DC.

The device used to measure the luminance was a Tektronix model J6203 1° Narrow Angle Luminance Meter. The detector was placed 84 inches from the EL source thus insuring that the source fell entirely within the 1 degree viewing angle as well as insuring the EL source was viewed as a point source.

Identical measurements were made except this time the EL panel was wired directly to the 415 Hz generator used in the main experiment with the detector located 101 inches away from the EL source. The results for both experiments are tabulated below for both red and green sources. Note that the measurements were essentially the same using the inverter or using the 415 Hz generator directly. Also note the dramatic reduction in EL photometric brightness when the red filter was used.

Table 3. Luminance Measurements for Red and Green Sources

	RED EL	GREEN EL
12 V. dc with inverter	1.4 ft-L	8.5 ft-L
415 hz generator	1.4 ft-L	8.4 ft-L

2. The Equivalent Intensity of EL

These EL panels are assumed to closely approximate a Lambertian surface, one whose luminance is the same in every direction over the hemisphere. The luminous intensity in a given direction of this emitter varies only with the cosine of the angle between the normal to the surface and the given direction. An important relation for Lambertian surfaces is:

$$1\ \frac{\text{cd}}{\text{ft}^2} = \pi \text{ ft-Lamberts} \tag{11}$$

A Lambertian source emitting one lumen per square foot has a luminance of 1 ft-L. The derivation of this relation is as follows (Cotton, 1960).

Figure 17 represents a Lambertian source emitting into a hemisphere of radius r. Suppose there to be an annular ring located at θ,

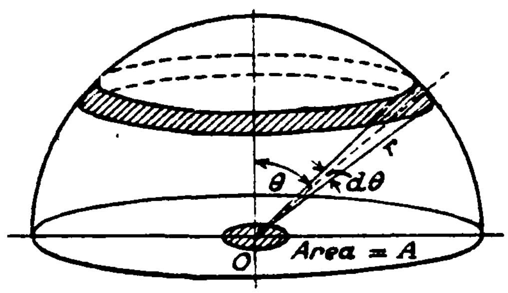


Figure 17. Lambertian Source Emitting Into Hemisphere

of width $d\theta$. The area of the ring is $2\pi r\sin\theta\ d\theta$. If $r = 1$, then the area of the hemisphere is numerically equal to the subtended solid in steradians:

$$dw = 2\pi\sin\theta d\theta \tag{12}$$

Let the luminance of the emitter be L. Its luminous intensity, I, is equal to the product of its luminance and the source area projected in the direction θ:

$$I = L\ A\ \cos\ \theta \tag{13}$$

But the luminous flux, $d\phi$, received by the annular ring is just:

$$d\phi = Idw \tag{14}$$

and

$$\Phi = LA \int_{0}^{\pi/2} (\cos\theta)\ 2\pi\ \sin\theta\ d\theta \tag{15}$$

Therefore:

$$\frac{\Phi}{A} = L \tag{16}$$

Stated in words, the luminous flux per unit area is equal to the product of the luminance and π. When the unit of length used is the foot then the unit for luminance is the foot-Lambert (ft-L).

The above relation provides the means to arrive at a value for the intensity of the EL source. Table 4 below provides the calculated intensities for the number of EL panels lighted. To put these calculated intensities in perspective, columns four and six indicate the

Table 4. Calculated Equivalent Intensities for EL

LIGHTED PANELS	LIGHTED AREA (FT^2)	I(cd) GREEN EL	SIZE (AMPS) GREEN IC	I(cd) RED EL	SIZE (AMPS) RED IC
1	.62	17	.25A	3	
2	1.24	33		5	
3	1.86	50	.55A	8	
4	2.48	66		11	
5	3.10	83	.77A	14	.25A
6	3.72	99		16	
7	4.34	116	1.15A	19	
8	4.96	132		19	
9	5.58	149		25	
10	6.20	166		27	
11	6.82	182		30	
12	7.44	199		33	
13	8.06	215		35	.55A
14	8.68	232	2.03A	38	
15	9.30	248		41	

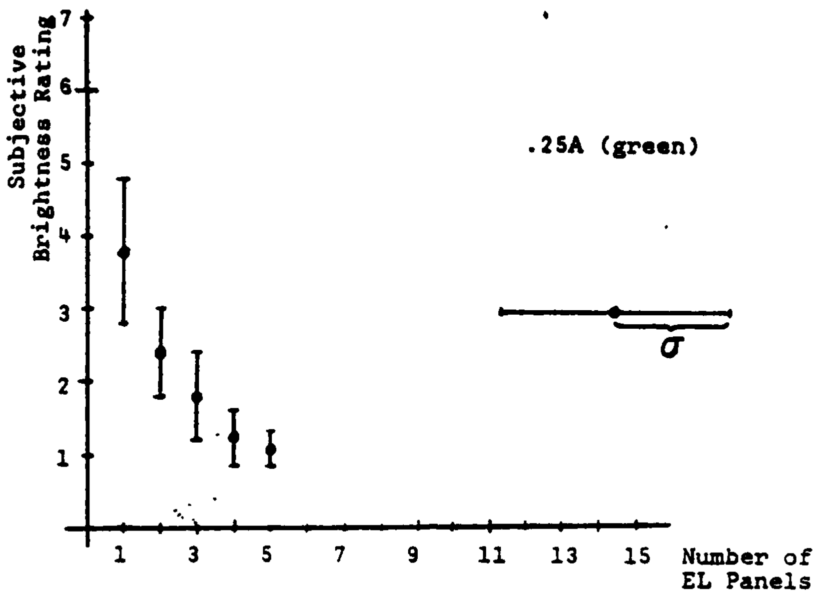
tabulated average intensities for various red and green 12 volt, incandescent aids-to-navigation. Thus, one may arrive at a theoretical intensity equivalence for the EL panels and the incandescent sources. Since both sources are considered point sources at the proper distance, this amounts to a brightness equivalency.

III. RESULTS AND DISCUSSION

A. ANALYSIS OF THE BRIGHTNESS EQUIVALENCY TEST

1. Graphical Analysis (Green EL Source)

The purpose of this portion of the experiment was to determine approximately how many EL panels were required to equal in brightness each of five Coast Guard standard 155 mm aid-to-navigation sources. Figures 18 through 22 are plots of the number of lighted EL panels versus the corresponding brightness rating given by the observer as compared to the indicated incandescent source. As an aid to the reader, Figure 18 also restates the brightness rating scale. These plots show qualitatively how the addition or deletion of panels affects the perceived brightness. One may also choose from these plots the approximate number of EL panels required to equal a particular incandescent source. For example, Figure 19 indicates that a brightness rating of 4 (EL and incandescent equal in brightness) corresponds to approximately 2 EL panels for a green .55A incandescent source. These plots represent simple averages of all the observations. No provision was made for different experimental conditions between observations



<u>Subjective Brightness Rating Scale</u>

(1) EL source much brighter than incandescent source

(2) EL source moderately brighter than incandescent source

(3) EL source slightly brighter than incandescent source

(4) EL source equal in brightness to incandescent source

(5) incandescent source slightly brighter than EL

(6) incandescent source moderately brighter than EL

(7) incandescent source much brighter than EL

Figure 18. Brightness Rating Vs. Number of EL Panels for a Green .25A Incandescent Source

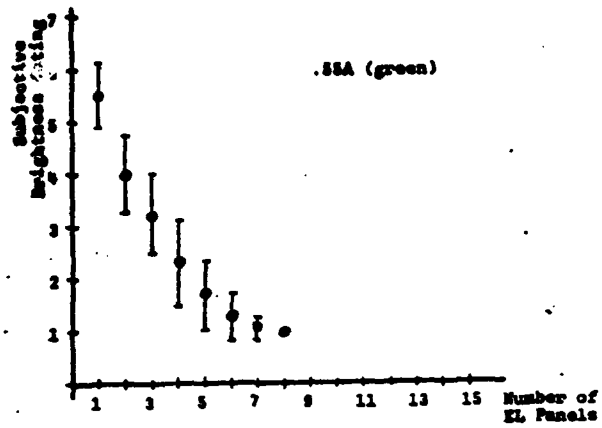


Figure 19. Brightness Rating Vs. Number of EL Panels for a Green .55A Incandescent Source

