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USAARL REPORT NO. 72-3

STATIC COMPARISON OF VERTICAL TAPE AND VERTICAL LIGHT EMITTING DIODE DISPLAYS

By

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U. S. ARMY AEROMEDICAL RESEARCH LABORATORY

Fort Rucker, Alabama

FINAL REPORT

Prepared For:

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St. Louis, Missouri

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Part II consisted of a human factors facial design evaluation for one vertical tape display and four prototype LED displays. All displays were found to be deficient when compared to military standards and research recommendations.

Part III consisted of a photometric evaluation of the four LED displays. The results showed that these displays were unacceptable for viewing under high ambient light conditions and that gross luminance differences between individual diodes existed within the same display.

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ABSTRACT

This study was performed in three parts. The first part consisted of comparing a prototype light emitting diode vertical display with a current vertical tape display, for reading speed and accuracy, under two viewing angles, three levels of illumination, and two time conditions. The results indicated that the sixteen (16) aviators (subjects) over-estimated the LED instrument while the vertical tape instrument was under-estimated. In addition, absolute errors in reading were greater for the LED display than they were for the vertical display. Time conditions and angles did not have a significant effect, while illumination level for the LED's was of importance.

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APPROVED: Robert W. Bailey
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COL, MS
Commanding

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INTRODUCTION

An instrument in an airplane cockpit is nothing more than a link between the pilot and some condition of the aircraft, either its mechanical functioning or its relationship to the ground and other objects. The aircraft instrument is an information transmitter, usually of visual information, and as such, the operating or design characteristics of the instrument, and the instrument face, can determine whether it is a good or poor transmitter of information. Some of the design characteristics which have received study involve the use of vertical instruments, primarily vertical tape instruments and round, dial type instruments. Several studies have shown the advantages of vertical tape instruments over dial instruments for the display of engine status information.[9] The use of vertical tape instruments can require up to 50 percent less space than round dial instruments.[1] Not only is there a space savings, but more important, pilot quick-scan monitoring ability, reading time, and reading accuracy is enhanced by the use of vertical tape instruments.[9] In addition to these findings, the ability to read vertical tape instruments in low levels of ambient illumination is enhanced over round dial instruments due mostly to the inherent design of each type. Vertical tape instruments are generally back-lighted, whereas round dial instruments are usually post-lighted. Because of back-lighting, vertical tape displays have much clearer color coding for operating ranges on the display face under monochromatic red cockpit lighting (used at night to protect dark adaptation), while only shades of gray can be seen of the color band on conventional dials under red cockpit illumination. Based on all of these considerations, plus the almost universal pilot acceptance of vertical displays, it would seem that the use of vertical displays would be desirable.

Another major area of interest in conjunction with the "goodness" of an instrument's information transmitting capability involves the design characteristics of the face of the instrument. A great deal of study has evolved on the subject of human factors design criteria for "facial" characteristics of an instrument. This has resulted in standards and recommendations for the dimensions and/or proportions for numbers, scale markings, scale units, width of numbers and markings, which will lead to maximal information transmission for a given sized instrument. Several studies have been done which can serve as guidelines for instrument face design for optimum information transmission. Some of the features which have been investigated are:

a. Length of Scale Unit (the length on the scale which represents the numerical value that is the smallest unit to which the scale is to be read).[6,8]

b. Scale Markers (the number and characteristics of markers on the scale).[7]

c. Numerical Progression of Scale (the numerical values represented by the major and minor scale markers).[12]

d. Stroke Width (ratio of the thickness of the stroke to the height of the letter or number).[3,4]

e. Number Height and Width (the numeral height and width).[5]

Based in part upon these and other research studies, military standards such as MIL-M-18012B have been set forth which specify the dimensions or ranges of dimensions for facial characteristics to satisfy the criterion of optimum information transmission for a given instrument.

The Army currently employs vertical tape instruments in the OV-1C and OV-1D aircraft which are multi-engine reconnaissance aircraft. These vertical tape instruments are first generation types of vertical displays. The state-of-the-art of some vertical instruments has improved. It is now possible, in some displays, to use inferred movement vertical displays rather than the vertical tape. The reliability of these inferred movement displays is estimated to be many times higher than the type of vertical tape currently used in the OV-1 aircraft. In addition, considerable weight reduction should be experienced due to the solid state construction of the inferred movement displays.

The type of inferred movement display under consideration as an alternative to the vertical tape display is a light emitting diode display which resembles a vertical tape instrument in facial design, but in which a stack or column of light emitting diodes replaces the vertical tape. Before an inferred movement display can or should be substituted for a vertical tape display, a systematic evaluation must be done, not only to ascertain the good points or advantages of light emitting diode displays, but also to uncover any shortcomings of these displays.

The purpose of this study was to evaluate light emitting diode displays in three areas: (1) an experimental comparison of a light emitting diode display and a vertical tape display to discover if any differences between these two types of displays existed with respect to reading speed and accuracy; (2) a human factors design criteria evaluation to ascertain whether displays submitted for study met military specifications and/or empirically determined specifications for size and proportionality of facial characteristics; (3) a photometric evaluation of the light transmitting characteristics of the light emitting diode and vertical tape displays.

Since these three evaluations constitute essentially three separate studies, each with unique methods, subjects, and apparatuses, they will be reported separately and a summary of all results will be presented in a fourth section.

PART I

Experimental Comparison of Reading Accuracy and Speed of A Vertical Tape Display and A Light Emitting Diode Display

PURPOSE

The purpose of this study was to compare a prototype LED display and a currently employed vertical tape display for reading accuracy and speed. This was done under three levels of illumination, two viewing angles, and two timing conditions.

