

**DEVELOPMENT OF HIGH CONTRAST
ELECTROLUMINESCENT TECHNIQUES FOR
AIRCRAFT DISPLAYS**

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FOREWORD

This paper describes the results of a program initiated by the Control Systems Research Branch, Flight Control Division, of the Air Force Flight Dynamics Laboratory, under Task 619009, "Advanced Display Generation Techniques," and Task 619007, "Human Factors Research," through the direction of Lt Colonel Marion R. Richards, Mr. John H. Kearns, Mr. Edward L. Warren, and Captain Paul T. Kemmerling.

Captain Carlton J. Peterson has served as the Task Scientist for the display techniques program since September 1963 while Mr. Hugh A. Smith, a member of the technical staff of Bunker-Ramo Corporation working under Contract AF 33(657)-8600, has performed human factors studies related to the in-house solid state display program since October 1964. This paper was prepared by Captain Peterson and Mr. Smith to disseminate information pertaining to recent developments in high contrast electroluminescent (EL) display techniques. Section I describes the development of the techniques, while Section II describes certain aspects pertaining to the human factors evaluation of a prototype high contrast display. Joint presentation of this information was motivated by a desire to show the necessity for the interdisciplinary approach to display design.

This technical paper has been reviewed and is approved.



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ABSTRACT

This paper outlines the steps taken by the Air Force Flight Dynamics Laboratory to develop a new display technology capable of meeting display requirements of future manned weapon systems. A description is made in the first part of this paper identifying the basic concept and resulting development of high-contrast electroluminescent (EL) displays both from an engineering and psychophysical standpoint. The problem of display legibility, quite often confused with display brightness, is also discussed with respect to its effect on the limitations of EL displays. Finally, information is presented identifying how this limitation was overcome and why such progress is considered to be an important contribution to the development of solid-state displays. The second part of this paper describes the human factors aspects of the high-contrast EL program. The inherent weakness of transilluminated displays, the variables related to readability, the effects of the anticipated upper limits of environmental lighting, and the study of one of the first high-contrast EL displays are discussed.

Contrails

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SECTION I

HIGH-CONTRAST SOLID-STATE DISPLAYS

During the past decade, improvements in display technology have lagged behind those of computers, communication systems, and manned vehicles. The most apparent reason for this lack of progress has been the inability of systems-oriented engineers to develop advanced display mechanizations, and for research-oriented engineers to develop practical display formats. Obviously, improved displays and display techniques have evolved during this time period, but at a rate insufficient to meet demands. Such a situation would normally be blamed on material or state-of-the-art limitations; however, in this case, it is more likely due to a compromise of display design principles and the inability of display engineers to carry improved mechanization concepts to meaningful applications. The Control Systems Research Branch (FDCR) of the Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, is attempting to overcome this situation by pursuing the design of aircraft displays as an interdisciplinary effort through a complete understanding of both the man and the weapon system.

As a part of the overall control-display program under Project 6190, the Air Force has initiated an applied research effort to study advanced solid-state display generation techniques. This research is being performed to meet unique display requirements recognized during the analysis of proposed weapon systems, and to expand the capabilities of today's display technology.

The advanced display program is specifically directed toward the total display design effort so that optimum tradeoffs can be made, from basic electrical and optical phenomena to whole-panel human-engineering considerations.

THE SOLID-STATE DISPLAY CONCEPT

The reason for interest in the development of solid-state displays is very simple, as it stems from a realization of the improvements to be gained by the fabrication of nonmechanical displays and the resulting display capability provided for the Air Force. Advantages of solid-state over electromechanical or other electronic generation techniques are normally evaluated in terms of weight, size, and power. Equally important are the advantages of display flexibility, scale variability, digital and analog operation, improved reliability, and ultimately, the reduction of display cost. Display flexibility refers to the ability to fabricate displays that would be impossible or at least impractical to mechanize electromechanically, and scale variability refers to a real and unique capability of solid-state displays to permit accurate expansion of any given parameter.

An example of a situation in which such capabilities could be applied is in the display of attitude information in a V/STOL aircraft. In hover, attitude has been found to be an extremely significant display parameter. It is necessary to hold attitude precisely during the hover so that the thrust vector is not deviated from the vertical unless there is a desire to introduce translational velocity. In hover, the ability to provide an expanded scale of attitude around zero pitch and roll would be of significant advantage to the pilot. Naturally, this expanded scale would only be used during a small portion of the total mission, so it would be necessary to revert to the regular scale whenever required. Such a capability could be equally useful in the display of altitude or the display of flight-path angle in certain vehicles. The point being made is that such flexibility is not available today using electromechanical display techniques. A final advantage that will be discussed is that solid-state displays can be operated directly from either digital or analog signals. This capability is desirable when considering that although

digital transducers and computers are here and are being used in certain advanced aircraft, there is no escaping the fact that analog sensing devices, transducers, and computers are going to be in existence for a long time.

SOLID-STATE DISPLAY DEVELOPMENT

With such advantages recognized, what then were the technical problems which required solution prior to the development of practical solid-state displays? These problems were primarily those being treated by several research groups throughout the world. Therefore, initial efforts under Project 6190 addressed themselves to both EL lamp technology, in terms of developing fabrication techniques for high-resolution segmented displays, and to the development of solid-state control circuitry by which these segmented displays could be discretely controlled. These efforts were successfully completed under contract and provided the capability of fabricating solid-state displays with formats as shown in Figure 1. At that time, it was not possible to sufficiently develop the techniques for operational use, but it was possible to prove the feasibility of the solid-state display approach.

The next problem requiring review in the task of achieving a practical, operational, display capability (still ignoring the apparent intensity and life limitations of EL phosphor materials) was to identify the control requirements of solid-state displays. Since an EL display can exist as a discrete lamp, a set of segmented lamps, or a more complex high-resolution matrix display, the problem of continuous display control, the characteristics of basic control mechanisms, and the design of advanced control circuitry were considered to be of significant interest to the development of solid-state displays. Results of research in these areas were quite satisfactory because they either solved or provided conceptual guide lines for the practical and inexpensive fabrication of solid-state displays. This left one major limitation, the intensity and effective life of EL phosphors. Unfortunately, the past three years of worldwide research on EL phosphor materials resulted in only marginal improvements. This lack of success made it quite apparent that it would not be possible to depend on phosphor improvements to achieve acceptable daylight ambient readability of solid-state displays. Obviously, this conclusion had a strong impact on the solid-state display program, as improved phosphor characteristics appeared to be the only logical rationale available to Air Force Flight Dynamics Laboratory engineers. Fortunately, awareness of this situation motivated a study of human perception, where a simple but important determination was made that low-emission displays could be used under daylight conditions if they had acceptable contrast. Naturally, this in no way solved the problem because the only practical way that acceptable contrast can be achieved in an aircraft display under normal conditions is to control the ambient light incident to the display itself. Without describing the difficulties of such a requirement when considering all aspects of the control-display problem, it should be sufficient to state that the control of ambient illumination is only acceptable in a cockpit at the surface of the display panel. There are many absorptive techniques that could be used for such control, but in each case restrictions are either placed on the viewing angle or on a severe reduction of the already low emission intensity of the display.

HIGH-CONTRAST DISPLAY DEVELOPMENT

In-house experimentation with absorptive techniques resulted in the conclusion that some form of optical filtering scheme would permit the best solution to the ambient absorption problem. Evaluation of the state-of-the-art of high-intensity EL phosphors in conjunction with various neutral-density overlays demonstrated, what is a generally known fact, that filters can improve display readability under certain ambient conditions. The interesting part of this conclusion was that such techniques were not already in use because research-oriented personnel were striving to increase, not decrease, the emission intensity of EL displays, even at the expense of display legibility. By directing various research organizations to look at

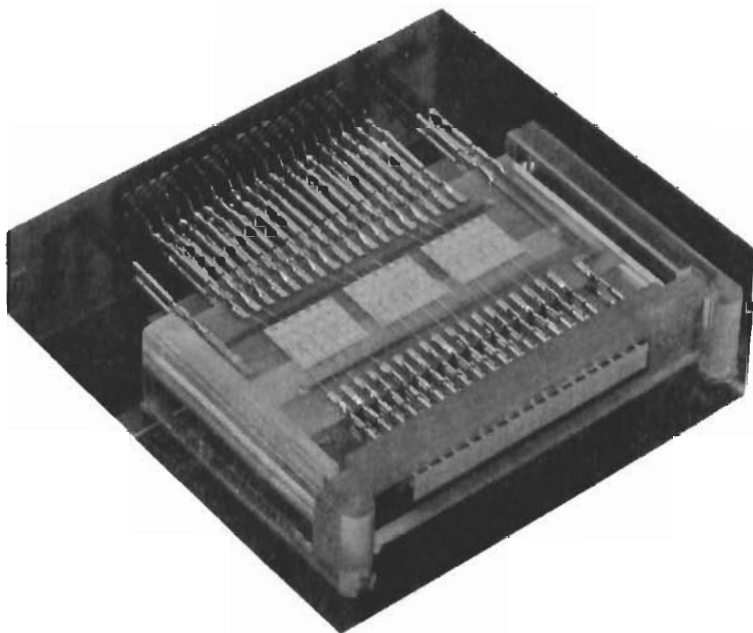
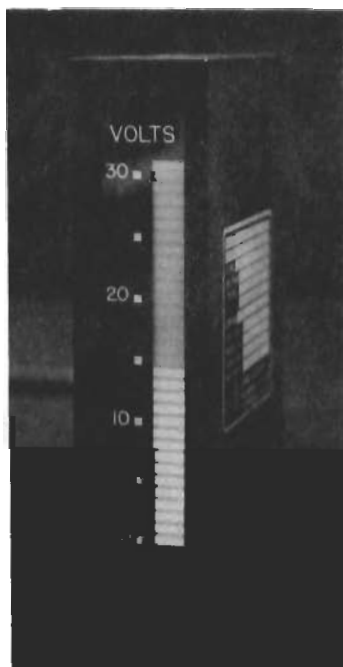
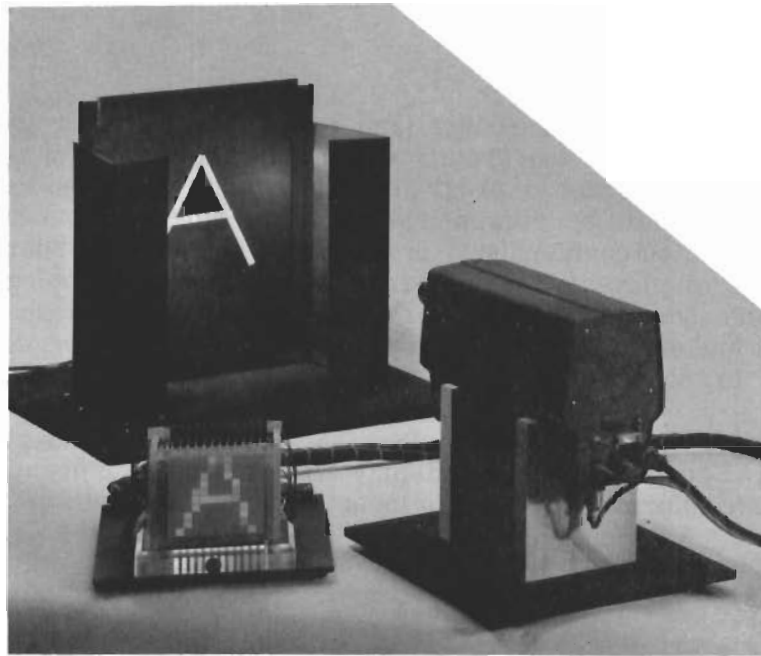


Figure 1. Photoconductive and Ferroelectric Controlled Solid-State Displays

the whole solid-state display legibility problem realistically, a number of techniques have recently been put into practice permitting the absorption of a high percentage of ambient light without greatly reducing the emitted light of the EL display. This development has resulted in an extremely significant breakthrough in solid-state display technology.