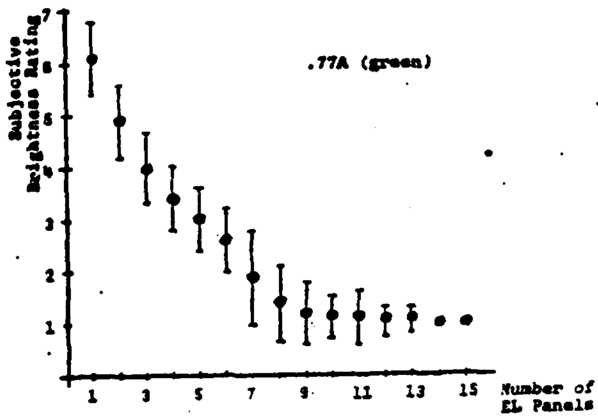


Figure 20. Brightness Rating Vs. Number of EL Panels for a Green .77A Incandescent Source

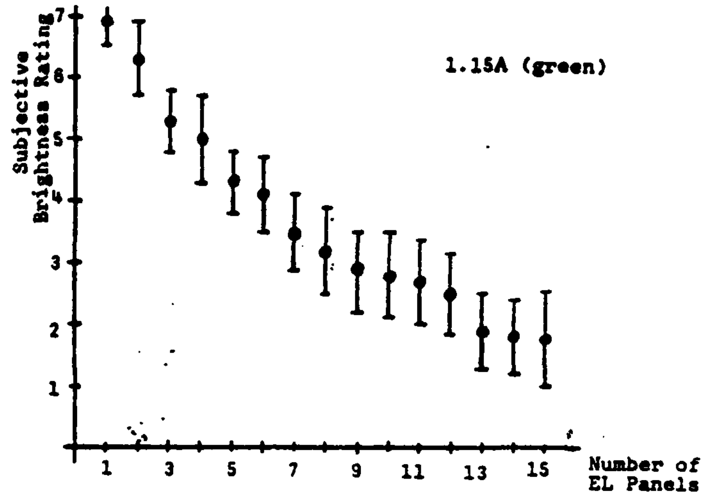


Figure 21. Brightness Rating Vs. Number of EL Panels for a Green 1.15A Incandescent Source

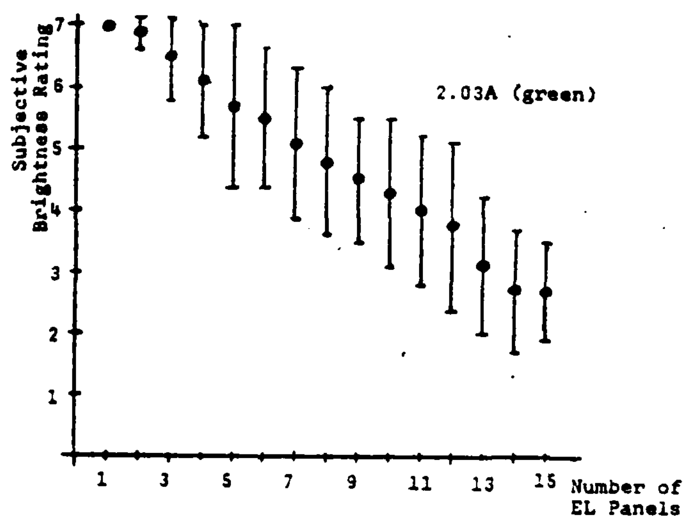


Figure 22. Brightness Rating Vs. Number of EL Panels for a Green 2.03A Incandescent Source

The impact of the atmospheric conditions on the observations is important. It is of particular interest in this case to determine if low visibility conditions significantly affect the perceived brightness of the EL. The real test for any lighted aid is how well it performs under low visibility conditions, when it is needed most. Table 5 lists the number of observations carried out at the various visibilities during the course of the experiment.

Table 5. Atmospheric Conditions

Visibility (miles)	Number of Observations
1	1
2	3
3	2
6	1
8	3
10	3
15	3

Figures 23 through 27 portray the effect of visibility on the number of EL panels required to achieve equal brightness with the indicated incandescent source. The ordinate axis represents the number of EL panels required to equal in brightness the incandescent source for that particular graph. The abscissa is the visibility in miles. Note