METHOD

Subjects

Subjects for this study were sixteen (16) Army aviators who were qualified in, or currently flying, one of the US Army's multi-engine aircraft, the OV-1 Mohawk. Mean age and flying time data is presented in Table 1-I.

Table 1-I

Subject Data

Mean Age	29.10 Years
Mean Total Flying Time	3096.80 Hours
Mean Total OV-1 Time	1211.56 Hours
Mean Total Flying Time in C & D Model OV-1	296.70 Hours
Color Vision Defects	None

Apparatus

The apparatus consisted of an aircraft seat in which the subject was seated, in front of a large display board (see Figure 1-I). The display board was constructed from 3/4 inch plywood painted black, with a 5 1/4" x 1 3/4" aperture located at an angle below and distance from the subject's eyes commensurate with the viewing distance and angle for the torque instrument found in the cockpits of OV-1 aircraft. The instruments were installed in the aperture for each test. An electronically controlled shutter was placed between the subject and display. The entire apparatus was located in a light-proof room, the walls of which were painted flat black.

Subjects were seated in a standard aircraft seat and secured by a shoulder harness. This was done in an effort to maintain the same head/eye distance from the instruments for all subjects. To prevent auditory cueing, the subjects wore head-phones through which 46 db SPL pink noise was transmitted in order to mask the noise of the shutter opening, and the sound of the relays actuating the shutter.

Four prototype models of LED instruments were available for comparison with the vertical tape display. Of those, only one had scale characteristics which were similar enough to the current vertical tape instrument to allow comparison. Figure 2-I shows the vertical tape instrument, and Figure 3-I is the light emitting diode display employed.