THE HIGH-CONTRAST CONCEPT

The Air Force objective in the research and development of high-contrast solid-state display techniques has been to lay the groundwork for the fabrication of a family of legible, versatile, solid-state displays. Such a program was urgently required to develop long-life low-emission displays that could be viewed under daylight ambient conditions. The problem of display legibility, quite often confused with display brightness, has hindered the successful application of solid-state displays for a number of years. As the technology now stands, the solution to this problem does not lie with improved phosphors but rather with the proper manipulation of ambient and emitted light within the intimate layers of the display itself. This concept is considered to be the key to the development of practical solid-state displays.

Typical EL displays have a grayish-white surface that will normally reflect about 50 percent of all impinging light. Energizing such a display will result in the presentation of colored symbolic or alphanumeric information having a measurable contrast of

$$C = \frac{(\text{Information})_{xyz} - (\text{Background})_{xyz}}{(\text{Information})_{xyz}} \times 100 \% \quad (1)$$

where informational luminance of a uniformly reflective display is equal to the sum of the emitted and background luminance (Reference Appendix I for the nonuniform case), so that

$$C = \frac{(\text{Emitted})_{xyz}}{(\text{Emitted})_{xyz} + (\text{Background})_{xyz}} \times 100 \% \quad (2)$$

If we now assume that the emission color is equal to the reflected color, then

$$C = \frac{E}{E + B} \times 100 \% = \frac{100 \%}{1 + B/E} \quad (3)$$

Now, in the case of normal EL displays approximately half of the ambient light incident to the display surface is reflected, so that

$$C = \frac{100 \%}{1 + .5 A/E} \quad (4)$$

From this equation it can be shown that EL display contrast is simply a function of the ratio of ambient light to emitted light. This identifies how the contrast of an EL or any other emission or rear projection display is reduced by an increase of ambient light. The addition of a neutral-density filter in front of such a display would have the following effect on the contrast equations,

$$C_n = \frac{(E \times T)}{(E \times T) + (B \times T^2)} \times 100 \% \quad (5)$$

where T equals the transmissivity of the filter and T^2 is the result of the ambient light passing through the filter twice, so that

$$C = \frac{100\%}{1 + T (.5 A/E)} \quad (6)$$

Since the general rule of thumb for improvement of display readability is normally the improvement of contrast, this tradeoff appears quite handsome. Actually, such a tradeoff is useful as long as display intensity, angular size of the data, preadaptation of the subject, time of exposure, and other conditions are not made correspondingly worse in the trade. The fact that this was not always accomplished is why neutral-density filters sometimes helped to improve display readability and sometimes did not. Display intensity is actually the only variable of interest to this report, because the other parameters mentioned normally remain constant.

The goal of further work in this area has been to develop contrast schemes that would permit acceptable levels of display intensity while at the same time reduce the level of ambient-light reflection. Equation 6 does not appear to permit much room for improvement of such a tradeoff, but this is of no consequence as the equation is only a convenient vehicle for describing experimental results and is not directly related to the mechanization itself. In other words, it is possible to achieve greater absorption of reflected light from a display without an associated reduction in emission light if proper thought is placed on the problem. As the state-of-the-art exists today, EL displays can be fabricated with a measurable contrast of

$$C = \frac{100\%}{1 + T^2 (.5 A/E)} \quad (7)$$

while still maintaining the same emission output achievable with a filtered display of $E \times T$. The equations for reflectivity of ambient light under the previously discussed conditions are

$$R = .5 \times 100\% = 50\% \text{ (normal)} \quad (8)$$

$$R_n = .5 \times T^2 \times 100\% = 50 T^2\% \text{ (neutral density)} \quad (9)$$

$$R_h = .5 \times T^3 \times 100\% = 50 T^3\% \text{ (high contrast)} \quad (10)$$

It should be realized that no mention has been made of the front air-glass reflectance which could actually add to this figure (4 to 5% for uncoated and .5% for coated glass). Now, if a display contrast of at least 30 percent is desired along with a 2-percent reflective, 35-percent transmissive EL display emitting 25 footlamberts, then the maximum ambient illumination which could be tolerated would be increased from 118 to 955 footcandles using high-contrast techniques (Figure 2). The emission intensity of a normal EL display as seen with the same 30-percent contrast and with the same 955 footcandle illumination would have to emit over 200 footlamberts. Extrapolation of data shown in Figure 3 was made to identify the possible development of future high-contrast display characteristics. The 1-percent reflectance, 27-percent transmissive point is expected to be achieved soon through a Flight Dynamics Laboratory sponsored contract.

There appear to be many techniques available for the improvement of EL display contrast; however, at the present time the best approach utilizes a thin-film nonhomogeneous neutral-density filter. This filter, positioned between the front glass plate of the display and the phosphor dielectric layer, absorbs light passing straight through the structure, and most important, absorbs light scattered from collisions with the nonhomogeneous material. In the case of a 2-percent reflective, 35-percent transmissive display, absorption due to scattering

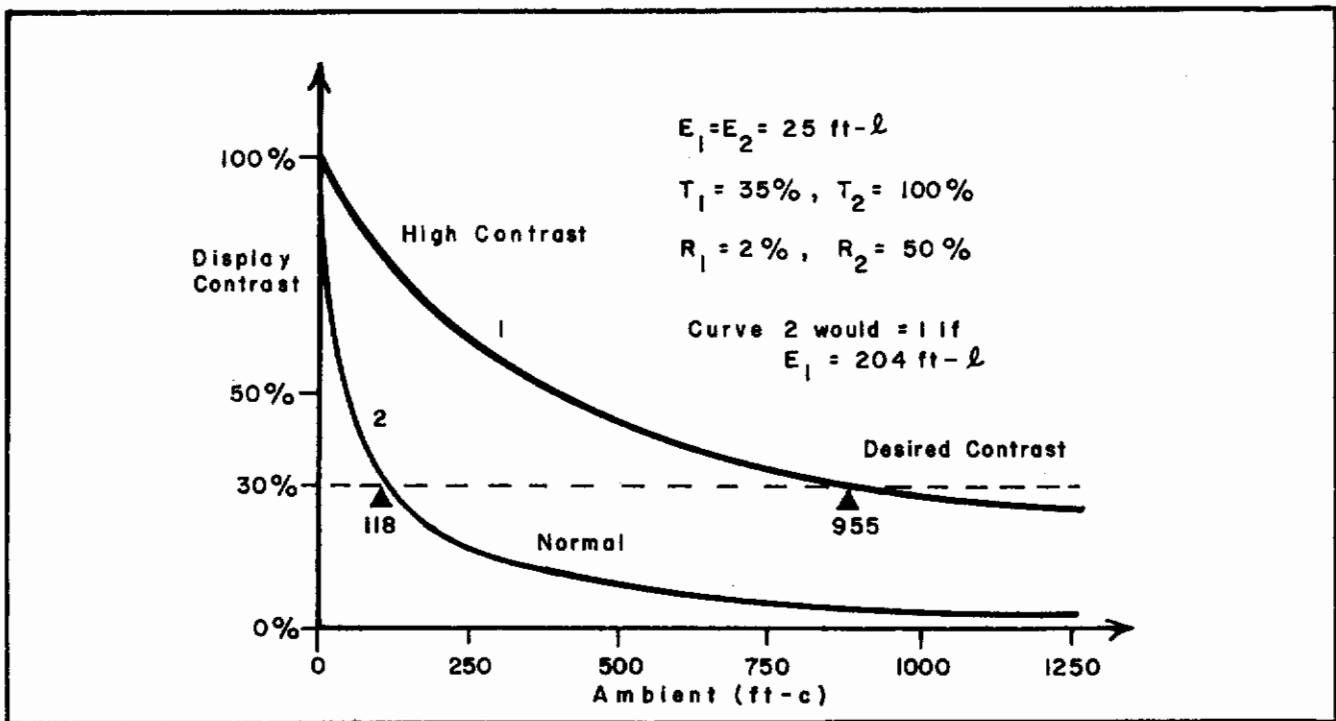


Figure 2. Normal vs High-Contrast EL Displays

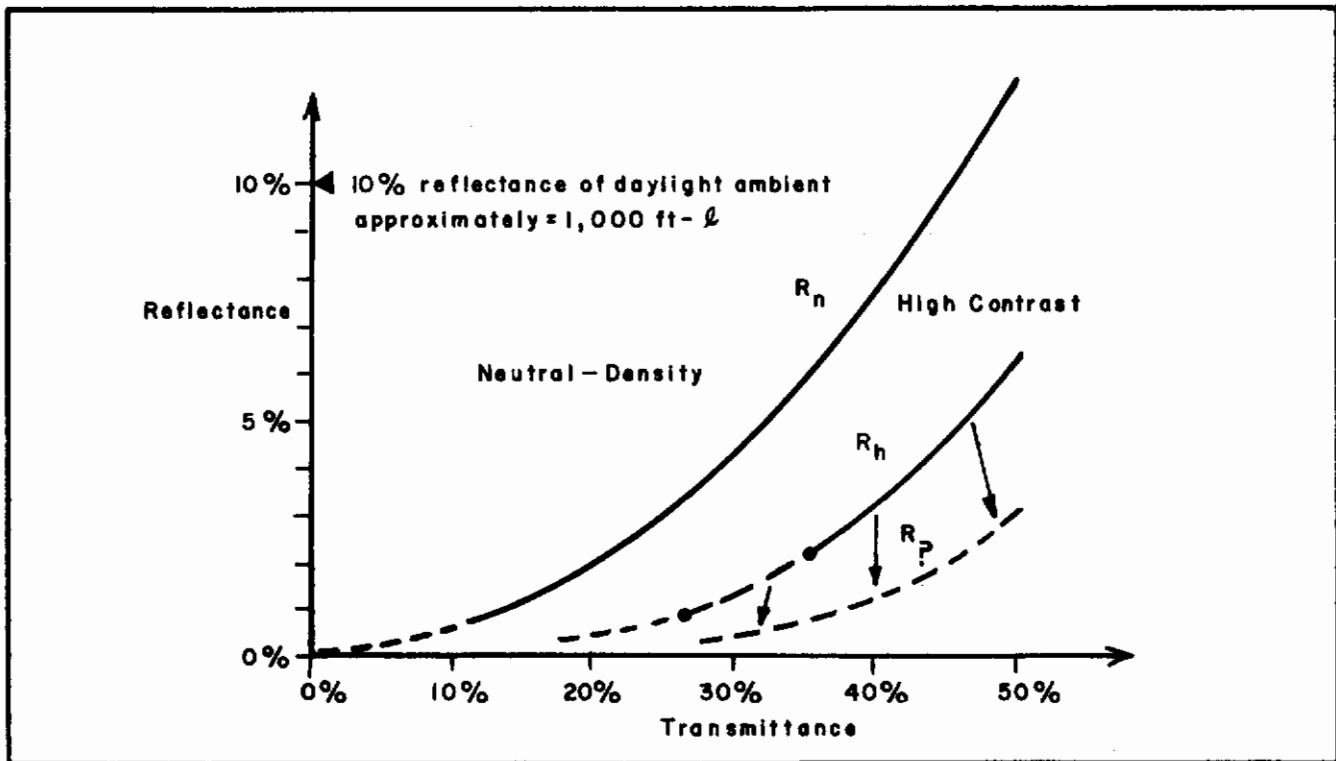


Figure 3. EL Display Reflectance

reduces a 6-percent reflectance, achievable with neutral-density filters, to 2 percent using the nonhomogeneous thin-film filter. In a practical sense, this decrease in reflectance means it would either be possible to use the display under higher ambient conditions or it would be possible to reduce the intensity of the display and extend its lifetime while achieving the same level of legibility at lower ambient conditions. Figure 4 shows the contrast relationship between a normal, neutral-density filter, and two different high-contrast EL displays as they would appear to a pilot under operational ambient conditions. Under a 10,000-footcandle ambient illumination display No. 2 would have a contrast based on a background reflection of 100 footlamberts and a maximum emission output of 13.5 footlamberts; display No. 4 would have a contrast based on a background reflection of 5,000 footlamberts and a maximum emission output of 50 footlamberts.