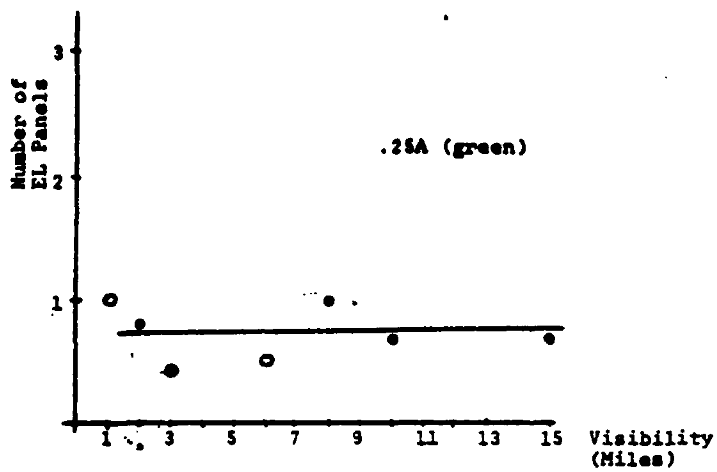


Figure 23. Visibility Trend for EL Panels When Compared to a Green .25A Source

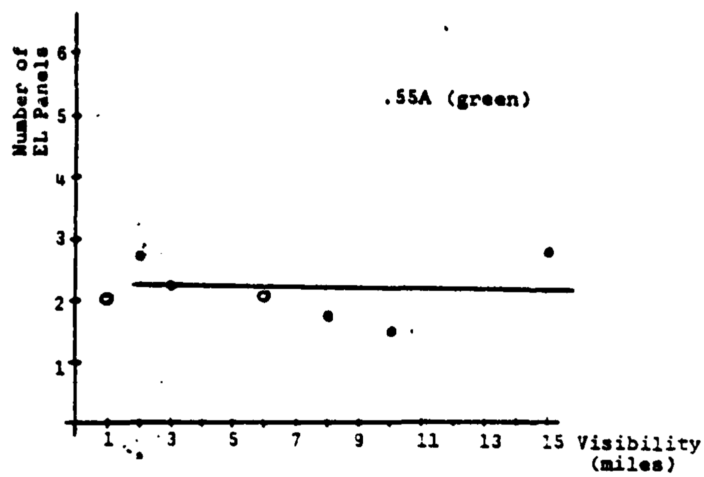


Figure 24. Visibility Trend for EL Panels When Compared to a Green .55A Source

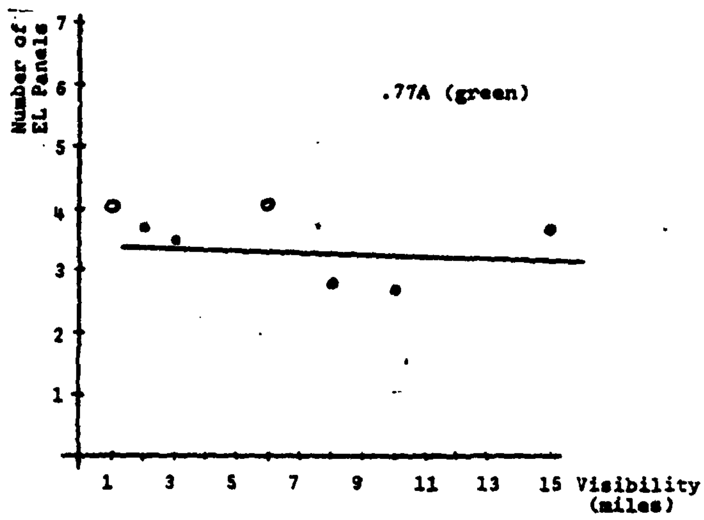


Figure 25. Visibility Trend for EL Panels When Compared to a Green .77A Source

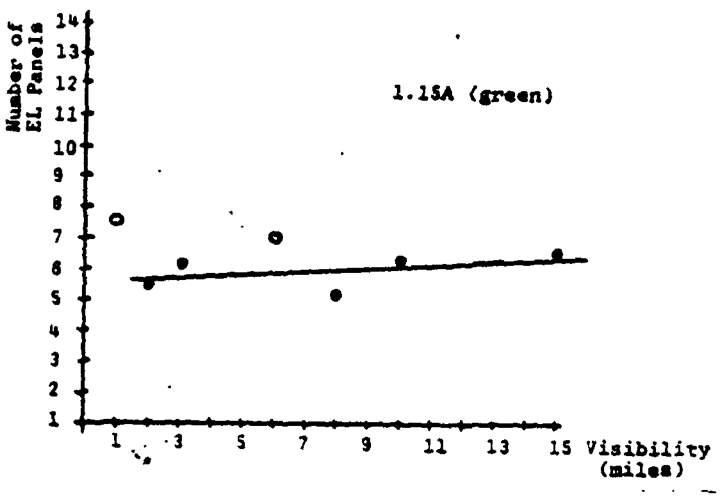


Figure 26. Visibility Trend for EL Panels When Compared to a Green 1.15A Source

that in Table 5 visibilities of 1 mile and 6 miles had only one observation apiece and thus are of lowest reliability. On the graphs this is indicated by using an "open circle" as the datum. The data points in Figures 23 through 27 represent the average number of panels required for the actual visibility levels. The solid line is a least squares linear regression without using the 1 and 6 mile visibilities. The nearly zero slope indicates no linear relationship exists between the visibility and the number of panels required to achieve equal brightness with a selected incandescent source, except that Figure 27 points out an interesting anomaly. In the 2.03A case, there appears to be a very definite relationship. This linear relationship, though reduced, remains evident even when the 1 and 6 mile observations are included. This plot indicates that as one decreases visibility, the number of EL panels required to equal the 2.03A source goes down. On exceptionally clear nights, one would need about 12 EL panels to equal the green 2.03A incandescent source, but at visibilities as low as 1 mile, only 7 EL panels would be required. The regression lines for each comparison case are plotted in Figure 28 to aid in visualizing the trend.

Figures 29 and 30 require careful explanation. The dual axis is labelled in intensity units (candela) and in corresponding incandescent lamp size. For example, a green 1.15A source in a 155 mm lantern corresponds to an intensity (at standard voltage) of 120 cd. The abscissa axis is the number of EL panels required to achieve equal brightness with a particular incandescent source. The solid line is a plot of the Lambertian relation:

$$1 \text{ cd/ft}^2 = \pi(\text{ft-L})$$

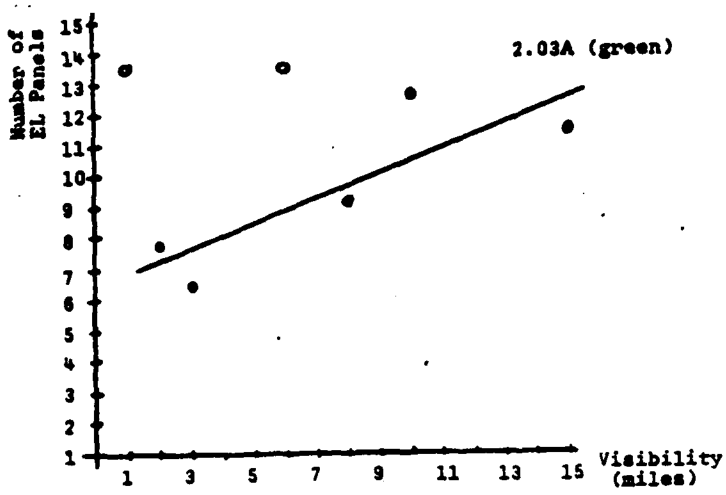


Figure 27. Visibility Trend for EL Panels When Compared to a Green 2.03A Source

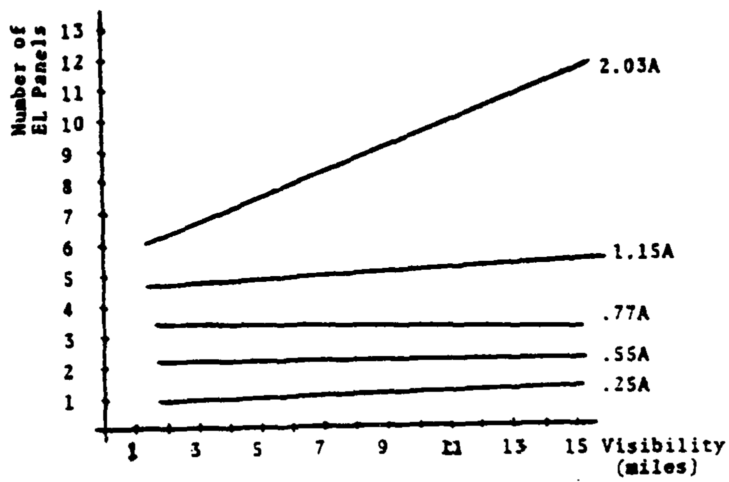


Figure 28. Composite Visibility Trends for All the Incandescent Sources

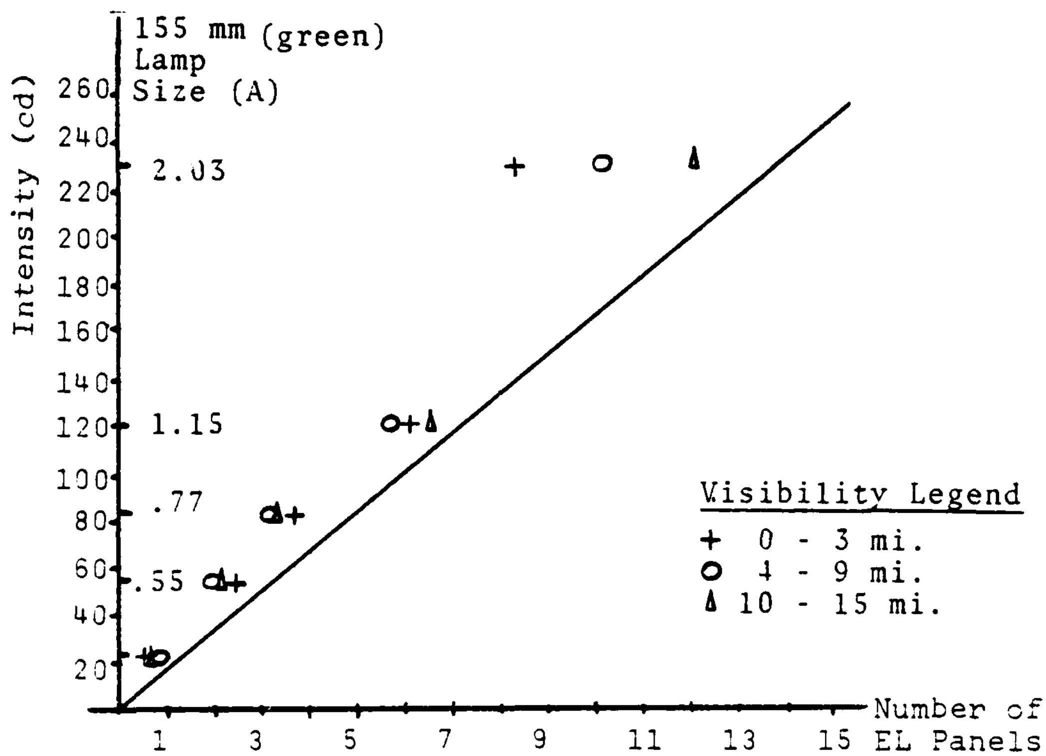


Figure 29. Effect of Visibility on Comparative Brightness

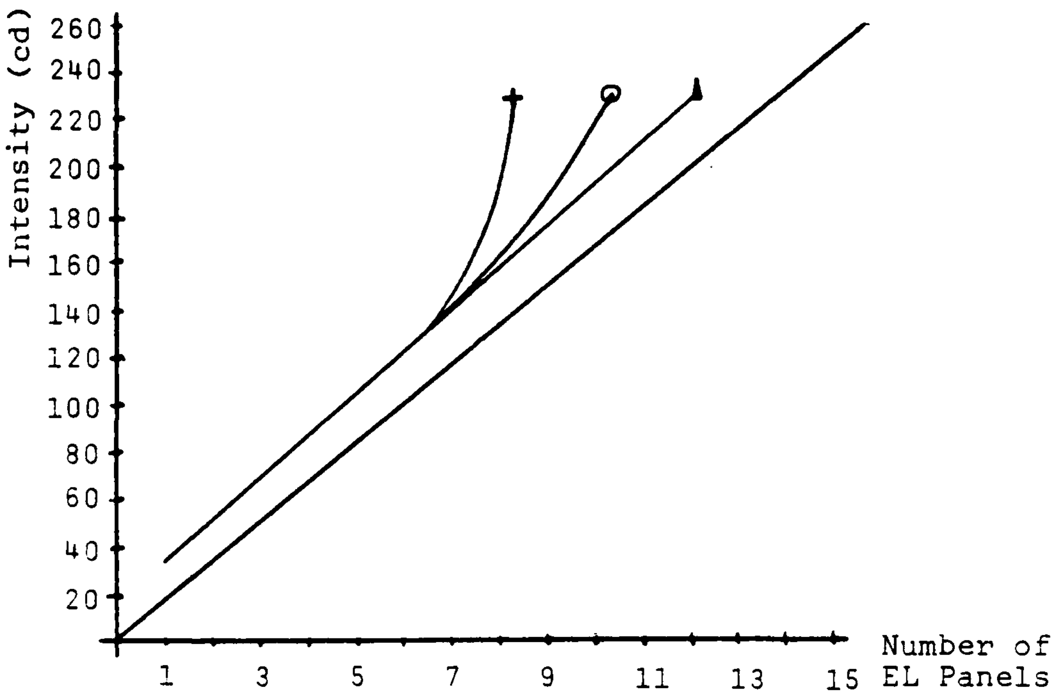


Figure 30. Visibility Trend for Equal Intensity Sources

which yields the theoretical equivalent intensity of the EL panels given their area and luminance in foot-Lamberts. As the legend indicates, there are then 3 data points for each incandescent source comparison. For example, when comparing brightness between the EL and the 1.15A incandescent source, one arrives at three values; i.e., one for each of the visibility conditions. The following assumption is made in plotting the data. Since both sources are point sources and therefore affect the eye in proportion only to their intensity, it is assumed for the purpose of this plot, that when the observer reports the two sources equal in brightness then they must have the same effective intensity. Therefore, if the observer reported that there was equal brightness between 6 EL panels and the 1.15A incandescent source, the ordinate coordinate would be the tabulated intensity for the 1.15A green incandescent lamp from Table 1 and the abscissa coordinate would be 6, the number of EL panels required for equivalent brightness. This method provides an interesting and vivid picture of the apparent effect of visibility on EL.

There are several points of interest here. First, note that regardless of the visibility, the EL seems to perform slightly better than the theoretical curve would indicate. Equal brightness appears to occur about 1 panel less than theory would predict for the four lowest size lamps. Second, note the dramatic effect that visibility appears to play in the 2.03A case. For good visibility (10-15 miles), the linear relationship between the number of EL panels and the intensity holds very well. As the visibility drops, however, this linear relationship appears to break down.

2. Statistical Analysis (Green EL Source)

Table 6 below represents a statistical summary of the observations. An analysis of variance was carried out considering the three visibility categories as treatments. The null hypothesis (H_0), for each incandescent source was $\mu_1 = \mu_2 = \mu_3$, where μ is the population mean. The test was conducted at the .1 level. The null hypothesis could be rejected only in the 2.03A case. The difference in means in the 2.03A case could not be attributed to chance fluctuations at that level.

Table 6. Statistical Summary of Observations

GREEN INCANDESCENT SOURCE SIZE (AMPS)	VISIBILITY					
	0-3 miles		4-9 miles		10-15 miles	
	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ
.25A	.583	.607	.75	.433	.67	.471
.55A	2.42	.449	1.87	.217	2.17	.80
.77A	3.67	1.07	3.13	.545	3.17	.745
1.15A	6.08	1.06	5.625	.82	6.58	1.06
2.03A	8.33	2.49	10.25	2.46	12.08	.975

Table 7 provides another view of the data. Column 1 is the incandescent source size that the EL source was compared to. Column 2 lists the average intensity for each of these incandescent sources. Column 3 is referred to as the "equivalent brightness" intensity and is determined as follows. As shown in Figures 18 through 22, an equal brightness rating corresponded to a particular number of EL panels. This number of panels, converted to area in square feet, was used in the Lambertian relation to yield the "equal brightness" intensity.

The data from columns 2 and 3 in Table 7 are plotted in Figure 31. Since a linear relation seemed likely, a linear equation was developed using the least squares technique. This regression line is plotted as the solid line in the figure. The correlation was calculated to be .998 indicating that the line fits the data very well and that there is a strong linear relationship between the incandescent intensity and the "equal brightness" intensty of the EL source. To support this

Table 7. Tabulated Intensities

COLUMN #1 Incandescent Source Size (amps)	COLUMN # 2 Incandescent Intensity (cd)	COLUMN # 3 Equal Brightness Intensity (cd)
.25	23	16
.55	55	32
.77	83	48
1.15	120	95
2.03	230	175

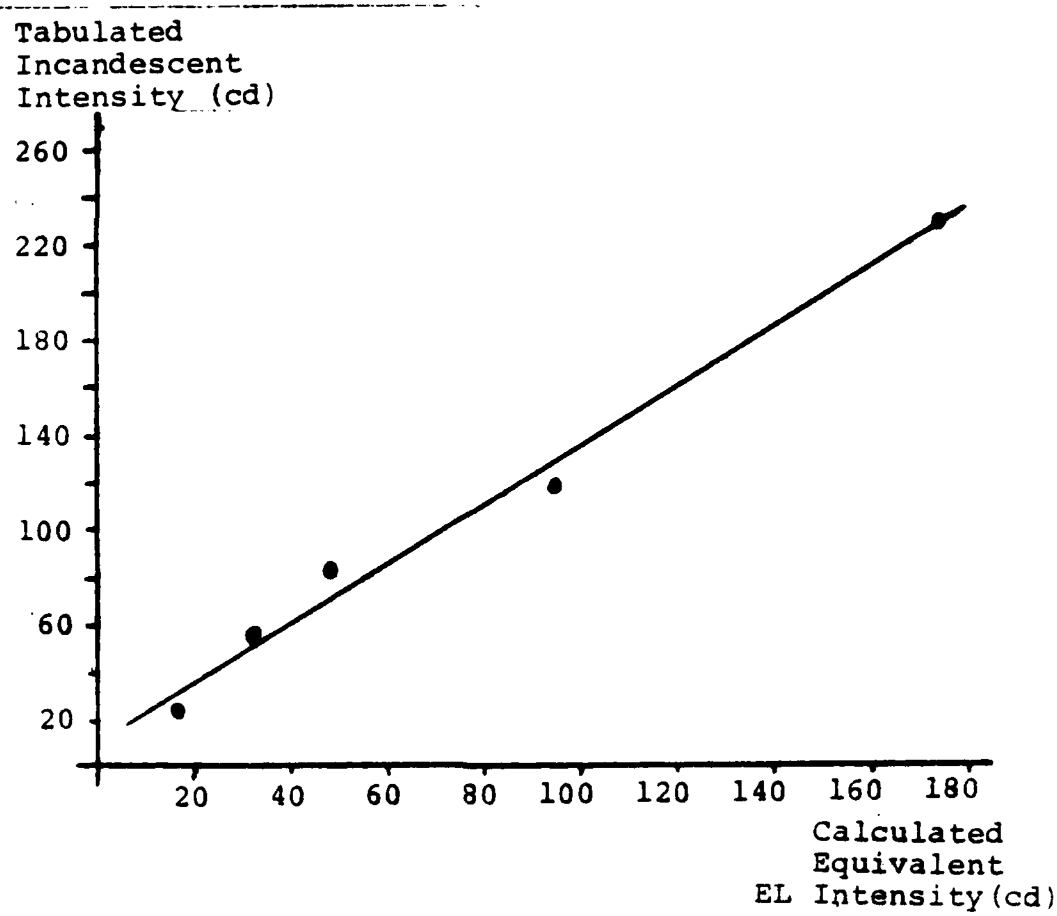


Figure 31. IC Intensity Vs. EL "Equal Brightness" Intensity

conclusion, a two-sided 95% confidence interval was constructed for the slope, B, of the regression line:

$$B = 1.24 \pm .26$$

Therefore, B is discernable from zero. Though care must be exercised, one may predict the "equivalent brightness" intensity (and thus the source area) for a given incandescent source within the limits of the tested data.