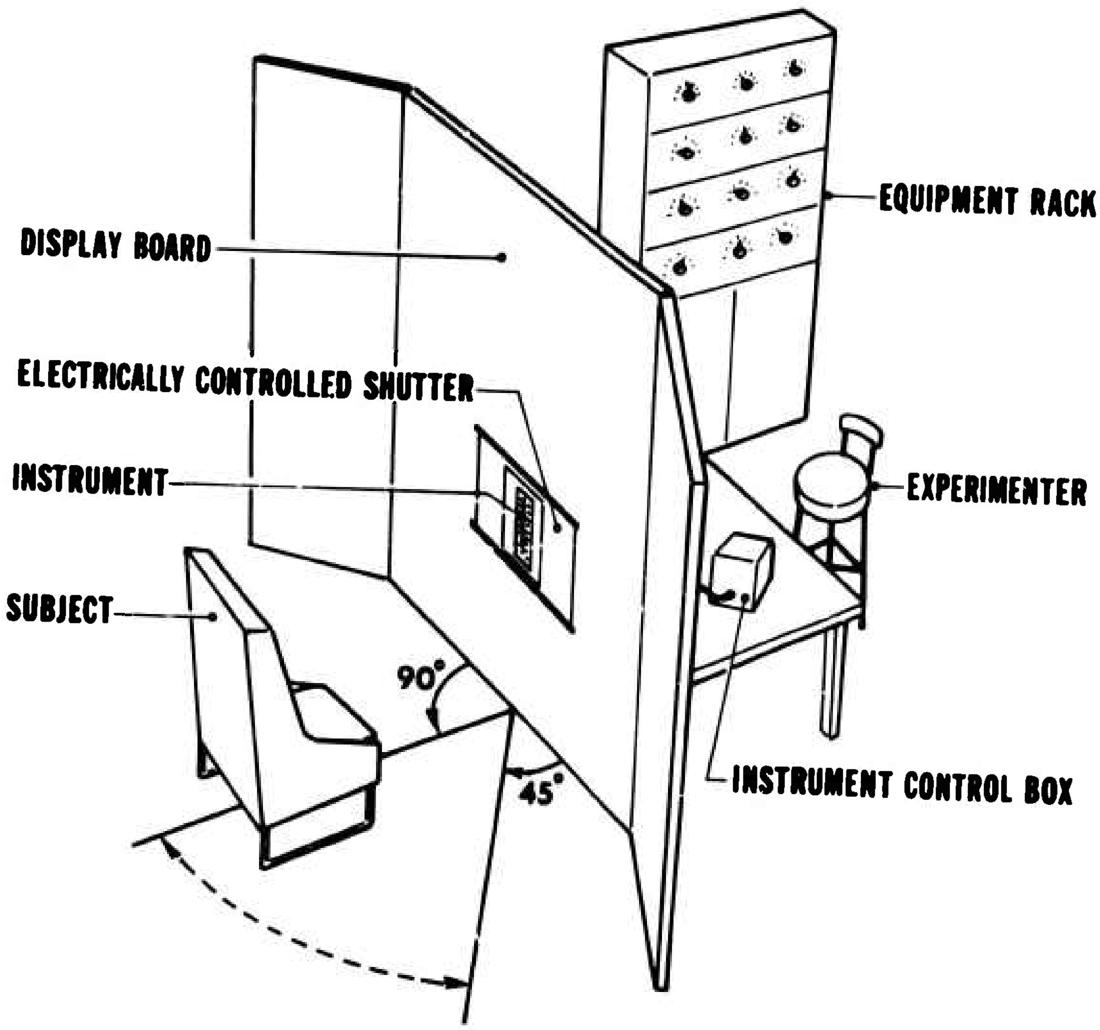


Figure 1-I

Instrument Display Panel

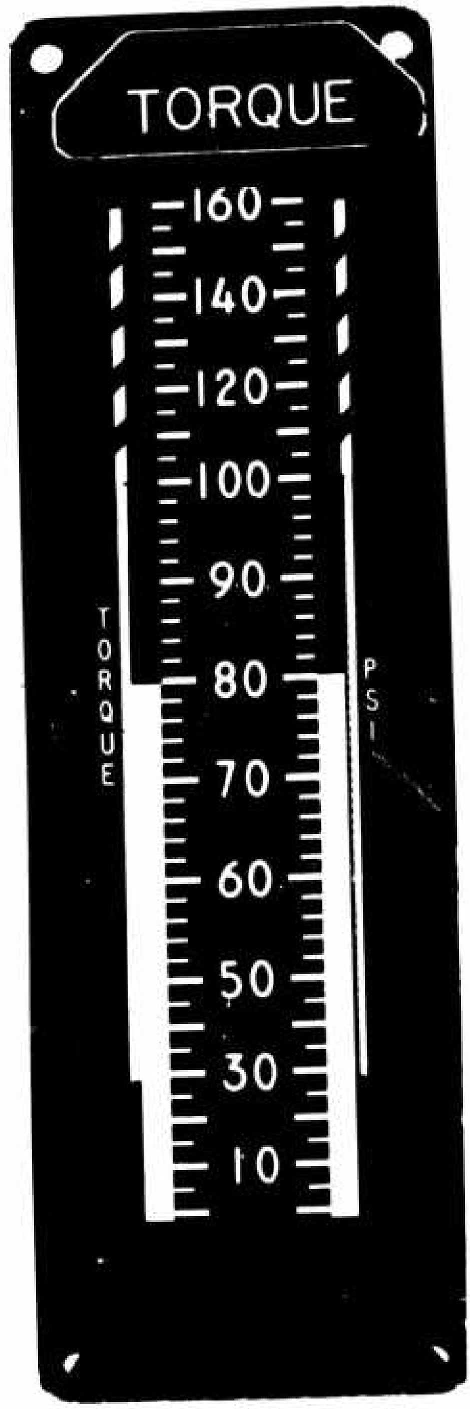


Figure 2-I

Vertical Tape Display

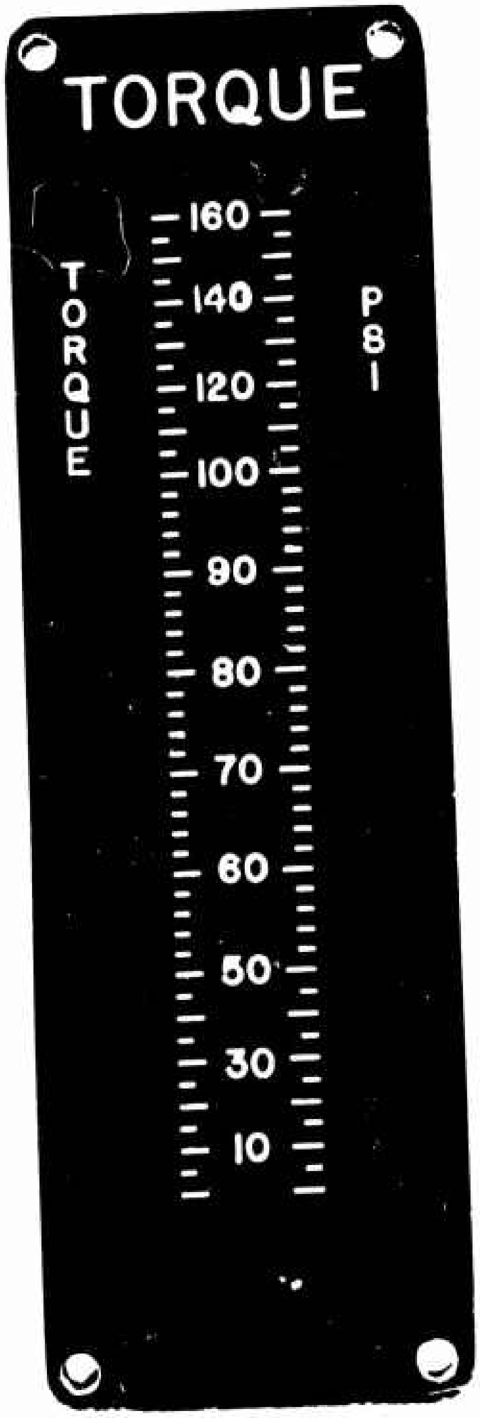


Figure 3-I

Light Emitting Diode Display

The control box for the vertical tape instrument allowed an unlimited selection of values or settings to be displayed. The LED control box allowed only a limited selection of values, and fourteen (14) values were selected to be displayed on both of the instruments. These values were selected such that half of them fell on either a major or minor graduation mark and required no interpolation, and half fell between graduation marks, which required interpolation. Only whole number values were employed. The values were not distributed evenly over the entire normal operating range, but were biased toward the high end of the scale.