The successful application of high-contrast, low-emission EL displays in T-39 and C-135 aircraft (Figure 5) made possible by the timely feedback of critical information from the human-factors analysis described in Section II has done much to accelerate support for future solid-state-display development programs.

Equally important to the acceptance of the solid-state display concept has been the effort to provide practical human-factors guidance in the design of new display formats and in the identification of optimum aircraft-display characteristics. The use of low-emission displays in high-ambient surroundings, the generation of apparent motion in segmented EL displays, and the determination of solid-state display compatibility with existing display components are but a few of the topics requiring human-factor analysis.

THE FUTURE OF SOLID-STATE DISPLAYS

Solid-state displays may very well be the displays of the future, especially if key accomplishments are made in: the development of bulk-phenomena materials for display-integrated electronics, the improvement of solid-state display tolerance to temperature extremes, and the utilization of solid-state display mechanization concepts in the development of meaningful and useful displays.

Such achievements as the elimination of the apparently insurmountable requirement for EL phosphors of higher emission intensity has already had a strong and favorable impact on the future of solid-state displays.

Since the progress of the Air Force solid-state display program has been based entirely on an attempt to understand all aspects of the control-display problem, it was mandatory that research be performed to study solid-state display informational and operational requirements. One such effort resulted in the design of an experimental solid-state altimeter display (See Figure 6 and Appendix II).. The possibility exists that such a display could evolve from this program; however, the primary goal of the effort has been to understand and identify the problems associated with complex solid-state displays. Obviously, there are still many engineering and psychophysical questions that must be answered about such displays.

Previous efforts in the area of solid-state display have been hindered by two limitations: the emission intensity of field effect EL phosphors and the complex control circuitry required in high-resolution solid-state displays. As a result of engineering efforts on EL phosphors and contrast techniques, and human factor guidance on the applicability of low-emission, low-reflectivity displays to the cockpit, the first limitation has been significantly reduced. Equally important, the work performed on control circuitry has resulted in the conclusion that simple, inexpensive, and reliable control circuits will soon be available for use in solid-state displays.

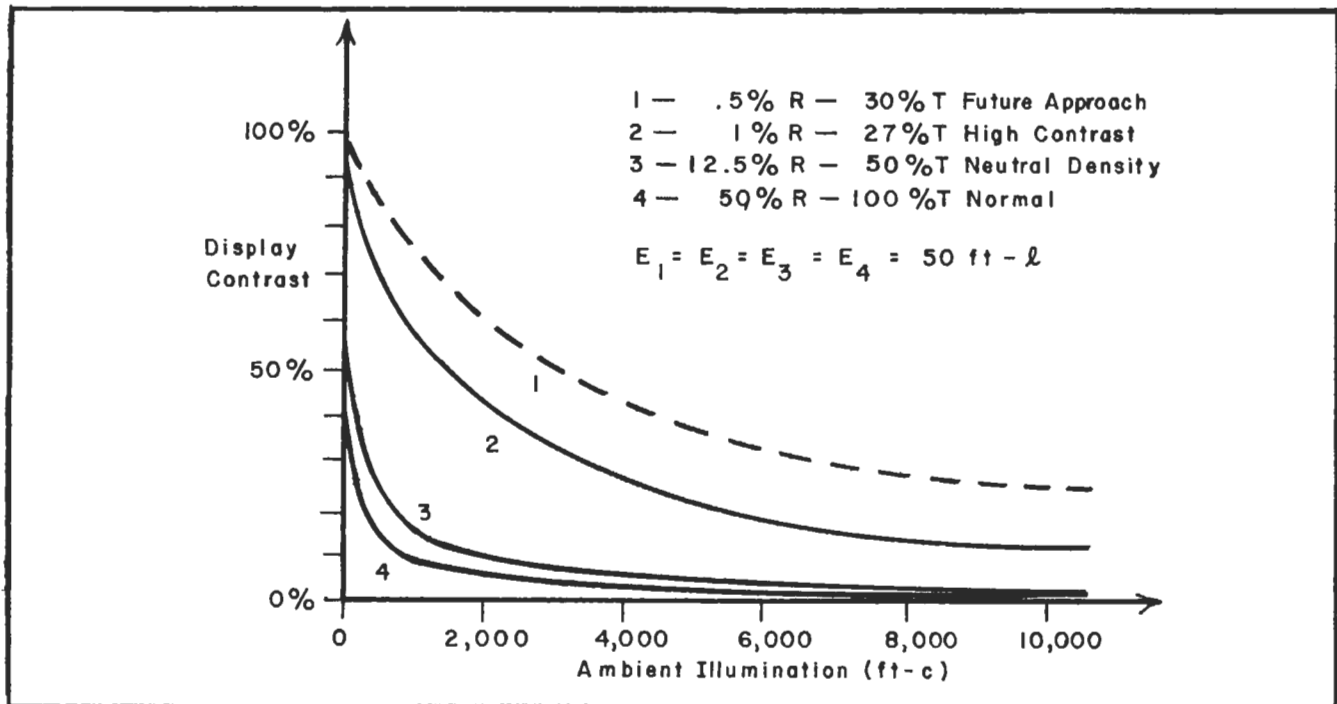


Figure 4. EL Display Contrast

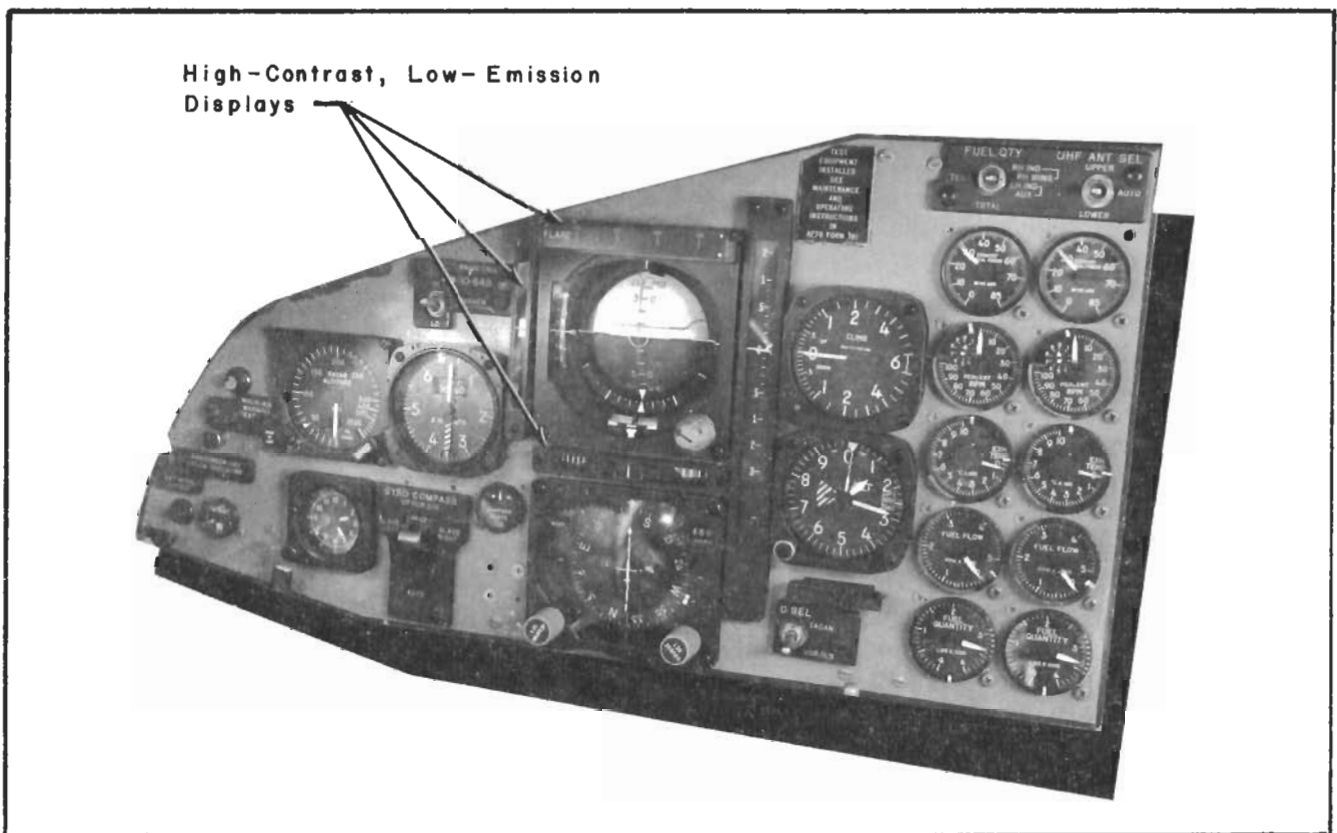


Figure 5. Modified T-39 Instrument Panel

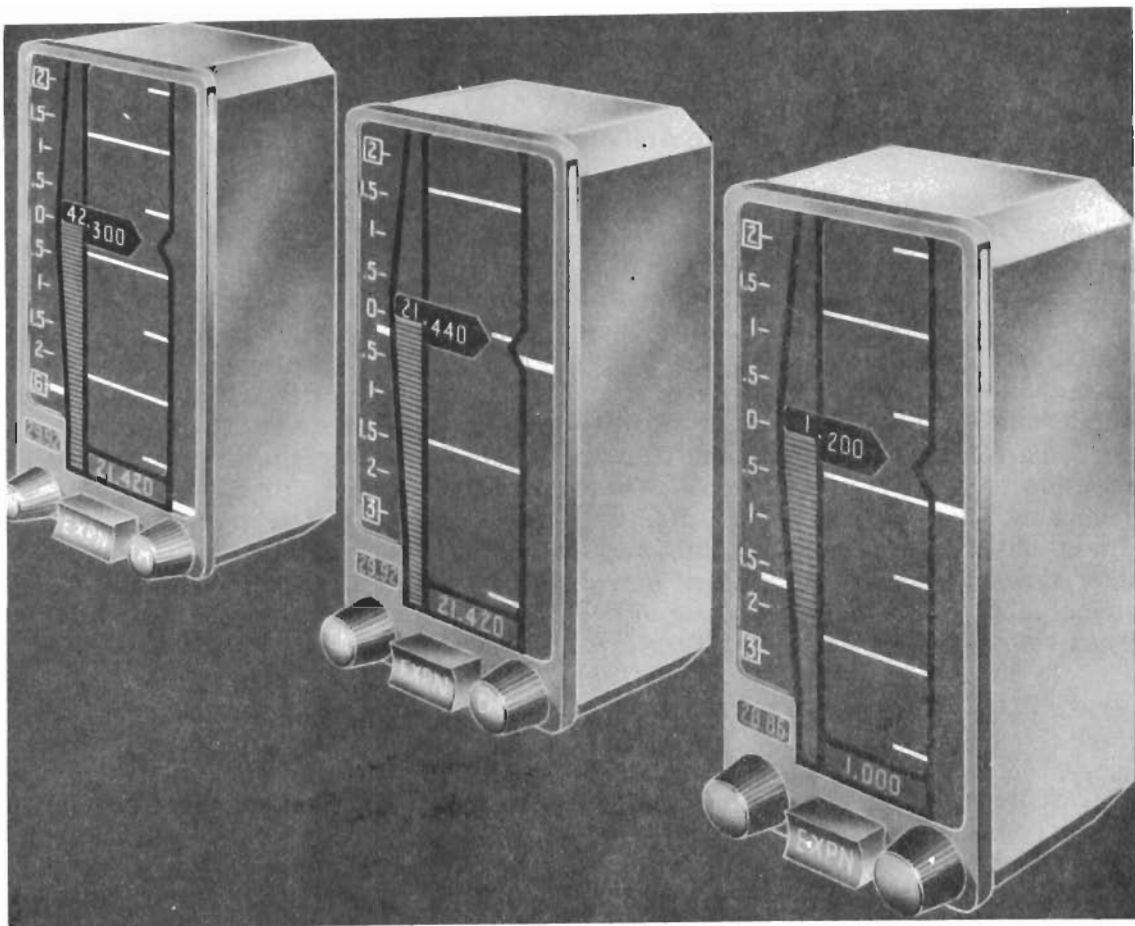


Figure 6. Experimental Solid-State Altimeter Format

SECTION II

HUMAN-FACTORS EVALUATION OF A HIGH-CONTRAST LANDING SEQUENCE INDICATOR

The innovations of techniques to increase the contrast of an EL or transilluminated display have been used to reduce the effects of ambient light on the display. A neutral-density filter can do this since the ambient illumination must pass through the filter twice (once, as it passes through to the display, and once again, as it is reflected from the display), but the emitted light has to pass through the filter only once. The employment of the neutral-density filter method lowers the luminance of the display, but raises its contrast. An extension of this technique makes use of a color filter whose spectral distribution is similar to that of the display. This causes the ambient illumination to pass through the color filter twice, which reduces the ambient reflected light to the color of the display. For the best effect, the spectral distribution of the color filter and display should coincide and be narrow thereby permitting a maximum absorption of ambient light and a minimum absorption of emitted light. The employment of this method would yield an increase in brightness contrast with little loss of display luminance, but would cause the loss of color contrast. Another technique, which has been recently developed, makes use of a filter layer adjacent to the phosphor layer. This has an effect similar to that of a neutral-density filter, except that a neutral-density filter characteristically yields a lower contrast when it transmits the same amount of light emitted from the display.