3. <u>Graphical Analysis (Red EL Source)</u>

Figures 32, 33, and 34 again relate the brightness rating to the number of lighted EL panels as discussed above. Only three incandescent sources were tested here since the red EL at maximum intensity was not able to equal the brightness of .77A, 1.15A, or 2.03A sources.

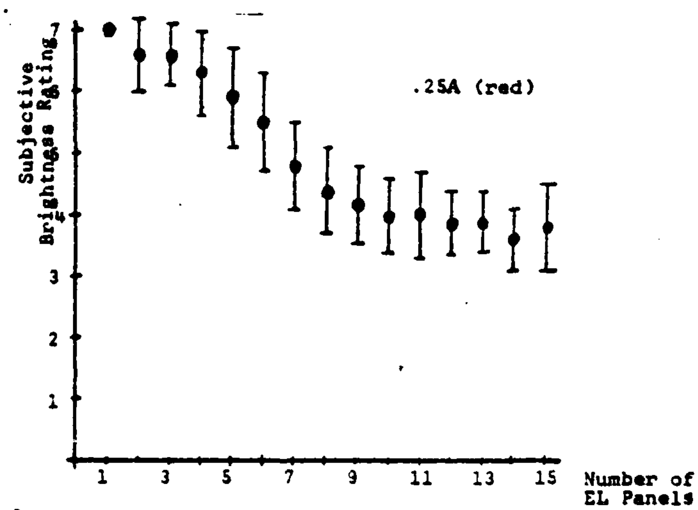


Figure 32. Brightness Rating Vs. Number of EL Panels for a Red .25A Incandescent Source

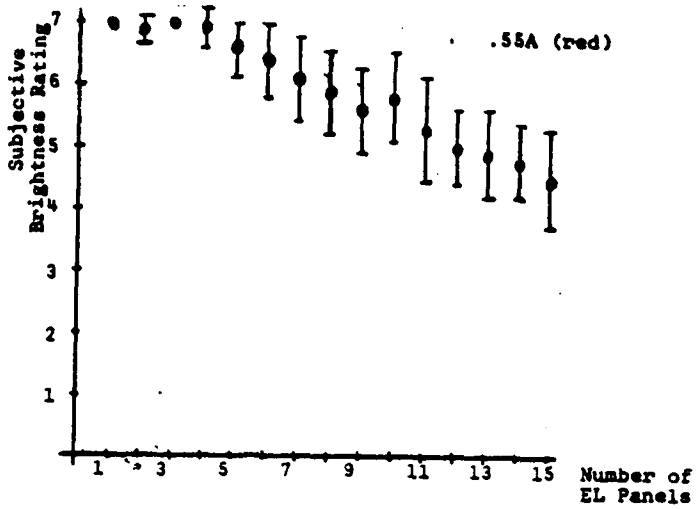


Figure 33. Brightness Rating Vs. Number of EL Panels for a Red .55A Incandescent Source

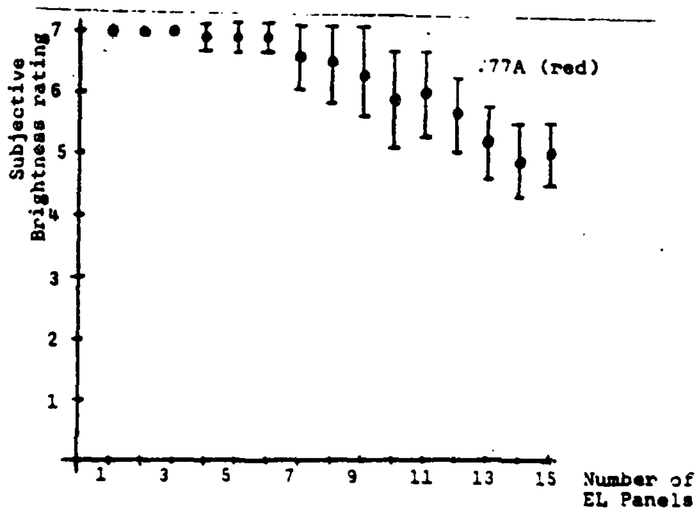


Figure 34. Brightness Rating Vs. Number of EL Panels for a Red .77A Incandescent Source

Figure 35 is a plot of the number of red EL panels required for brightness equivalence as a function of the visibility. Again, the nearly zero slope indicates at a .1 confidence level that there is no linear relationship between visibility and the required number of panels to equal a red .25A incandescent source.

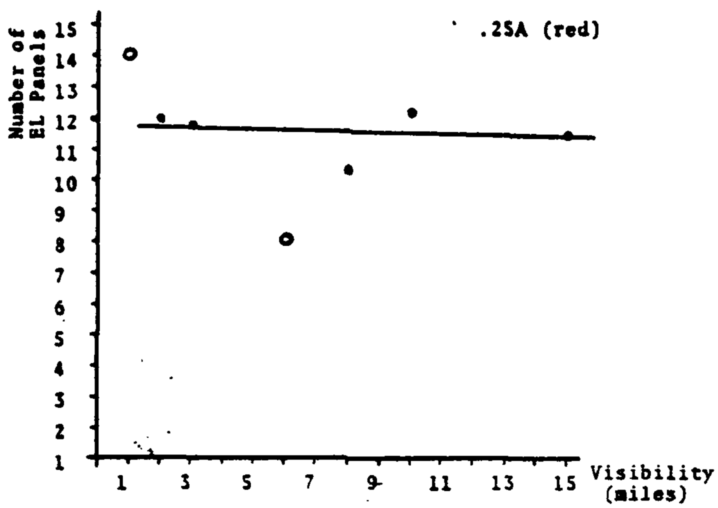


Figure 35. Visibility Trend for Red .25A Source

In Figure 36, only the red .25A source data could be plotted since even the .55A source required in excess of 15 EL panels for equivalent brightness. Note that the data points indicate the red EL to perform not as well as theory predicts.

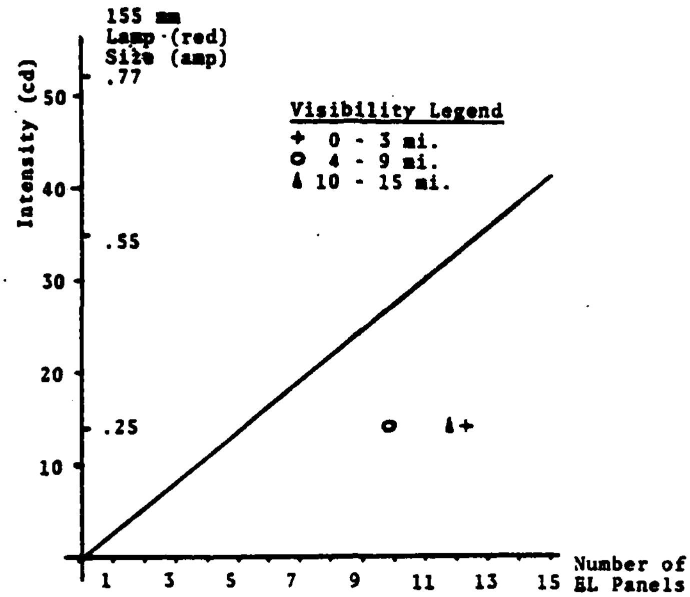


Figure 36. Red EL Visibility Trends

4. <u>Discussion of Green EL Brightness Test</u>

From the data, it appears that the green EL source performs better than the Lambertian relation would predict. There are two possibilities for this considered here. First, the measured luminance (ft-L) of the EL source has a direct effect on these results. The calibration of the luminance meter could not be verified, thus creating some uncertainty as to the validity of the measured luminance. This would affect the slope of the straight line in Figure 29, but would not account for the 2.03A anomaly. Second, it has been suggested (Pieroway, 1981) that the EL emission mechanism itself may have an unexplained effect of increasing the visual sensation.

As stated, regardless of the visibility conditions there was no statistically significant difference in EL performance for the lower intensity values. The anomaly for the 2.03A case could possibly be explained as due to the increase in area. As Figure 22 indicates, this comparison test required the most panels (hence larger source area) to be lighted. Brightness, the criterion used by the observer, is a psychological concept and can't be measured. But a brightness comparison is a valid measure of difference in sensation and is essentially a detection task. As stated earlier, for point sources the key parameter is the intensity, and the EL angular size fell well within the region of point sources. Even accepting ±25% as a reasonable variance as the Roscommon tests (Blackwell, 1949) would indicate, the EL source at maximum intensity could be considered a point source and therefore, essentially coherent.