Experimental Design

The design employed in this study was a four factor design with repeated measures on three factors. The three within-subjects independent variables were: Instrument (Vertical Tape versus LED); Viewing Angle (0° versus 45°); and Timing Condition (Forced-Time Trials versus Subject-Controlled Time Trials). The between-subjects independent variable was Level of Illumination (Sunlight versus Total Darkness versus Intermediate Illumination). There were a total of sixteen (16) subjects in the study---eight subjects were assigned at random to the Total Darkness group and eight to the Intermediate Illumination group. Data for the direct sunlight group is not included in this study since this group was discontinued early when it was found that even at the highest intensity settings, the LED display could not be read in sunlight due to the extremely low contrast level. The eight subjects in the total darkness and intermediate illumination groups were tested on both instruments at both viewing angles with both forced-time and subject-controlled time trials. Subjects in both illumination level groups received the forced-time trials first, followed by the subject-controlled time trials. Within these two conditions, however, the order of presentation of the four Instrument/Viewing Angle conditions was randomized.

The dependent variable for all conditions was the magnitude and direction of reading error. Latency measures (viewing times) were also recorded on Subject-Terminated trials. The experimental design is outlined in Table 2-I.

Table 2-I

Experimental Design

Between Subjects Variable	Within Subjects Variables							
Level Of Illumination	Forced-Time Trials				Subject-Controlled Time Trials			
	Vertical Tape		LED		Vertical Tape		LED	
	0°	45°	0°	45°	0°	45°	0°	45°
Intermediate Illumination 8 Ss								
Total Darkness 8 Ss								

Procedure

The subject was brought into the experimental room, seated in the aircraft seat and read a standard set of instructions. The test instruments were then installed in the display board one at a time in order to let the subject familiarize himself with the instruments. At this time, if the subject was in the group tested in total darkness, the lights were turned off and the subject was allowed to adjust the internal lighting on the two instruments (by directing the experimenter who ran the controls) to a comfortable reading level. For subjects in the intermediate lighting condition, the lighting consisted of two, eight-foot fluorescent ceiling lights. For subjects in the sunlight condition, the apparatus was moved outside and situated so that the sun was above and behind the subject. This condition, as previously mentioned, was discontinued when it was found that the LED instrument could not be read in direct sunlight because of the extremely low contrast levels afforded by the red diodes.

Forced Time Trials

This condition was employed in order to test the quick-scan readability of the instruments, and to assure sufficient errors for analysis. This was done by empirically determining a viewing time which would produce approximately 50 percent reading errors on the control instrument, the vertical tape. This time was determined, on the basis of a pilot study, to be 1.30 seconds.

The operation of the shutter was explained to the subject, and subject was given several practice trials to assure that he understood the procedure. A cue light, situated 21 inches above the instrument came on to signal the start of a trial. The shutter opened two seconds after the offset of the light. The shutter stayed open for 1.30 seconds after which it shut and the subject responded by saying aloud the reading on the instrument. This was recorded by the experimenter. This procedure was repeated for 14 trials (values) for each instrument at both viewing angles (56 trials) with an inter-trial interval (ITI) of 15 seconds.

Subject-Controlled Time Trials

The procedure for these trials was the same as that for the Forced Time trials except that after the cue light went out and was followed by the shutter opening, the shutter remained open until the subject pressed a hand-held microswitch to close the shutter and terminate the trial.

Subjects were given the instruction that when the shutter opened, to read the instrument as quickly and as accurately as possible, and then to immediately press the switch to close the shutter and stop the clock. After closing the shutter, subject was to give his response which was recorded, along with the latency, by the experimenter. Following this, a new value was set on the instrument by the experimenter and following a 15 second ITI, the next trial was initiated. The subject was again given 14 trials (values) for each instrument at each viewing angle making a total of 56 trials.

RESULTS

Figures 4-I and 5-I show the overall results of the comparisons for two levels of illumination, two timing conditions, and two viewing angles. Figure 4-I, Column A shows the LED instrument to have a higher mean absolute error than the vertical tape under both the forced-time condition and the subject-controlled time condition. This same relationship held for the two levels of illumination, intermediate light and total darkness (Figure 4-I, Column B), and the two viewing angles, 0° and 45° (Figure 4-I, Column C).