Aircraft instruments employing this filter-layer high-contrast technique have been developed and their application are being considered. It was not obvious whether instruments employing the above technique would be acceptable throughout the entire range of light conditions encountered in aircraft during daylight operation. Therefore, a survey was made of the ambient light conditions encountered in daylight operation of aircraft, and a demonstration facility was established in which one of the instruments, a landing sequence indicator, was subjected to these ambient conditions. It was evident from this demonstration that a more formal evaluation would be necessary.

The display provided for this evaluation was one of the first aircraft landing sequence indicators developed using the high-contrast technique. This display is divided into rectangular areas, and each area, when on, is completely illuminated except for the alpha or numeric information. The display, shown in Figure 7, has a -13 percent contrast between the off display

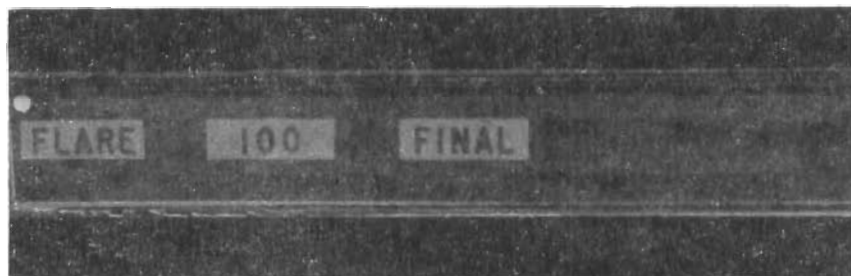


Figure 7. Landing Sequence Indicator

areas and the background. (Appendix III provides the definition of and rationale for percent contrast used in this report.) The contrast between the on display areas and the background is either between -13 and 0 percent or greater than 0 percent, depending on the emission intensity,

the amount of light reflected from the display areas, and the amount of light reflected from the background. The effect is the appearance of a dark character on a light rectangular background, which in turn is on a background that is (in room ambient illumination) darker than the rectangle.

The ability of a pilot to effectively read a display is dependent upon: 1) the operational ambient light conditions encountered, 2) the characteristics of the display, and 3) the time he may remain visually fixated on the display. This display is basically transilluminated or light emitting, which normally makes the use of the display sensitive to ambient light. This display is also limited in the level of emission, which could make its use sensitive to light adaptation and glare. These variables (ambient illumination, light adaptation, and glare) are also present to varying degrees in the daylight operation of aircraft, and therefore were selected as the main variables (along with display emission) in this study. The literature pertaining to these variables and operator performance is presented in Appendix IV. It should be noted that neither spectral glare nor flash blindness were included in either the literature search or the evaluation of the high-contrast EL landing sequence indicator. Both flash blindness and spectral glare result in the loss of ability to read a display, and consequently would be of no value in an evaluation of a display technique.

Consideration was given to the number of subjects which would be required, the number of measures to be explored, and the method of presenting the stimuli. Studies which require a large number of trials for each subject, and which are not designed to be statistically analyzed, usually make use of only one or two subjects. Since the experimenter could not consistently force the subject to respond as fast and as accurately as possible it was decided that two subjects would be necessary so that a check could be made on their relative performances. Due to the number of data points anticipated for the four independent variables and their interactions, it was decided that there would be only three measures taken along each independent variable. The selection of these measures was made in consideration of the daylight use of aircraft. The method used in conducting the study was agreed upon after making the judgment that subject response times would be more relative to the generalizations to aircraft displays than would threshold measures. The method selected permitted each subject to control each display presentation duration. His correct response removed the display, and the time required to respond correctly was the dependent variable.

METHOD

Subjects

Two subjects, both USAF pilots, were used in this study.

Apparatus

The apparatus consisted of an adaptation screen, glare screen, incident flooding lamp, display (as shown in Figure 8), and also subject response and experimenter controls. The lighting for adaptation, glare, and incident illumination was provided by No. 2 photo flood lamps.

The environment provided for the study was an open laboratory with standard overhead lighting. It was not necessary to establish lighting conditions darker than the lighted laboratory since the interests of this evaluation were in the use of the display under daylight conditions.

The display used in this study was a newly developed prototype high-contrast EL landing sequence indicator, which was provided for human-factors evaluation of daylight application. Three display areas of this landing sequence indicator were used in this study. Each was an 11/16 by 7/32 inch rectangle with labels of FLARE, 100, and FINAL, as shown in Figure 7. The display areas were composed (in effect) of dark letters or numbers on a light background. The display emission could be varied up to 11 footlamberts.

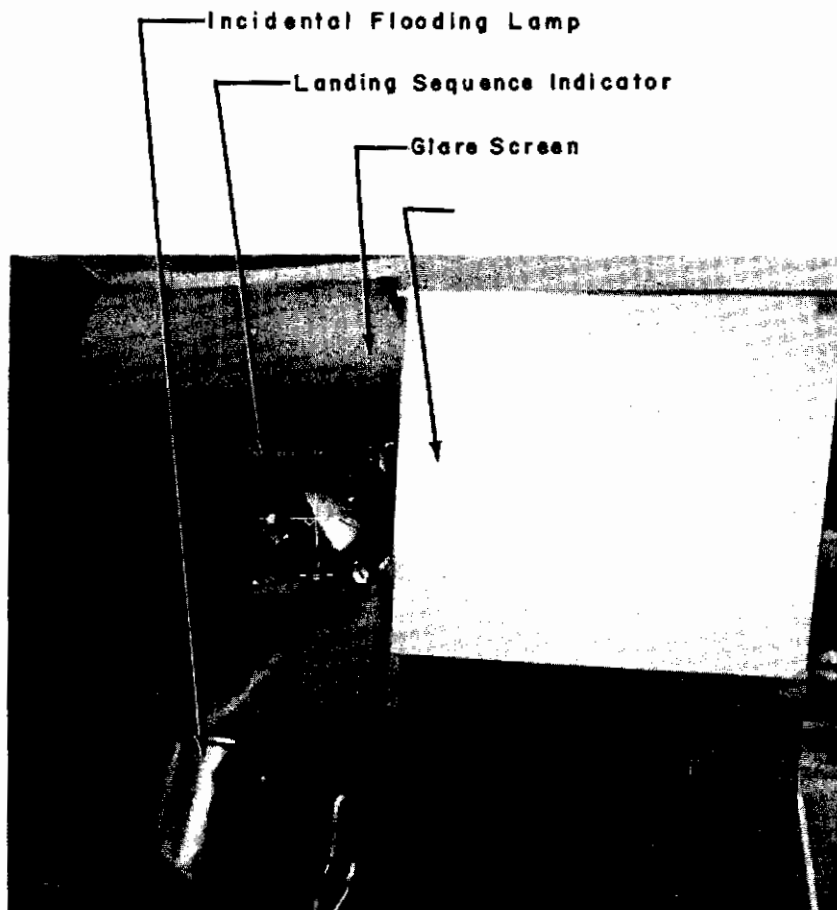


Figure 8. Environmental Apparatus (Adaptation Screen, Glare Screen, and Incidental Flooding Lamp) and Landing Sequence Indicator

The adaptation screen was made from a one-half inch plexiglass sheet frosted on both sides, having a rectangular area of $14\frac{1}{2}$ (base) by $12\frac{1}{2}$ inches exposed to the subject. The center of this screen was $11\frac{1}{2}$ inches from the center of the display areas used in the study. A photo flood lamp and reflector were mounted behind the screen, and provided up to 11,000 footlamberts at the center of the screen.

The glare screen was also made from a one-half inch plexiglass sheet frosted on both sides. It had an area of 12 (base) by 4 inches exposed to the subject. The base of this screen was 5 degrees above the display areas used in this study. A photo flood lamp and reflector were mounted behind the screen, and provided up to 11,000 footlamberts at the center of the screen. It should be noted that neither screen was uniformly bright since the light falling on the screens was not collimated. All light measures were taken at the central and brightest area of each screen.

The incident light flooding the display was provided by a photo flood lamp and reflector which was mounted approximately 45 degrees down, and 12 inches away from the display. A partition was placed between this lamp and the subject so that no direct light from the lamp could reach the subject's eyes.

A P-4A Flying Helmet and shield were used in the adaptation portion of the study for exposure to 5,000 and 10,000 footlamberts. The helmet shield was a neutral-density filter which transmitted approximately 12 percent of the incident light.

All surface luminances were measured by a Spectra Brightness Spot Meter, Model UB 1/2, manufactured by the Photo Research Corporation, Hollywood, California.

The subject-response part of the apparatus was a row of three microswitches mounted on the forward part of the subject's arm rest. This configuration permitted the subject to rest his right arm on the arm rest, and his first three fingers on the response switches. Figure 9 shows this configuration.

Procedure

Each subject was seated approximately 28 inches away from the adaptation screen and 30 inches away from the display and glare screen. The subject was instructed as to the correct response position for testing. Each display area was then identified by the experimenter to the subject not only by their labels, but also as being the first, second, and third display areas, which would correspond to their responses of depressing either the first, second, or third response switch.¹ The subject was instructed to respond to the display as rapidly and accurately as he could. The subject's attention was then directed to a mark at the center of the adaptation screen, which served as the starting position for each measurement. He was informed that a buzzer would be used to call his attention to the display for all responses. The subject was instructed about the conditions which he would experience, and was given five practice trials. This was followed by ten trials which were taken as the measures of his response to the experimental condition.

Conditions

In the base response condition all photo flood lamps were off, and the apparatus was illuminated only by the overhead laboratory lights. The display areas had a reflectance of 3.7 percent and the background had a reflectance of 4.2 percent. Under room light conditions the off display areas reflected 1.0 footlambert while the background reflected 1.15 footlamberts. From these readings the contrast between the display areas and the background was calculated to be -13 percent. Base line responses of both subjects were measured with a display area luminance of 5.4 footlamberts (1.0 reflected and 4.4 emitted). Under these conditions the contrast between the on display areas and the background was 79 percent. The glare screen was replaced by a dark blue cloth.

The glare response condition had only the glare photo flood lamp on, and the glare lamp was set so that the central portion of the glare screen emitted 10,000 footlamberts which would be equivalent to bright clouds. The display background reflected 1.15 footlamberts, and the display areas in the off state reflected 1.0 footlambert (-13 percent contrast with the background). The display areas in the on state were set to 4 footlamberts (1.0 reflected and 3.0 emitted), which provided a 71-percent contrast with the background.