There are sources which cannot be regarded as either point sources or area sources but lie somewhere in between (de Boer, 1951). These sources generally range in angular size from 10 minutes of arc to one degree. de Boer's size correction factors however apply only to threshold illuminance levels.

In regard to the size of the EL source, observer input proves helpful. Several observers experienced initial uncertainty in their task due to a conflict in judging what seemed to be a "larger", "duller" source (EL) with a "sharper", "more precise" source (IC). In each case where the seeming conflict arose, the observer chose to reject the "duller" EL source. Randomly, the observers were asked to describe the sources. Comments received for the EL source were typically, "fuzzy", "diffuse", "blurry", "larger", and "glowing". Comments received for the incandescent source were typically, "sharper", "more precise", "star-like", and "more distinct."

These types of comments were received slightly more often when the larger numbers of EL panels were lighted but not exclusively. Interestingly, several observers reported both sources to "twinkle" during low visibilities, although the EL was reported to "twinkle" somewhat less than the incandescent source.

5. Discussion of Red EL Brightness Test

The method employed to obtain the red EL source was inefficient. As stated earlier, the essentially green emitting phospher is red filtered by overlaying a synthetic red material supplied by the EL manufacturer. Referring to Figure 16, it is immediately evident that in terms of efficiency, a high price must be paid using this technique. However, colored filters of this type typically do not have sharp band passes so that some wavelengths other than "red" are passed. The results obtained from Figure 35 are then somewhat questionable. Clearly, a red EL panel made from properly doped phosphers that emit in the red band would be more efficient.

Figure 32 reveals that an equal brightness rating required most of the 15 EL panels to be lighted. Hence, if there was an area effect involved in causing "better-than-predicted" performance, one would assume it would manifest itself here. Yet the "poorer-than-predicted" performance of the red EL would seem to contradict the area effect.

B. ANALYSIS OF THE SPATIAL ARRANGEMENT TEST

1. Graphical Analysis

This test was conducted using only the red filtered EL. A particular EL pattern was displayed and the spotlight test source was incrementally intensity adjusted. At each increment, the observer was asked to make a comparative brightness rating on a scale from one to seven (refer to Figure 18). Although the region of primary interest was the relative intensity setting for which the observer reported both sources of equal brightness (rating of 4), the observer was interrogated until ratings of 3, 4, and 5 were obtained. For each observer, the numerical brightness ratings spanned a relative intensity scale from 1 to 20. For each subject the brightness rating of each particular relative intensity level was tabulated. The mean brightness rating, $\bar{X}$, and its standard deviation, σ, for each relative intensity was calculated and plotted as shown in Figures 37, 38, and 39. The ordinate axis is the observer's rating of the brightness while the abscissa is the relative intensity displayed by the spotlight test source while the EL pattern remain fixed. In this analysis, the different visibility conditions were not considered. The simple mean of all observations was taken without consideration of atmospheric conditions. This approach was taken based on the analysis of the brightness equivalency test for this intensity level.

A review of these graphs indicate that the observed brightness levels were similar for the different patterns. A least squares method of linear regression ("comparative brightness scale" on "relative intensity") was conducted for each graph and the results compiled in

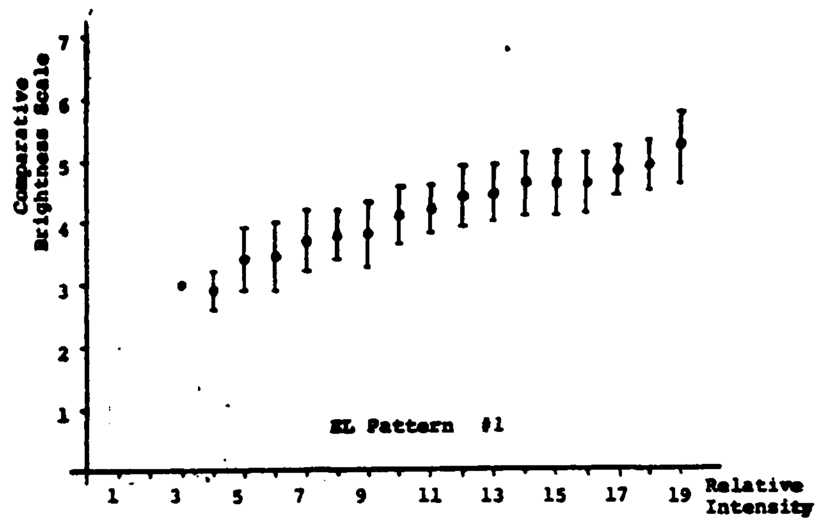


Figure 37. Comparative Brightness of Red EL as a Function of Relative Intensity for Pattern 1

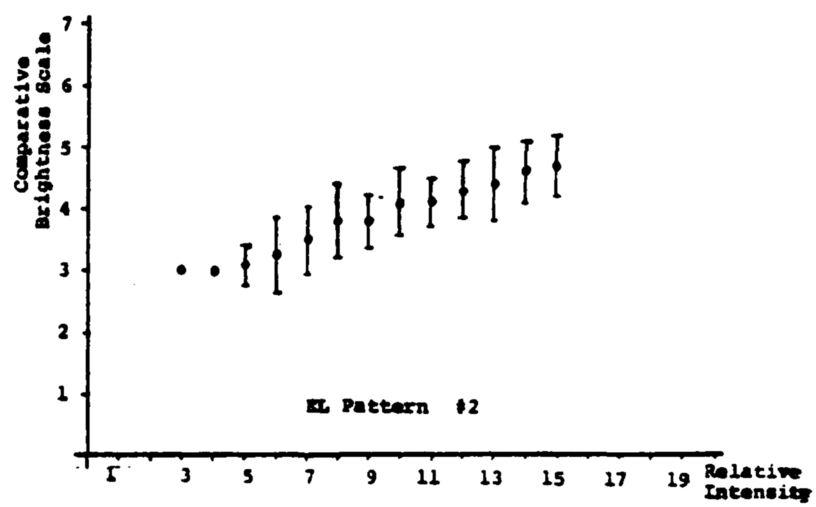


Figure 38. Comparative Brightness of Red EL as a Function of Relative Intensity for Pattern 2

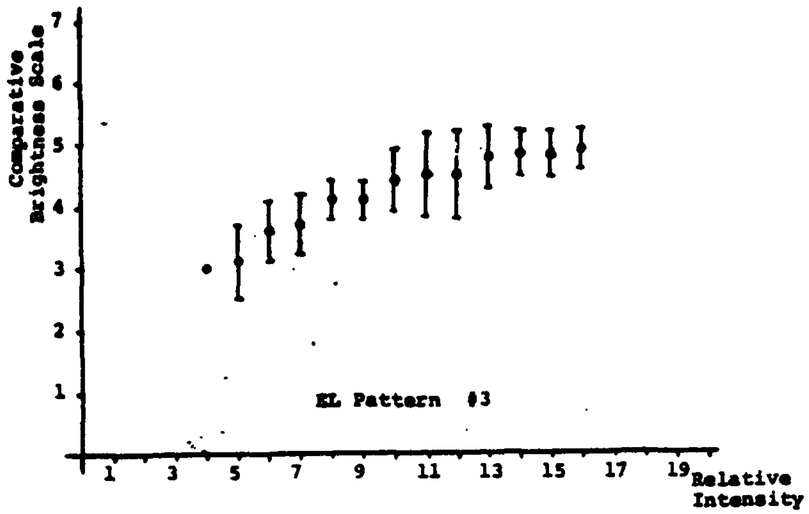


Figure 39. Comparative Brightness of Red EL as a Function of Relative Intensity for Pattern 3

Figure 40. The labelled regression lines point out the expected strong linear relation between brightness rating and relative intensity.