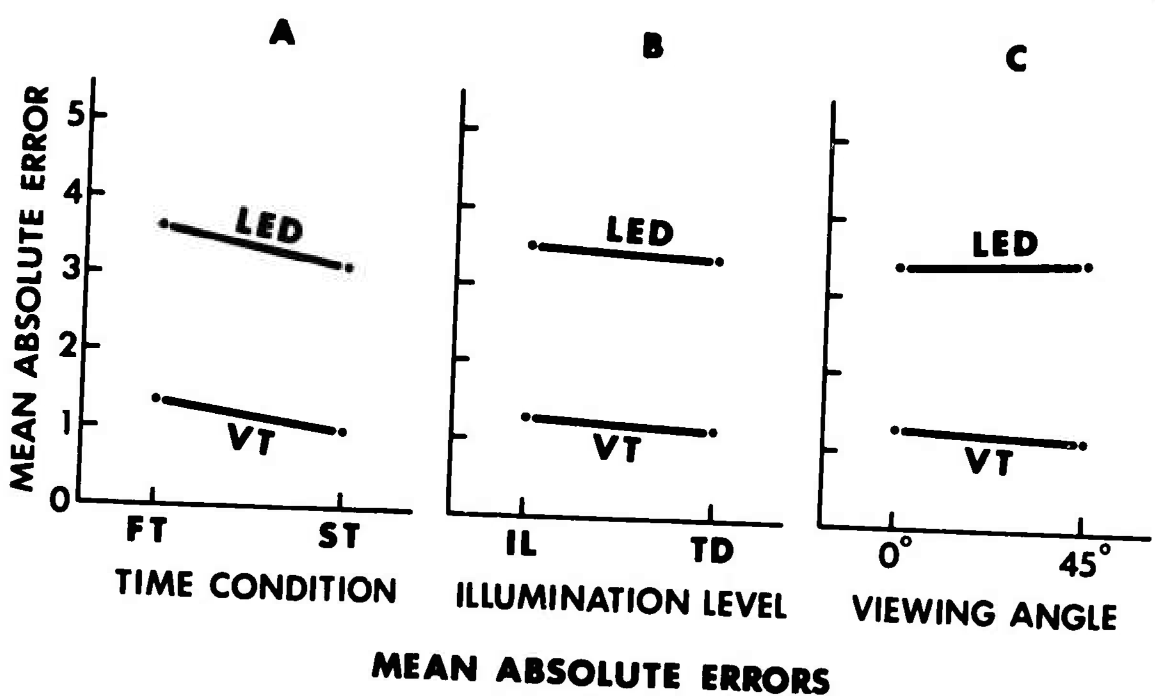


Figure 4-I

Mean Absolute Errors for the Vertical Tape Display Versus the Light Emitting Diode Display Under Conditions: A - Forced Time Vs. Subject-Controlled Time; B - Intermediate Light Vs. Total Darkness; C - 0° Vs. 45° Viewing Angle

A separate analysis of variance was performed on the absolute error scores for the Forced Time and Subject-Controlled Time Trials. The data was analyzed in this fashion in order to study, in more detail, possible interaction effects between illumination level, viewing angle, and type of instrument. Each of the analyses was performed using a mean absolute error score for the 14 trials for each subject in each condition.

The analysis of variance for the error scores (see Appendix A-I) for the Forced Time Trials yielded a significant main effect of Instruments ($F_{1,\ 14} = 54.54$, $p < .01$). The main effect of Illumination Level was not significant nor was the main effect of Viewing Angle. None of the first or second order interactions were statistically significant. The analysis of variance performed on the error scores (see Appendix B-I) for Subject-Controlled Time Trials revealed a significant main effect for Instruments ($F_{1,\ 14} = 92.32$, $p < .01$). The main effects of Illumination Level and Viewing Angle were not significant, nor were any interactions.

The main effect of Instrument Type can be seen in Figure 4-I as the difference between the LED display and the vertical tape display at every point on Figure 4-I, Columns A, B, and C. The lack of any other main effects or interactions is demonstrated in Figure 4-I by the failure of the relationship between the LED and vertical tape to change significantly over the different conditions.

It can be seen from Figure 5-I that the LED display is consistently <u>over</u>-read by approximately three "points" regardless of the time allowed for reading, the illumination level, or the viewing angle. The vertical tape display is consistently <u>under</u>-read by approximately one-half "point" regardless of any of the conditions.

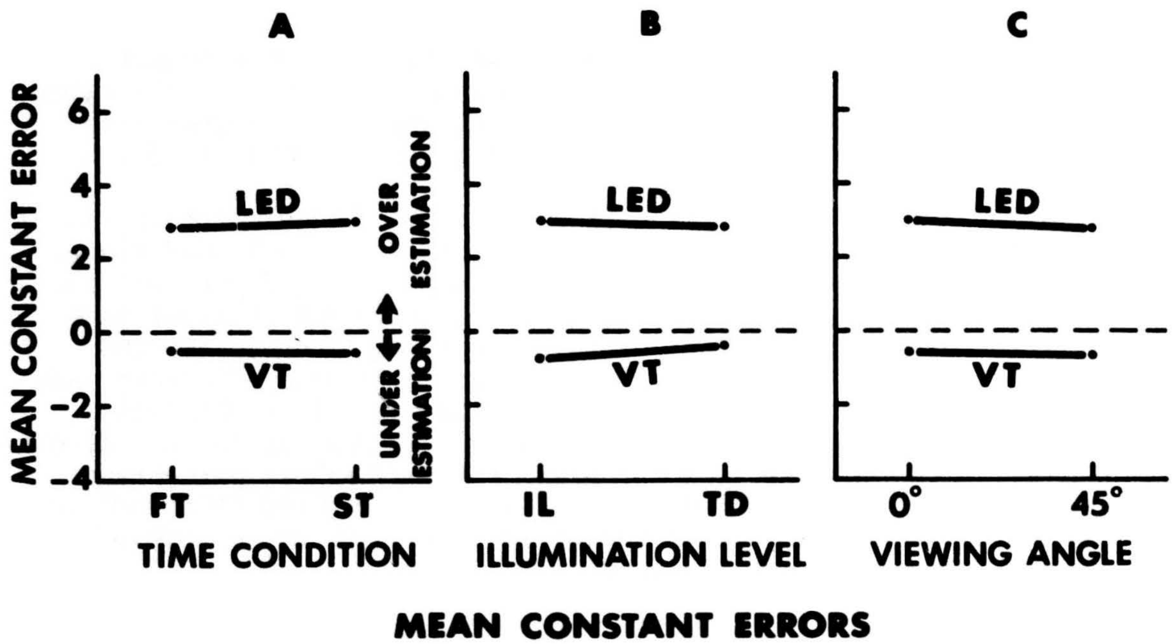


Figure 5-I

Mean Constant Errors for the Vertical Tape Display Vs. the Light Emitting Diode Display Under Conditions: A - Forced Time Vs. Subject-Controlled Time; B - Intermediate Light Vs. Total Darkness; C - 0° Vs. 45° Viewing Angle

Table 3 shows the response latencies (viewing times) for the two illumination level groups under the subject-controlled time condition. Within each group, mean latencies are given for each instrument at each viewing angle.