The adaptation response condition made use of only the adaptation photo flood lamp, and it was set so that the central portion of the adaptation screen emitted either 10,000, 5,000, or

¹It should be noted that a consequence of the design of this display is that measures of readability, or even recognition cannot be taken. Having subjects read the display would soon result in position learning, and would result in collecting data on area identification. Consequently, the subject's task was to identify the rectangular area which was on.



Figure 9. Response Apparatus (Helmet Shield Was Used in Exposure to 5,000 and 10,000 Footlamberts)

1,000 footlamberts (which sampled ambient light levels up to that caused by bright clouds). However, the subjects did not adapt to 10,000 or 5,000 footlamberts because the helmet shield described above was used by the subjects at these levels. As a consequence of this the subjects only adapted to approximately 1,200 and 600 footlamberts when using the helmet shield, and 1,000 footlamberts when the shield was not used. The adaptation lamp was turned off at the same time a buzzer called the subject's attention to the display, and thus the adaptation screen was not considered to be a source of glare. The display areas in the on state were set to either 12, 8, or 4 footlamberts (1.0 reflected and either 11, 7, or 3 emitted), which resulted in 90, 86, or 71 percent contrast with the background, respectively. The use of the helmet shield did not change the percent contrast of the display with the background, but did reduce the luminance of the display from 12, 8, or 4 footlamberts to approximately 1.44, 0.96, or 0.48 footlamberts, respectively. The glare screen was replaced by a dark blue cloth.

In the display flooding response condition only the display flooding flood lamp was on. It was set so that the display background reflected either 100, 80, or 60 footlamberts of the light incident to the display which sampled ambient light levels up to the upper limit expected in aircraft except those which have bubble-type canopies. The luminance of the background as well as the on and off display areas are given in Table I. The glare screen was replaced by a dark blue cloth.

TABLE I
Relationship of Display On and Off Area
Luminance and Contrast to Display Flooding

	LUMINANCE AND CONTRAST PARAMETERS					
	Ft- <i>l</i>	Percent Contrast	Ft- <i>l</i>	Percent Contrast	Ft- <i>l</i>	Percent Contrast
Display Background	100	—	80	—	60	—
Display On Areas	98	- 2	81	1	63	5
	94	- 6	77	- 4	59	- 2
	90	-10	73	- 9	55	- 8
Display Off Areas	86	-13	70	-13	52	-13

RESULTS

The arithmetic mean and standard deviation of each condition measured in this study are given in Table II. These data (the mean and the ± 2 standard deviation range) are also presented in graphic form in Figures 10 through 14².

Glare

Figure 10 shows that the subject's response times to the most undesirable combination of glare and display luminance (10,000 footlamberts glare and 4 footlamberts display) was approximately the same as for the base response condition. It was concluded that more favorable combinations could not have appreciably better response times, and the trials combining greater display emission and/or less glare were cancelled.

Adaptation

Figures 11 through 13 show the interactions of display luminance, level of adaptation, and the resulting subject responses. Also shown is the subject's response to the base response condition. From these figures it can be seen that adaptation to 1,000 footlamberts does not appreciably retard the subject's response time for any of the three display luminances. Adaptation to a level of approximately 600 and 1,200 footlamberts resulting from fixating on a 5,000 and 10,000 footlambert adaptation screen while protecting the eyes with the helmet shield did retard the subject's response times, especially at lower display luminance levels.

² It should be noted that the study was not continued into the interactions of three and four variables. The reasons for this will be presented in the discussion portion of this report.

TABLE II

Arithmetic Mean (\bar{T}) and Standard Deviation (SD) of the Responses
for the Two Subjects Under all Conditions Measured

CONDITION: Base Response Time		\bar{T} .60	SD .09	\bar{T} .66	SD .08
CONDITION: Response Time With Glare of 10,000 Ft-L and Display of 4 Ft-L					
		\bar{T} .64	SD .08	\bar{T} .63	SD .08
CONDITION: Response Time for Level of Adaptation and Display Luminance					
Adaptation (ft-l)	Display Luminance (ft-l)	\bar{T}	SD	\bar{T}	SD
1,000 *	4	.72	.10	.72	.09
	8	.73	.12	.69	.08
	12	.71	.13	.67	.07
5,000 **	4	.87	.16	.93	.13
	8	.81	.06	.85	.06
	12	.87	.16	.79	.17
10,000 **	4	1.01	.21	1.40	.33
	8	.77	.10	1.04	.14
	12	.82	.08	.90	.15
CONDITION: Response Time for Level of Display Flooding and Display Emission					
Flooding (ft-l)	Display Luminance (ft-l)	\bar{T}	SD	\bar{T}	SD
60	55	.83	.05	.92	.13
	59	.72	.10	.76	.07
	63	.69	.06	.69	.08
80	73	.85	.05	.90	.10
	77	.75	.04	.82	.09
	81	.77	.05	.72	.10
100	90	.98	.08	.96	.16
	94	.84	.06	.78	.11
	98	.73	.06	.79	.08

* Without helmet shield

** With helmet shield

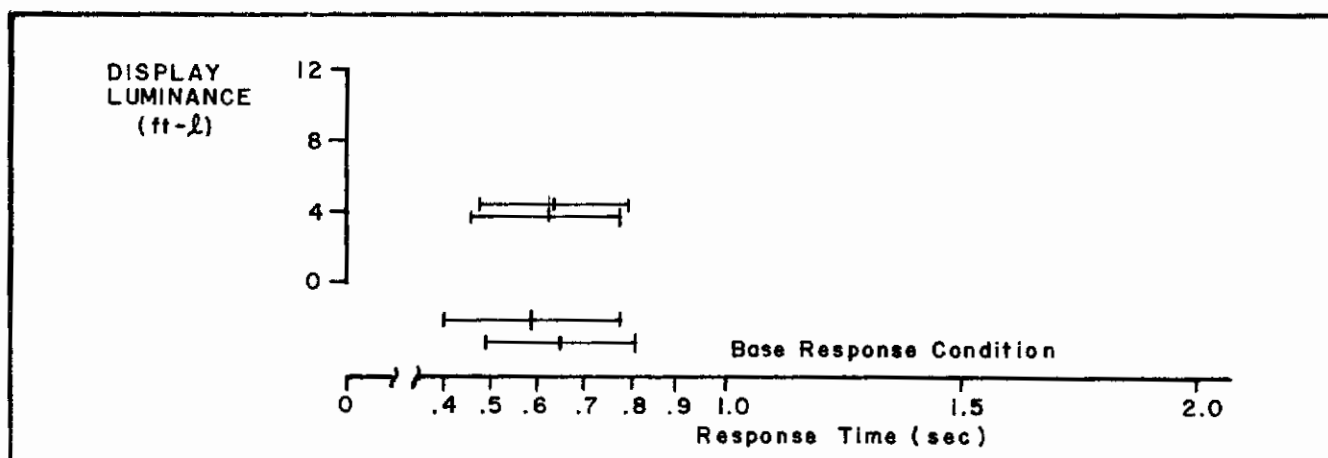


Figure 10. Effect of 10,000-Footlambert Glare on the Subjects' Response Time to a 4-Footlambert Display (Glare 5 Degrees Above Display)

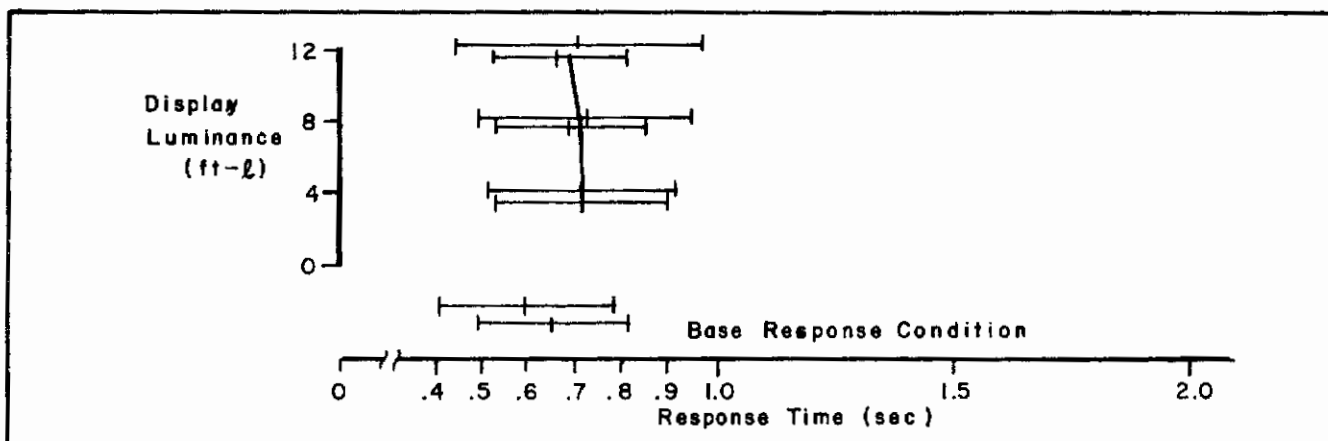


Figure 11. Effect of Adaptation to 1,000 Footlamberts (Without Helmet Shield) and Display Luminance on Response Time

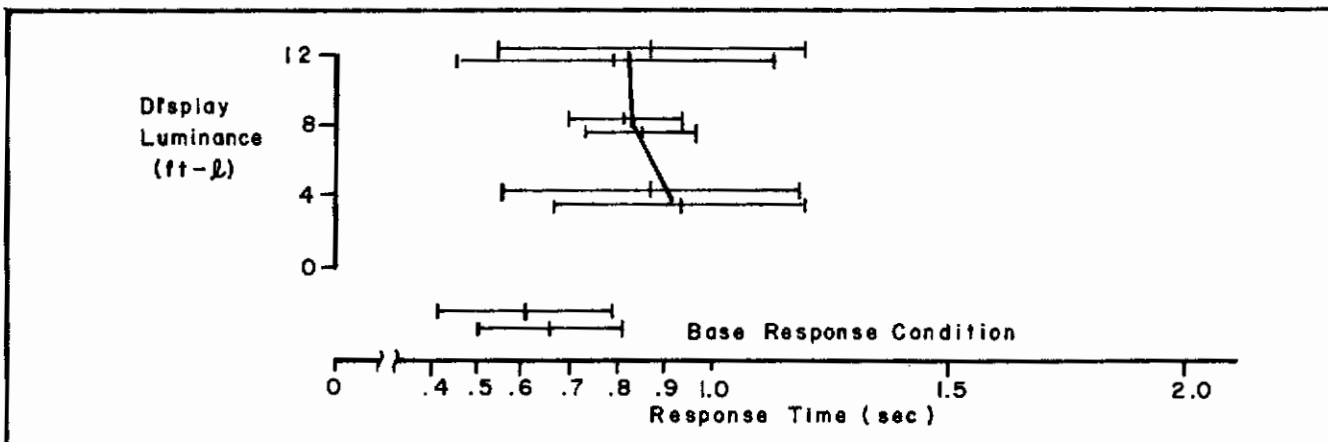


Figure 12. Effect of Adaptation to 5,000 Footlamberts (With Helmet Shield) and Display Luminance on Response Time