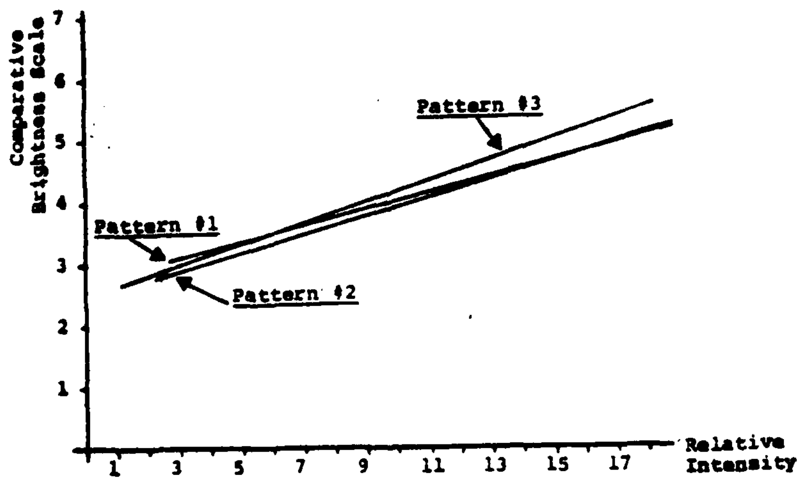


Figure 40. Regression Lines for All Three Red EL Patterns

2. Statistical Analysis of Spatial Arrangement Test

An analysis of variance was conducted to verify that at the .1 level there was no statistically significant difference in the EL test patterns. The null hypothesis (H_0) was $\mu_1 = \mu_2 = \mu_3$; where μ is the population mean. The results of the ANOVA indicated that H_0 could not be rejected. Simply stated, there appeared to be no difference in the population means and therefore, at the .1 level there is no statistically discernable difference in the perceived brightness of the different patterns. Table 8 records the mean relative intensity and standard deviation for each of the test patterns when compared to the test spotlight.

Table 8. Spatial Arrangement Data Summary

TEST PATTERN	AVERAGE RELATIVE INTENSITY	σ
1	10.07	1.74
2	10.43	1.83
3	9.33	2.59

IV. CONCLUSIONS AND RECOMMENDATIONS

A. THE BRIGHTNESS EQUIVALENCE TEST

It should be stated at the outset that conclusions based on essentially 16 observations are subject to some uncertainty. Nevertheless, some general conclusions can be drawn from the data.

First, considering visibility merits alone, green EL is certainly a viable alternative to incandescence at this range. By the addition of panels one could represent any of the standard 155 mm incandescent sources as well as any sources in between.

Second, the EL panels are rugged and reliable. The experimental EL panels were exposed to high winds, rain, baking sun, and cold, wet, fog for nearly three months in the course of the observations and not one failure was experienced.

Third, the Lambertian relation used to convert luminance (ft-L) to intensity (cd) allows one to compute the number of panels necessary for an EL intensity equivalent to any particular incandescent source. Yet consistently the EL was perceived as the brighter source.

Fourth, there seems to be little change in the comparative performance of EL with incandescents as the visibility drops with the exception of the high intensity cases. This striking effect in the green 2.03A case would suggest that the EL performs much better at this intensity level than its incandescent competitor in low visibility conditions. The cause behind this phenomenon is unexplained.

Fifth, although the data would suggest that the red EL performed comparatively poorly, this must be strongly qualified. The use of red filter material to produce the red EL creates some uncertainty. The pass band of the red filter was not measured and thus its spectral output unknown. In any event, while the method contrived may be acceptable for cockpit lighting schemes or "exit" signs, its application to the aids-to-navigation field is impractical. For red EL emission proper dopants should be used to get the desired red emission.

Sixth, while the EL performed well in visibility tests, this does not insure that it has an application in aids-to-navigation. No mention has been made of the luminous efficacy (ratio of total luminous flux emitted to total lamp power input) of this source. A consideration of the power consumed (and thus operating cost) will be an essential factor.

Last, this experiment used a 415 Hz generator directly connected to the EL source and no problems were encountered. However, to run the panels off of a 12 volt, dc source requires the use of a highly inefficient inverter to convert dc to a 400 Hz ac source. This adds another component to the system increasing cost and decreasing reliability. In fact, during the course of laboratory spectral irradiance measurements of the EL, one of the inverters did fail. Regardless of EL performance, if the inverter fails then the system "catastrophically" fails just as in the incandescent case. It would be cold comfort for the discrepancy response personnel, awakened at 2. a.m., to realize that the inverter was at fault and not the panel itself.

B. THE SPATIAL ARRANGEMENT TEST

As indicated earlier, there appeared to be no statistically discernable difference in perceived brightness when the panels were arranged in different patterns. The nature of this test requires many more observations than were carried out here. It will be important to know if increasing the source size (while keeping the emitting area the same) affects the perceived brightness.

C. RECOMMENDATIONS

In general, further field tests and comparisons should be vigorously pursued. A similar experiment should be carried out with many more observers. This would lend more statistical reliability to the results.

EL power consumption should be thoroughly investigated. If the cost of operating EL from an energy consumption point of view is prohibitive, then this area of research could be slowed until technology produces a better EL device.

A study should be conducted to provide the most efficient inverter possible. Output waveform (and its effect on EL), efficiency, operating temperature, cost, and reliability are but a few of the areas of interest.

This investigation concerned comparing fixed light sources. A similar investigation focused on comparison of flashing light sources would also be crucial. The question to be addressed would be the influence of the Blondel-Rey factor in a flashing EL display.

Finally, an investigation is needed to determine if indeed the eye perceives EL brighter than photometric measurements indicate that it should. If so, the cause of the phenomenon would be of great interest.

APPENDIX A

A DISCUSSION OF EMISSION MODELS FOR ZNS POWDER PHOSPHORS

The history of electroluminescence is relatively recent, being essentially, a twentieth century development. The phenomenon was first reported by O. W. Lossew in 1923 (Lossew, 1923) while working with silicon carbide.

One of the most thoroughly studied EL materials is ZnS:Cu. The EL properties of this material were first discovered by Georges Destriau in 1936 (Destriau, 1936). So prominent were his efforts, in fact, that this phenomenon is sometimes referred to as the Destriau Effect. The study of electroluminescence is complex. The total mechanism for EL emission may be divided into two basic processes:

(1) The host crystal absorbs energy from the applied field, lifting electrons across the bandgap.

(2) Sometimes the excitation energy must be transported to a location where light emitting recombination (through recombination centers) occurs. This process can only occur through an indirect transition, due to the large bandgap.

There have been many models proposed to explain EL emission. Fisher's model (Fisher, 1963) relies on field intensification of charge carriers due to the presence of copper conducting inclusions embedded in the ZnS particles. The Bonfiglioli model (Bonfiglioli, 1969) states that the regions bordering stacking faults in the crystals become electron trapping centers. This region may be treated as an np junction consisting of the bulk ZnS crystal phosphor (n material) and the region around the fault (p material).

None of the proposed models is entirely satisfactory. In any event, treating ZnS as a semiconductor, the process must involve some avalanche excitation mechanism. A clear, precise, model would be beneficial to the development of EL.

APPENDIX B
INSTRUMENTS

1. Spectroradiometer/Photometer

The spectroradiometer used to make spectral measurements was an EG&G Model 580/585 Spectroradiometer System. This bench type system is pictured in Figure 41.

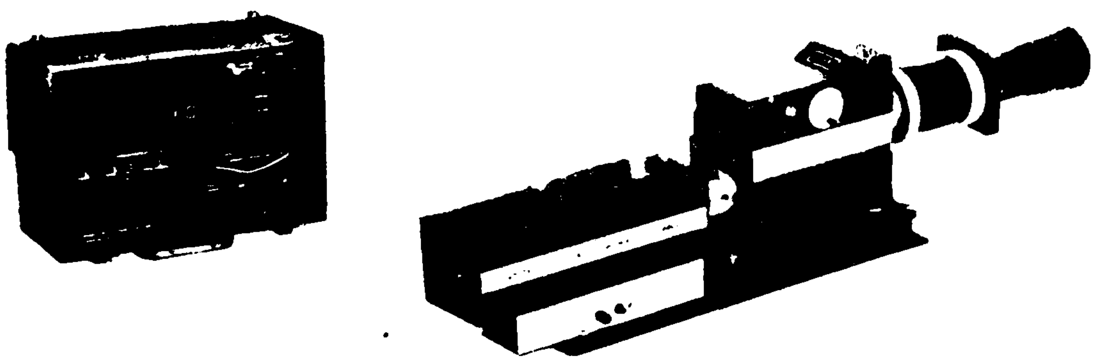


Figure 41. Spectroradiometer With High Sensitivity Detector Head

The system consists of a beam input optics system with a five degree field of view that uniformly illuminates the monochromator entrance slit. The monochromator housing can be fitted for IR, UV, or visible bands. (For EL the visible range was used.) Basically, the light enters the monochromator through the entrance slit, strikes the diffraction grating and diffracts according to wavelength. But only one wavelength strikes the concave mirror in such a way that the entrance slit image falls on the exit slit precisely. The monochromatic light which exists is then measured by the radiometer. The spectroradiometer system was factory calibrated and shipped directly to the author with a certificate of calibration dated June 21, 1982. It is assumed that the calibration data remained true throughout this investigation.