Table 3-I

Response Latencies (In Seconds) for Subjects Under Subject-Controlled Time Condition

	Intermediate Illumination		Total Darkness	
	0°	45°	0°	45°
Vertical Tape	1.28	1.33	1.73	1.73
LED	1.38	1.34	1.71	1.76

Subjects in the total darkness group took slightly longer (approximately 4/10 second) to respond that did subjects in the intermediate light group. The effect of viewing angle on response time was negligible, and not systematic as can be seen from Table 3-I.

Figure 6-I shows a histogram plot of the absolute errors in pounds of torque by instrument over all subjects and all conditions. A review of Figure 6-I shows that subjects made 360 (42 percent) correct responses (error magnitude equal to zero) to the vertical tape display compared to 50 (5.6 percent) correct responses to the LED display. Figure 6-I also shows that the preponderance of errors made by subjects reading the vertical tape display are of an absolute magnitude of one pound while the errors made in reading the LED display are distributed from one to about five with the highest percentage being at five. The distributions of errors by absolute magnitude for the eight time condition/illumination level/viewing angle combinations are shown in Appendices C-I through J-I.

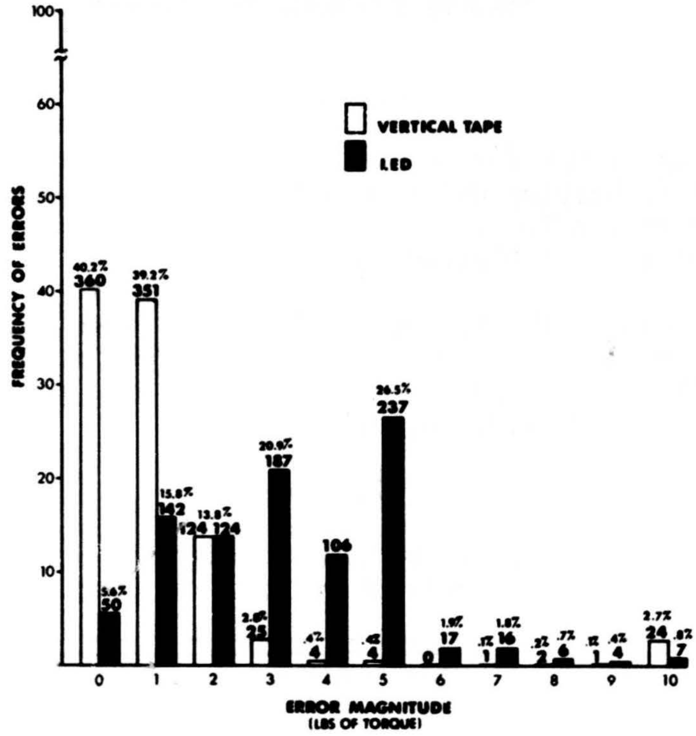


Figure 6-I

Distribution of Absolute Errors by Magnitude
and Frequency of Occurrence for the LED and Vertical Tape Instruments

DISCUSSION

The purpose of this study was to compare the light emitting diode concept of vertical instruments with the current vertical tape instrument. The primary question asked by this study was: "Can the LED instrument be read at least as accurately, in the same amount of time, as the vertical tape now in use?" In order to answer this question, a prototype LED vertical display was selected which most resembled the current vertical tape display in face design characteristics, and the accuracy with which these two instruments could be read under a variety of experimental conditions was explored. The instruments were tested under three levels of illumination: sunlight; total darkness; and an intermediate level of illumination which consisted of the available room lighting. The first finding of note was that testing in the sunlight had to be discontinued due to the fact that the LED instrument cannot be read in sunlight. The contrast level is so low at that level of illumination that the modal response from subjects viewing the LED display was that the instrument was broken or that the experimenter was presenting a zero reading. The vertical tape instrument can be read as well in sunlight as in any other illumination condition. The results show that there was no significant difference in errors for either instrument between the intermediate lighting and total darkness. Contrast level, once you get out of bright sunlight, did not affect the readability of either instrument, and the LED instrument had an error rate approximately three times as high as the vertical tape under both levels of illumination. Subjects were asked to read the two instruments from two viewing angles to see if there were distortions, or parallax problems in either instrument which would increase errors if the instrument had to be read at extreme angles. The results show that viewing angle did not contribute in any significant way to the error rate between the instruments.

Since subjects were forced to read the instruments at a speed which was known to produce about 50 percent errors on the vertical tape instrument in the forced time trials, a second condition was introduced in which the subject controlled the presentation time. Results show that subjects did take a little longer (about 4/10 second) to read the instruments in total darkness under these conditions, but that under intermediate light, they still limited themselves to about 1.3 seconds. This may be a function of the fact that the subject-controlled trials followed the forced trials, and subjects habituated to the 1.3 second viewing time, but that is a question for future study. The type of reading time, whether forced or subject-controlled, did not affect the error rate for either instrument.

The results indicate that regardless of viewing angle, level of illumination, or time allowed for reading, the light emitting diode display produces more reading errors, of a greater magnitude, than the current vertical tape.

The reasons for the higher number and magnitude of errors produced by the LED display are not readily apparent.