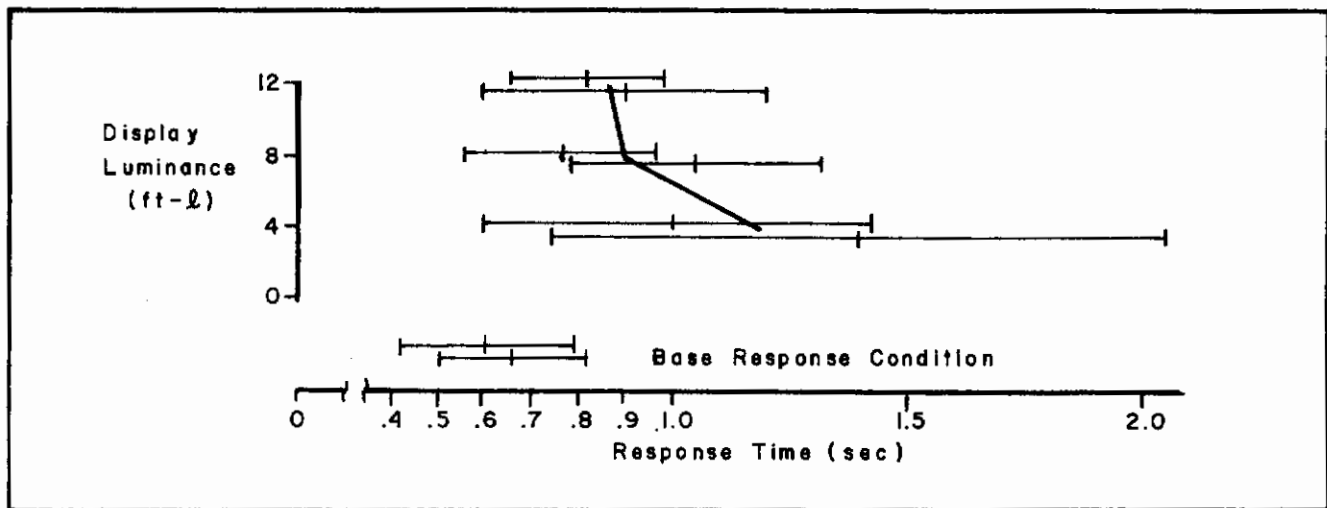


Figure 13. Effect of Adaptation to 10,000 Footlamberts (With Helmet Shield) and Display Luminance on Response Time

Flooding

Figure 14 shows the interactions of the level of display luminance, incident light (flooding) on the display, and the resulting subject responses. It can be seen from these figures that display luminance and background luminance interact with response time. Figure 15 also shows the relationship between the ratio of the display on area contrast to the display off area contrast.

DISCUSSION

Measures³ taken prior to recording the base response condition time indicated that the subjects would be fairly well matched. The base response condition measures of the subjects showed only .06 seconds between mean response times with only .01 seconds between standard deviations. It was decided that these values would serve as an index of the subjects' responses under the conditions of the study.

It was thought that glare alone could adversely affect the response times of the subjects. However, this was not the case, since the most undesirable combination of glare and display luminance resulted in responses nearly the same as the base response condition. Since the purpose of this study was to support the high-contrast EL development program, the collection of data in the study continued only as long as this data collection was meaningful.

Consequently, no further trials were taken with glare as an independent variable.⁴ It may well be found in a future study that glare may have an additive effect when combined with the incident flooding of the display and/or adaptation.

³ These measures were of response times to light stimulus and to buzzer stimulus, and in studying the differences among the response times of the first three fingers. No significant difference was found in the subjects' responses between the use of a light or buzzer as a stimulus, or the use of the first three fingers.

⁴ Glare would have been used as an independent variable in interaction with adaptation and incident flooding of the display if the study had been continued, but it seemed best to discontinue the study of interaction of variables because of the production of new high-contrast displays with better characteristics, and in light of the results thus far obtained.

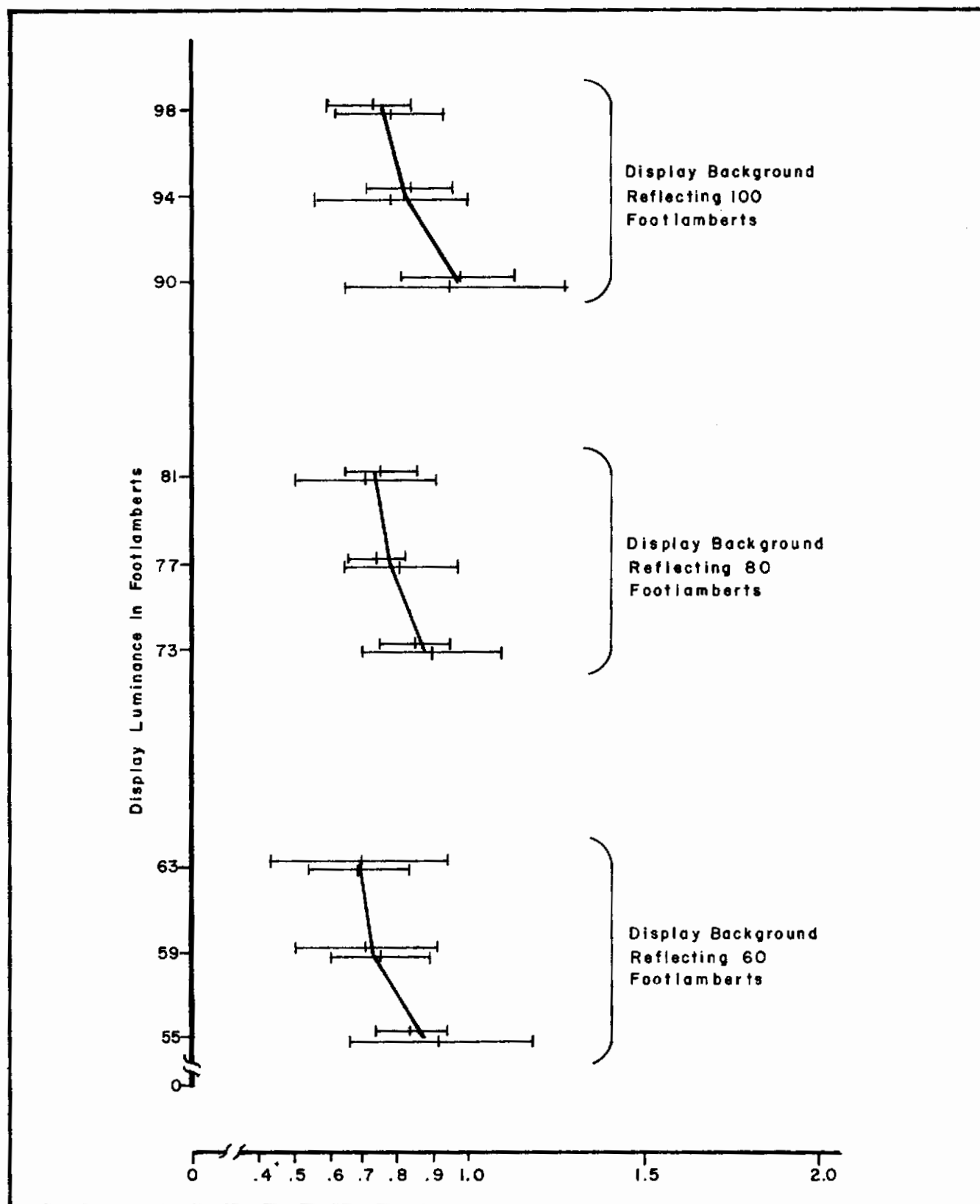


Figure 14. Effect of Incident Light (Flooding) and Display Luminance on Response Time

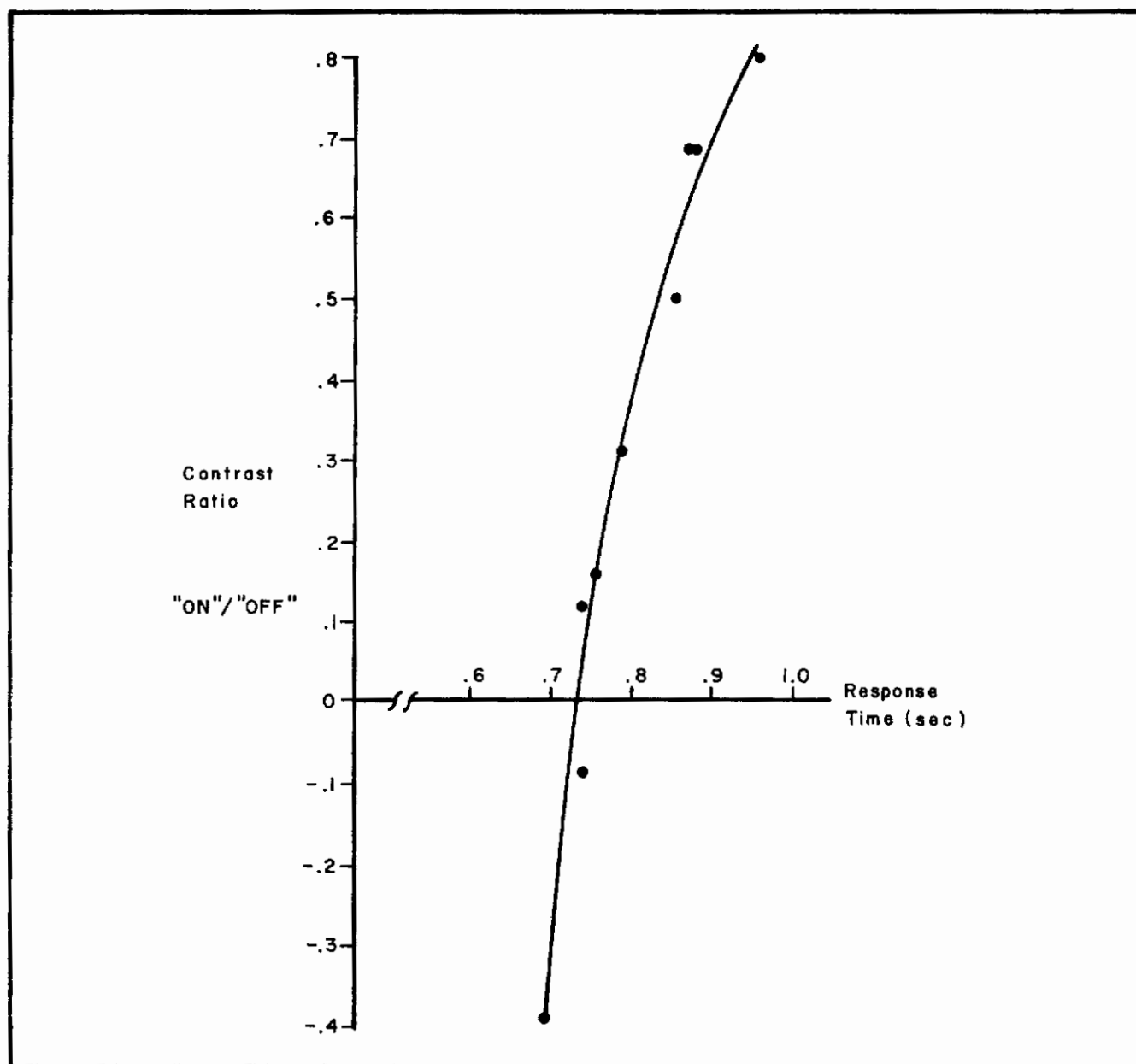


Figure 15. Relationship Between Contrast Ratio (Display On Area Contrast/Display Off Area Contrast) and Response Time

It was also thought that adaptation alone would have an effect upon the responses of the subjects. This expectation appears to have been supported. Display luminance seems to be the major factor interacting with adaptation, with the more luminous displays requiring less response time. It should be noted that the magnitude of the retardation in response may have been accentuated by the veiling effect that adaptation had not only on the emitting display areas, but also on the background. It was reported by the subjects that the loss of the background hindered them in identifying which display element was on. The adaptation reduced the non-homogeneous background (made up of the border of the instrument and the dark shading of the off display areas) toward a completely homogeneously dark background. Note should also be made of the use of the shield provided with the pilot's helmet. The decision to use such a shield was made after discussing the use the subjects normally make of their helmet shield.

It was concluded that pilots will not normally allow themselves to adapt to luminance levels as high as 5,000 or 10,000 footlamberts, and would draw down their helmet shield (or put on dark glasses when a helmet is not being used) to accomplish this. There is generally no objection to luminances of 1,000 footlamberts even though it is reported that some pilots will draw down their helmet shield or put on glasses when subjected to this level of luminance.