2. The Luminance Meter

The device used to measure the luminance of the EL source was a Tektronix Model J6523 1° Narrow Angle Luminance Probe. This device measured luminance in foot-Lamberts. The lens system can focus over the range from 18 inches to infinity. The spectral response of the sensor is calibrated within 2% of the CIE photopic curve.

Luminance meters do not measure luminance directly. They measure the radiant flux directly and after calibration and geometry is considered, the luminance may be obtained. The meter, in effect, measures the average intensity of a bundle of rays emitted by the source. Since the EL source is a uniform emitter, the averaging technique is quite acceptable. For any source, luminance varies not only with the projected area but also with the solid angle. This type of meter eliminates the solid angle variance by limiting the sensor aperture to one degree and measuring at relatively long distances. Then the luminance to a good approximation, varies only with the projected area.

3. Theodolite/Laser Range Finder

A theodolite was used to measure the vertical angle from the line-of-sight to the zenith. The Wild T2 Universal Theodolite can be used for triangulation, precise traversing, astronomy, tacheometry, engineering, cadastral survey, and even optical tooling. It allows measurement of both horizontal and vertical angles. The vertical angle was needed to provide the elevation of the sources from the observer. The elevation of sources was needed to validate the horizontal viewing assumption.

A laser range finder was used to determine the distance from the observer to the various sources. Ranger IV was manufactured by Laser Systems and Electronics. The device is capable of accurately measuring distances from three feet to eight miles. Its accuracy is to within .02 feet + 2 ppm. This device, of geodetic accuracy, is typically used for first order baseline determinations. The Ranger IV uses a directly modulated, 3 milliwatt, helium-neon laser (6328 Å) as the light source.

Typically, laser range finders use an intensity modulated laser source. The light is transmitted through the optical system to the reflectors at the source site. The signal is then received back through the optical system to a mulitplier. The phase difference between the outgoing modulated transmission and the received modulated transmission provides the distance information. Atmospheric calibration is provided through pressure and temperature inputs. Since the observers were not precisely located at the same observation point, the accuracy of the distance measurement was not limited by the distance measuring equipment but by the uncertainty of the observer position. The source distance then was accurate to within 5 feet.

BIBLIOGRAPHY

Allinikov, S., "Coated Electroluminescent Phosphers", United States Patent No. 4,097,776; 1978.

Beitel, R. J., "Spatial Summation of Subliminal Stimuli in the Retina of the Human Eye", Journal of General Psychology, Vol. 10, p. 311, 1934.

Blackwell, H. R., "Brightness Discrimination Data for the Specification of Quantity of Illumination", Illuminating Engineering, November 1952.

Blackwell, H. R., "Contrast Thresholds of the Human Eye", Journal of the Optical Society of America, Vol. 36, No. 11, November 1946.

Blackwell, H. R., Report of Progress of the Roscommon Visibility Tests, June 1947 - December 1948, Minutes and Proceedings of the Armed Forces - NRC Vision Committee, 23rd Meeting, 4-5 March 1949. (National Academy of Sciences, Washington, D.C.).

Bonfilioli, G., "On the Theory of the Destriau Effect", report from NTIS data base. Report No. AD 694128, September 1969.

Cotton, H., Principles of Illumination, New York. John Wiley and Sons, 1960.

de Boer, J. B., "Calculations on the Light Distribution of Approach and Runway Lights", Philips Research Reports, Vol. 6, p. 241, 1951.

de Boer, J. B., "Visibility of Approach in Runway Lights", Philips Research Reports, Vol. 6, p. 244, 1953.

Destriau, G., J. Chim. Phys., No. 33, p. 587, 1936.

Diamond, A. L., "Foveal Simultaneous Brightness Contrast as a Function of Inducing - and Test-Field Luminances", Journal of Experimental Psychology, Vol. 45, No. 5, p. 304, 1953.

Douglas, C. A. and R. L. Booker, Visual Range: Concepts, Instrumental Determination, and Aviation Applications, NBS Monograph 159, Optical Physics Division, National Bureau of Standards, June 1977.

Duntley, S. Q., "The Visibility of Distant Objects", Journal of the Optical Society of America, Vol. 38, No. 3, March 1948.

E-L Products Company, "Electroluminescent Panels", product brochure, East Aurora, New York.

Evans, G. F., "Calculating In-Band Flux Density of Blackbody Sources", Electro-Optical Systems Design, p. 39, November 1978.

Fisher, A. G., "Electroluminescent Lines in ZnS Type Power Particles", Journal of the Electrochemical Society, p. 733, July 1963.

Graham, C. H., R. H. Brown, and F. A. Mote, "The Relation of Size of Stimulus and Intensity in the Human Eye: I. Intensity Thresholds for White Lights", Journal of Experimental Psychology, Vol. 24, No. 6, p. 555, June 1939.

Graham, C. H., Vision and Visual Perception, New York. John Wiley and Sons, 1965.

Grum, F. and R. J. Becherer, "Radiometry", Optical Radiation Measurements, Vol. 1, p. 98, 1979.

Guth, S. K. and J. F. McNelis, "Visual Performance: A Comparison in Terms of Detection of Presence and Discrimination of Detail", Illuminating Engineering, p. 32, January 1968.

IES Lighting Handbook, 6th ed. Reference Volume, Illuminating Society of North America, 1981.

Lehmann, W., "Electroluminescent Large Area Image Display", Displays, Vol. 2, No. 1, April 1980.

Lossew, O. W., Telegrafia i Telefonia, No. 18, p. 61, 1923.

Middleton, W. E. K., Vision Through the Atmosphere, University of Toronto Press, 1952.

Midland Ross Corp., Grimes Division, "Electroluminescence", product brochure, Urbana, Ohio.

Pieroway, C. S., "Electroluminscent Lighting Applications", paper presented to the Illuminating Engineering Society of North America, Aviation Lighting Committee, November 1981.

RCA, Electro-Optics Handbook, RCA Solid State Division, Lancaster, PA., 1974.

Steedman, W. C. and C. A. Baker, "Target Size and Visual Recognition", Human Factors, p. 120, August 1960.

Stone, P. T., A. M. Clarke, and A. I. Slater, "The Effect of Task Contrast on Visual Performance and Visual Fatigue at a Constant Illuminance", Lighting Research and Technology, Vol. 12, No. 3, p. 144, 1980.

United States Coast Guard, Office of Engineering, Washington, D.C., Ocean Engineering Report No. 37, CG-250 Series, Visual Signalling, Theory and Application to Aids-to-Navigation, 22 June 1971.

United States Coast Guard, Office of Engineering, Washington, D.C., Ocean Engineering Report No. 12E, CG-250 Series, Luminous Intensities of Navigational Aids, 29 March 1972.

United States Coast Guard, Office of Engineering, Washington, D.C., Commandant Instruction M16500.3, Aids-to-Navigation Technical, 11 September 1979.

Walsh, J. W. T., Photometry, London: Constable and Company LTD., 1958.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 61 Department of Physics Naval Postgraduate School Monterey, California 93940	1
4.	Professor Raymond Kelly, Code 61 Department of Physics Naval Postgraduate School Monterey, California 93940	1
5.	Professor Sidney Kalmbach, Code 61 Department of Physics Naval Postgraduate School Monterey, California 93940	1
6.	Professor Eugene Crittenden, Jr., Code 61 Department of Physics Naval Postgraduate School Monterey, California 93940	1
7.	Commandant (G-PTE-1/TP41) United States Coast Guard Washington, D.C. 20593	2
8.	Lieutenant John R. Thacker 405 Kuntz Drive Lebanon, Ohio 45036	3
9.	U.S. Coast Guard Research and Development Center Avery Point Groton, Connecticut 06340	2

4-

DT