Observations of the instrument, along with subjects' comments, suggest one possibility. There is what several subjects termed a "spill-over" effect apparent on the LED display caused by the diffusing of the red light around the lighted diodes. This does not cause any real problem up the "stack" of diodes, except at the top where the subject has to read the value on the instrument. This "spill-over" resembles a "fuzzy" halo at the top making it difficult, if not impossible, to see exactly where the last diode stops. Another observation was that light from the top few lighted diodes tends to be picked up and reflected by adjacent unlighted diodes, and subjects have difficulty discriminating these from the lighted diodes. These two conditions taken together would tend to produce over-estimations by subjects since the "light stack" always appears to be a diode or two higher than it really is. If this were the case in the present study, the magnitude of over-estimation of the LED instrument would then be a function of the graduation interval on the instrument scale. Since the average graduation interval on the LED instrument was five, the "spill-over" would tend to produce errors of from one-half to one graduation interval or from two and one-half to five points. This hypothesis receives support from the data of the present study. Figure 5-I, Columns A, B and C show that the LED instrument was over-read by about three to three and one-half points under all conditions. Figure 6-I also shows that the majority of the errors produced by the LED instrument were from three to five, and Figure 5-I indicates that these were over-estimations, not under-estimations.

SUMMARY

A comparison of a prototype light emitting diode vertical display and the currently employed vertical tape display for reading accuracy and speed produced the following results:

1. The LED display was over-read, or over-estimated by a mean of three "points" regardless of viewing angle (0° or 45°) or illumination level (room light or total darkness).

2. The Vertical Tape display was under-read or under-estimated by a mean of .5 "points" regardless of viewing angle or lighting.

3. The LED display could not be read in sunlight because of extremely low contrast level.

4. Subjects made many more errors, as well as larger errors, when reading the LED display compared to the Vertical Tape display.

5. A hypothesis about possible sources of error in reading the LED display received some confirmation from the data of this study.

APPENDIX A-I

Analysis of Variance
2 x 2 x 2 x 8 (Illumination Level x Instrument x
View Angle x Subjects) For Forced Time Condition

Source of Variation	df	Sum of Squares	Mean Squares	F
Total	63			
Between Subjects	15	14.09	.94	
A (Illumination Level)	1	.37	.37	
S/A (Error)	14	13.72	.98	
Within Subjects	48	121.50	2.53	
B (Instruments)	1	81.27	81.27	54.54*
AB	1	.14	.14	
SB/A (Error)	14	20.84	1.49	
C (Viewing Angle)	1	.06	.06	
AC	1	1.35	1.35	
SC/A (Error)	14	6.98	.50	
BC	1	.50	.50	
ABC	1	.62	.62	
SBC/A (Error)	14	9.74	.70	

*$p < .01$

APPENDIX B-I

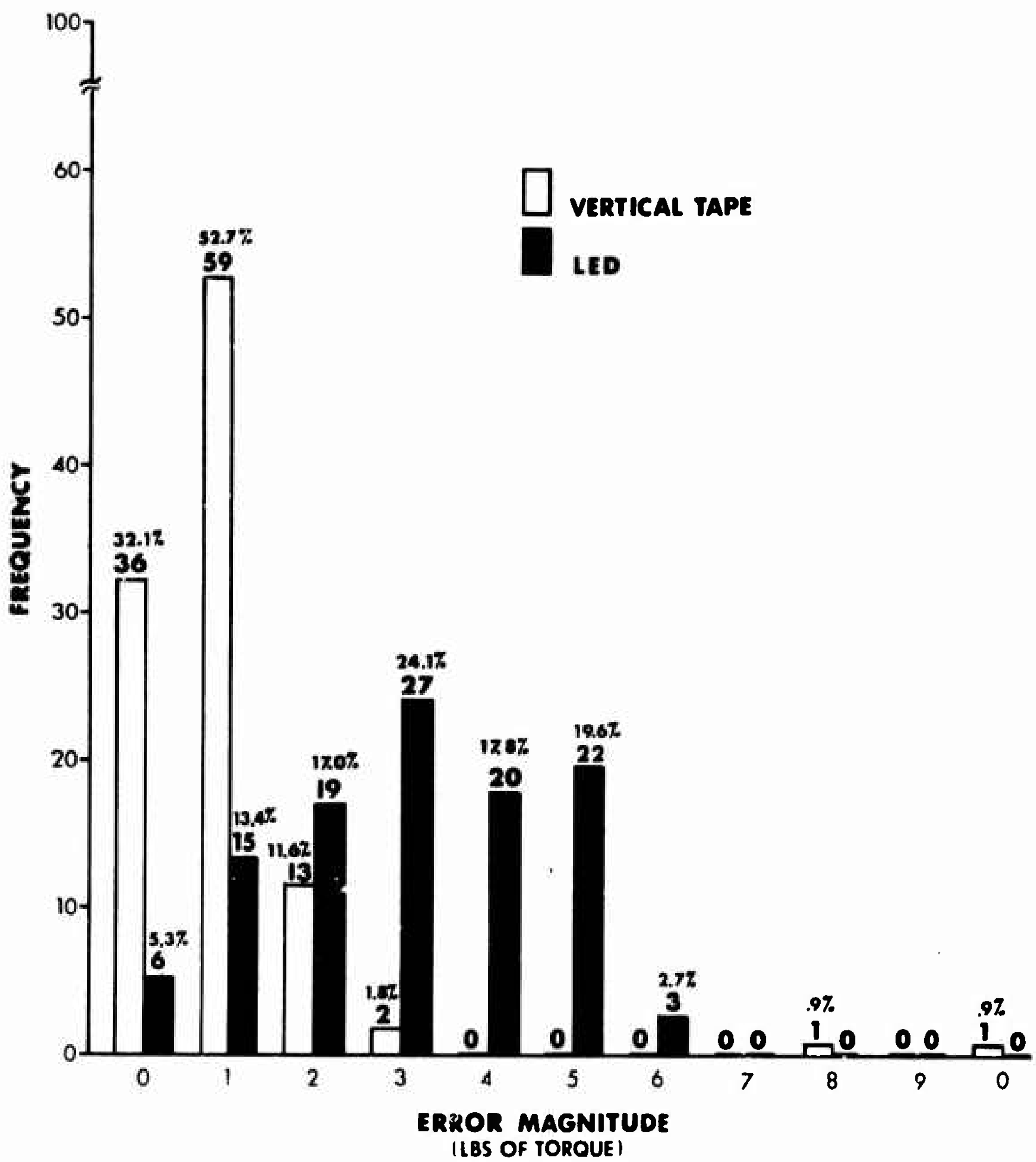
Analysis of Variance
2 x 2 x 2 x 8 (Illumination Level x Instrument x
Viewing Angle x Subjects) For Subject-Controlled Time Condition