Finally, it was thought that direct flooding of the display alone would adversely affect the response times. This did happen, and, as was the case with the adaptation, it was most apparent when the on display area only was emitting three footlamberts. It was noted that the emission of the display was not the only thing that correlated with the subjects' performance. The ratio of the display on area contrast with background to the display off area contrast with background also correlated with performance. The display off areas were always darker than the background, while the display on area approached the luminance of the background (and in two conditions were slightly brighter than the background). Thus the display had one area (on) generally blending into the background, and two off areas darker than the background. The more the on area blended into the background, the easier it was to be identified as being on. This statement alone would be ridiculous, but consideration must be made of the two off display areas which remained considerably darker than the background. As the display on area blended more into the background the two off areas became more obvious as being off. The third area had to be the one that was on, and it was concluded from the statements of both subjects that this was the manner in which the responses were taking place. It should be noted that since the newer displays have uniformly reflective background and display off elements, the subjects would not have the cues described above for the flooding of the display, and the subjects most likely would not have performed as well as reported.

The display characteristics described above are quite unique, and some consideration should be given to the possibility of exploiting this characteristic into an operationally useful display technique. Such a technique would have to employ a light-sensing device which would control the intensity of emission so that the off portions of the display would blend in with the background. The on portions of the display would then be the dark display elements. The light-sensing device would also have to control a logic-reversing mechanism which would permit the emission of the display elements to be the on portion of the display when the ambient conditions darken.

The daylight flight of aircraft normally exposes both pilot and display to light conditions which would preclude the use of EL for aircraft displays. Progress has been made in the techniques which provide tradeoffs between display luminance and contrast. This has resulted in the possibility of applying EL to displays which could not have made use of EL in the past. This report demonstrated that the high-contrast EL display technique used in this landing sequence indicator was sufficient so that on display areas could be identified under the conditions to which the display and subjects were subjected, and should be acceptable for those aircraft which do not have bubble-type canopies. Although this statement is not a complete endorsement of this particular high-contrast display technique, it is a statement which could not have been made of a conventional EL display. Unqualified acceptance of a high-contrast EL display technique for daylight use in any type of aircraft is the goal of this program.

Equally important in this program is the resolution of the question of whether uniform non-red display colors may be operationally acceptable in night operation of aircraft. Inherent in this are the questions: 1) Would replacement of currently used nonuniformly luminous red displays by uniformly luminous nonred colored displays result in a significant elevation of a pilot's adaptation; and if so, 2) To what extent may a pilot's adaptation be compromised in order to obtain improved presentation of displayed information? This question of night application of EL displays, as well as daylight use of EL displays, will be the subject of future investigations.

Contrails

APPENDIX I

NONUNIFORM REFLECTANCE HIGH-CONTRAST DISPLAYS

Experimentation with nonuniform reflectance high-contrast EL displays has resulted in the determination that low-emission displays should appear uniformly reflective in their off condition. Differences in reflection as small as one percent have been shown to cause severe degradation of the readability of a display when viewed under daylight ambient conditions. Evaluation of the factors critical to this determination are presented below.

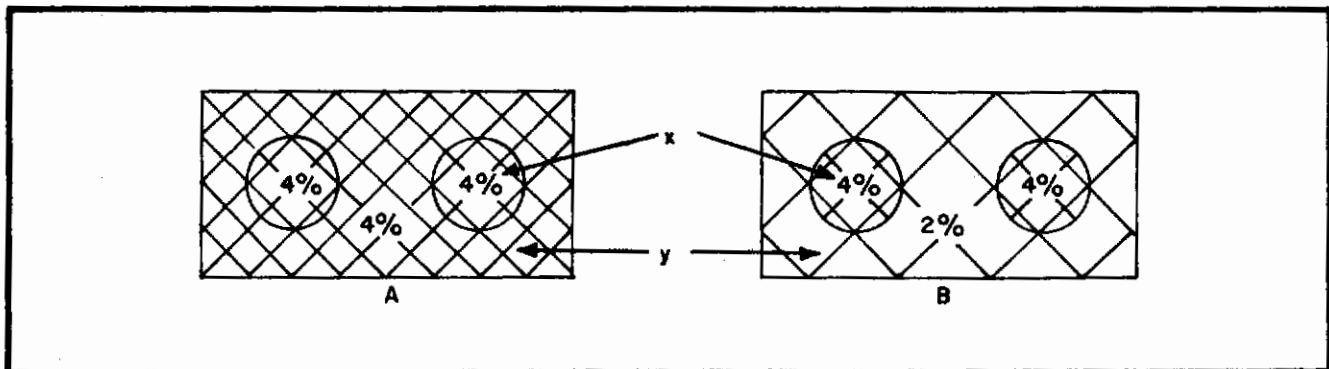


Figure 16. Uniform and Nonuniform Reflectance Displays

Assume that displays A and B (Figure 16) have a background reflectance of 4 and 2 percent, respectively and a common "information" reflectance of 4 percent. Now, display A will have a contrast of

$$C_A = \frac{(I + R_x A) - R_y A}{I + R_x A} \times 100\% \quad (11)$$

or

$$C_A = \frac{100\%}{1 + .04A/I} \quad (12)$$

where I equals the light transmitted through the filter surface; then display B will have a contrast of

$$C_B = \frac{I}{I + R_x A} \times 100\% + \frac{A(R_x - R_y)}{I + R_x A} \times 100\% \quad (13)$$

or

$$C_B = C_A + \frac{R_d}{R_x + I/A} \times 100\% \quad (14)$$

where the difference of reflectance would normally be greater than or equal to zero. Equation 14 shows that display B will always have a greater contrast ratio than display A. Normally, increased contrast is directly related to increased legibility; however, in this case the opposite is true. For example, if some ambient illumination was present while I

equaled zero, then C_A would equal zero-percent contrast and C_B would equal 50-percent contrast. Obviously, both displays are off when I equals zero so it would be necessary to mentally disregard the information presented in display B.

Depending on the magnitudes of the ambient illumination and display luminance, display A will become visible at some threshold point (possibly at 10-percent contrast). Under the same conditions, display B will have a contrast increase of 5 percent which, with the 10-percent threshold assumption, would not be sufficient for detection (Figure 17).

Assuming it would be possible to disregard the immediate background of display B such that the contrast reference was now the second 4-percent information block, then the on-off determination would again be achieved at or near the 10-percent contrast level. Unfortunately, when both segments are on or off together, the reference would have to revert to the lower reflectance background and it would again be impossible to determine the status of the display.

A more specific way of identifying this problem would be to calculate the value of I required to achieve a contrast increase over the off value of 10 percent for various conditions of display nonuniformity. For example, assume that display B is subjected to an ambient of 1,000 footcandles and has an information reflectance variable from 2 to 10 percent. To maintain threshold legibility under these conditions, I would have to increase from 2.2 to 100 footlamberts (Figure 18). It should be noted that when the informational reflectance is less than the background reflectance I must again be increased to achieve the desired 10-percent contrast level. Therefore, whenever a nonuniform display is used a severe penalty is incurred by either accepting a lower value of display contrast or by increasing the amount of display-emission intensity.

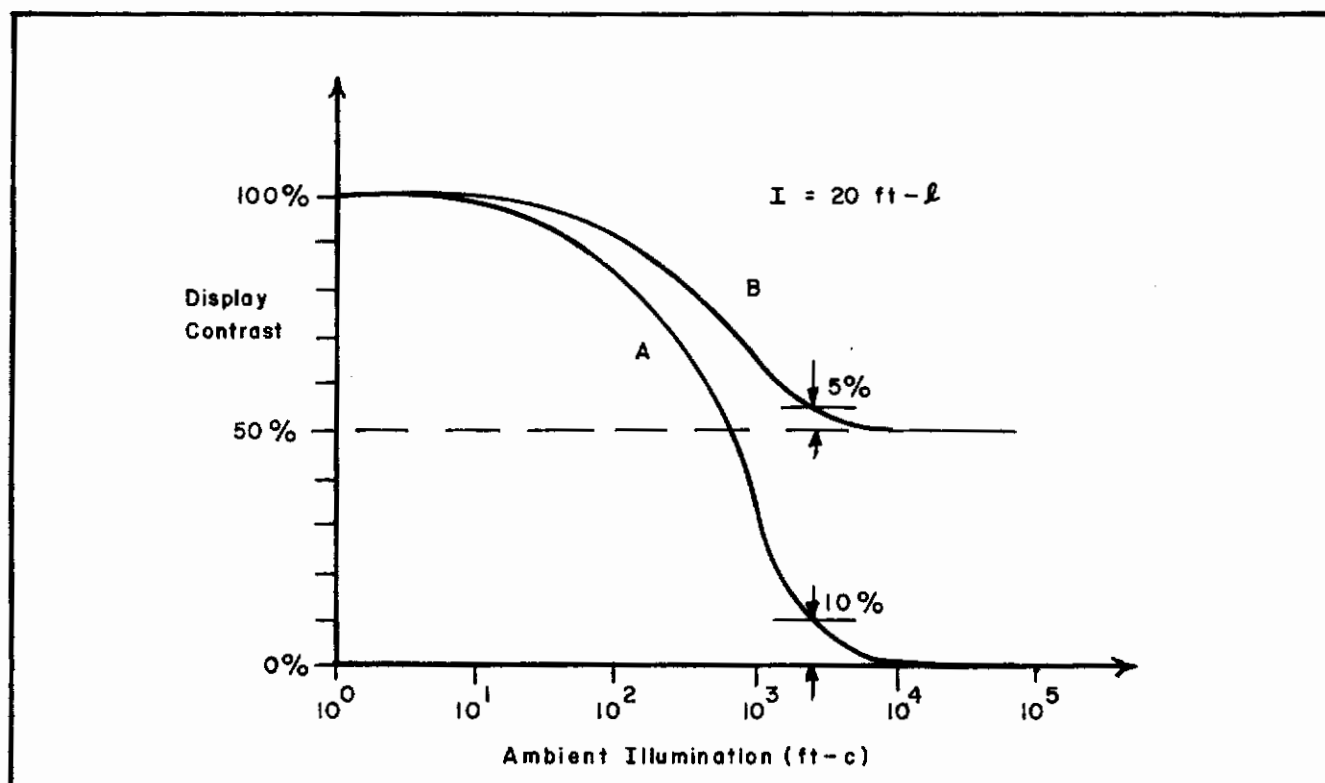


Figure 17. Uniform vs Nonuniform Display Contrast

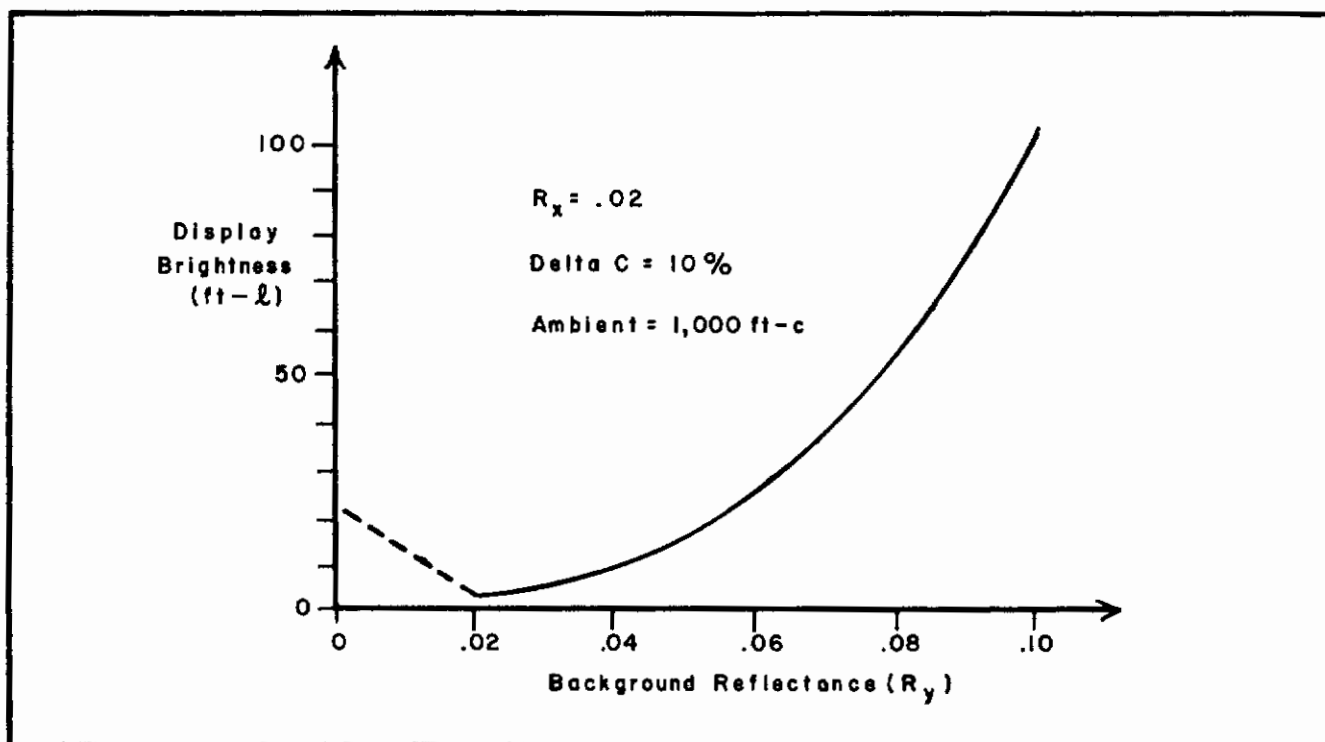


Figure 18. Display Luminance vs Reflectance Nonuniformity

APPENDIX II

DESIGN OF AN EXPERIMENTAL SOLID-STATE ALTIMETER DISPLAY

The display of altitude is based on continuous transmission of the following identifiable information: qualitative and quantitative altitude, relative position of the command altitude, rate of change of altitude, and absolute altitude. One of the key issues of altimeter design has been the requirement for display continuity. The standard moving-tape and round-dial indicators presently provide this information. As the state-of-the-art exists today, the use of solid-state techniques allows the designer to construct two forms of continuous displays, a moving-pointer display and a numberless moving-scale display. In the case of a moving-scale display, extreme concern must be given to the topic of relating numerical values to the numberless scale. In other words, graduation marks can be presented dynamically using relatively simple solid-state display switching techniques while moving numbers cannot.

The most significant number on a moving-tape display is the one associated with the 1,000-foot graduation mark just under the read line. The other numbers exist just to permit a simple means of translation of the correct 1,000-foot number to the read area.

A solid-state moving-scale display would normally consist of a segmented EL bargraph panel as shown in Figure 19. Each 1,000-foot line would be made up from three .03-inch emitting segments at every inch of the scale. The front transparent electrodes would normally be continuous over the whole display, and the rear electrodes would consist of .03-inch segmented conductors. Now if section A had an electrode pattern that was interconnected every inch, then conductors 1, 31, 61, and 91 would be electrically tied together, conductors 2, 32, 62, and 92 would be tied together, and so forth, while section B would have conductors 1, 16, 31, 46, . . . , and 2, 17, 32, 47, . . . tied together. Now if the group of lines 1_A , 2_A , and 3_A were on in section A while 1_B , 2_B , and 3_B were on in section B the pattern shown in Figure 21 would appear. Movement of the graduation marks would be accomplished simply by turning off segments connected to 1_A and 1_B and by turning on segments connected to 4_A and 4_B . Using this stepping scheme, the lines will always maintain a fixed separation and will appear to move together (taking .03-inch steps at a time). The relative positioning of the lines would normally be accomplished electronically on command from the altitude sensor. It should be noted that there are only thirty different nonrepetitive "pictures" achievable with this display. If higher resolution or greater separation were desired, the display would have to be fabricated and interconnected differently. Initial analysis of this display indicates that individual digital readout numbers should be suppressed to zero whenever they are changing too fast to be useful. The command, absolute altitude, and altitude rate presentations would be generated simply as a bar or column of light and would appear to move up and down the scale with .03-inch increments.

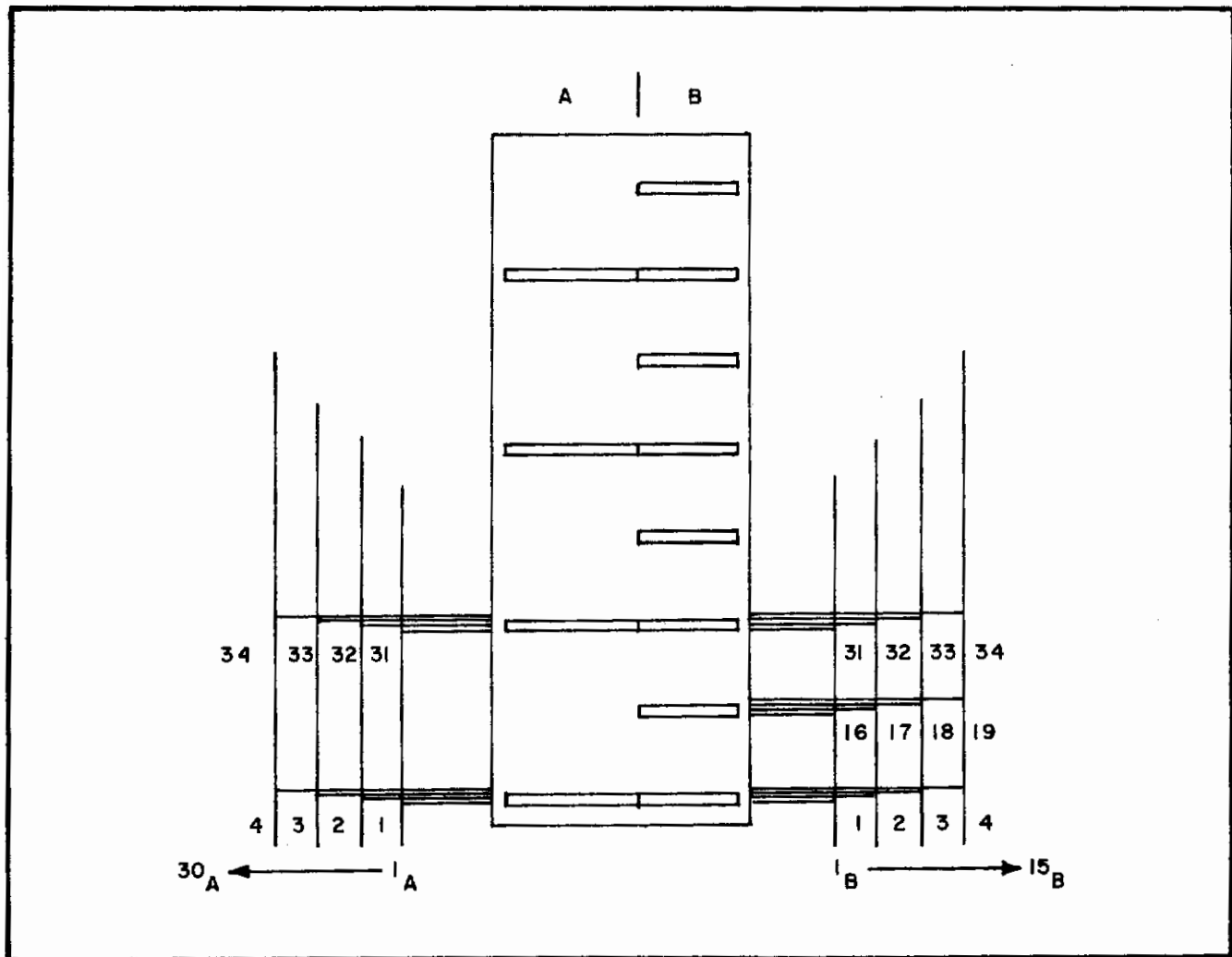


Figure 19. Moving-Scale Display

APPENDIX III

DEFINITION OF PERCENT CONTRAST

Percent contrast is defined here as:

$$(100)(-1)^n(B-D)/B$$

where n is 2 when the background is less luminous than the display element, n is 1 when the display element is less luminous than the background, B is the brighter area, and D is the dimmer area. The purpose of this definition is twofold: 1) It prevents the percent contrast from exceeding 100, which makes the values of negative and positive contrast equivalent, and 2) it permits a contrast ratio of the on display element contrast to the off display element contrast to be clearly presented (see Figure 15). It should be noted that such a contrast ratio should be a function similar to that of a log function, and allowing the contrast ratio to become negative provides a clearer best fit line than would be provided if the contrast ratio were always positive (which would yield a curve resembling a check mark).

APPENDIX IV

LITERATURE REVIEW

The review of the literature has been limited to studies which pertain to the variables of glare, adaptation, and contrast as they, in turn, pertain to the study of the high-contrast EL display. Display luminance is considered as an interaction variable with glare, adaptation, and contrast.

GLARE

Luchiesh and Moss (Reference 4) relate the effects of a glare created by a 100-watt frosted light bulb on visual performance. The measures were of the increase in test object size necessary to make it visible in the presence of the glare source at various visual angles from the test object. It was found that for a given visual angle between the glare source and test object the magnitude of the increase in size of the test object necessary to make it visible is inversely proportional to its luminance.

Wolf and Zigler (Reference 6) studied the effects that glare fields have upon the visibility of test targets, and found (in part) that the elevation of the visibility threshold was proportional to the size of the glare source, the luminance of the glare source, and the proximity of the glare source, and is inversely proportional to the luminance of the test target. From their data it would be expected that the threshold for the display areas used in the study of the high-contrast EL display should be near one footlambert for the 10,000-footlambert glare field. The results of the high-contrast EL display study show that the threshold was below 4 foot-lamberts.

ADAPTATION

The effects of adaptation to bright fields on the detection of dim targets has been studied by Brown (Reference 3) and by Baker (Reference 1). Both studies demonstrated a "raising" of the threshold, created by either a short exposure to a bright field, or adaptation to a bright field. The results of these studies indicate that the time required to detect a test object should increase with an increase in level of light adaptation, and decrease with the luminance of the test object. This effect was observed in the study of the high-contrast EL display.

CONTRAST

The studies of Blackwell (Reference 2) and Vos, Lazet, and Bouman (Reference 5) show that the liminal contrast becomes minimum when the adaptation is between one and 100 foot-lamberts, depending upon the visual angle of the test object. For visual angles approximate to that of the high-contrast EL display areas the contrast minimum begins between one and 10 footlamberts. This contrast is approximately 2 percent from Blackwell's data (for an estimated 98-percent-correct response threshold), and about 9 percent from Vos, Lazet, and Bouman's data. Inference from this data to the study of the high-contrast EL display would be difficult because of the complexity of the display. An on display area which only has a 1 percent contrast with the background may be easily detected because of its difference from the other off display areas which have a $-12\frac{1}{2}$ percent contrast with the background. However, the 2 to 9 percent contrast figures provide an identification of a nominal contrast region. This region should be of some assistance in specifying either the on display area contrast, or some combination of the on display area contrast and the contrast ratio of the on and off display areas.

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13. ABSTRACT This report outlines the steps taken by the Air Force Flight Dynamics Laboratory to develop a new display technology capable of meeting display requirements of future manned weapon systems. A description is made in the first part of this report identifying the basic concept and resulting development of high contrast electroluminescent (EL) displays both from an engineering and psychophysical standpoint. The problem of display legibility, quite often confused with display brightness, is also discussed with respect to its effect on the limitations of EL displays. Finally, information is presented indentifying how this limitation was overcome and why such progress is considered to be important contribution to the development of solid state displays. The second part of this paper describes the human factors aspects of the high contrast EL program. The inherent weakness of transilluminated displays, the variables related to readability, the effects of the anticipated upper limits of environmental lighting, and the study of one of the first high contrast EL displays are discussed.		

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