Source of Variation	df	Sum of Squares	Mean Square	F
Between Subjects	15	14.31	.95	
A (Illumination Level)	1	.005	.005	
S/A (Error)	14	14.31	1.02	
Within Subjects	48	92.51	1.93	
B	1	72.93	72.93	92.32*
AB	1	.10	.1	
SB/A (Error)	14	11.08	.79	
C (Viewing Angle)	1	.03	.03	
AC	1	.02	.02	
SC/A (Error)	14	6.05	.43	
BC	1	.03	.03	
ABC	1	.01	.01	
SBC/A (Error)	14	2.26	.16	

*$p < .01$

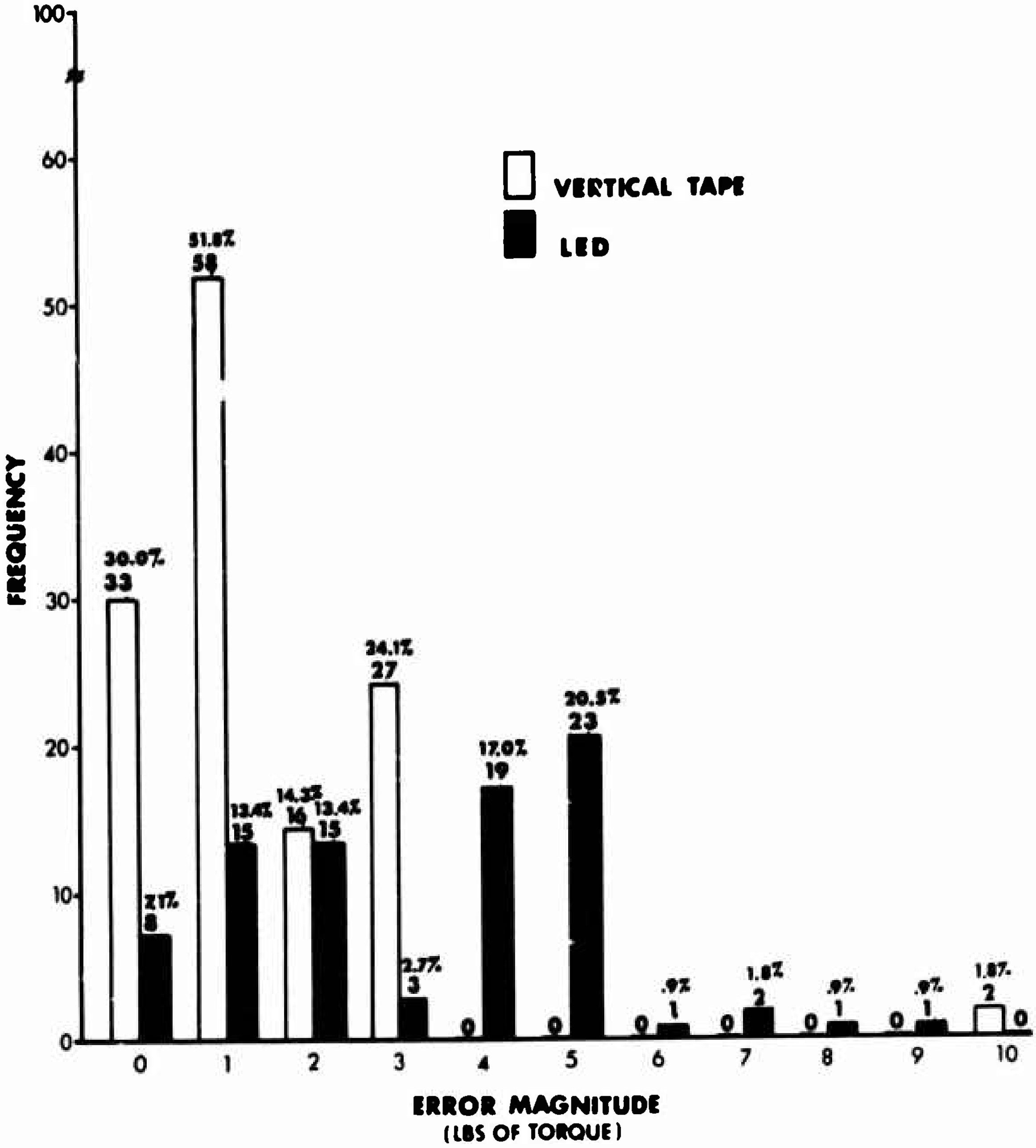
APPENDIX C-I

Distribution of Absolute Errors (Lbs of Torque)
for Subject Time, Intermediate Lighting, and 0° Viewing Angle



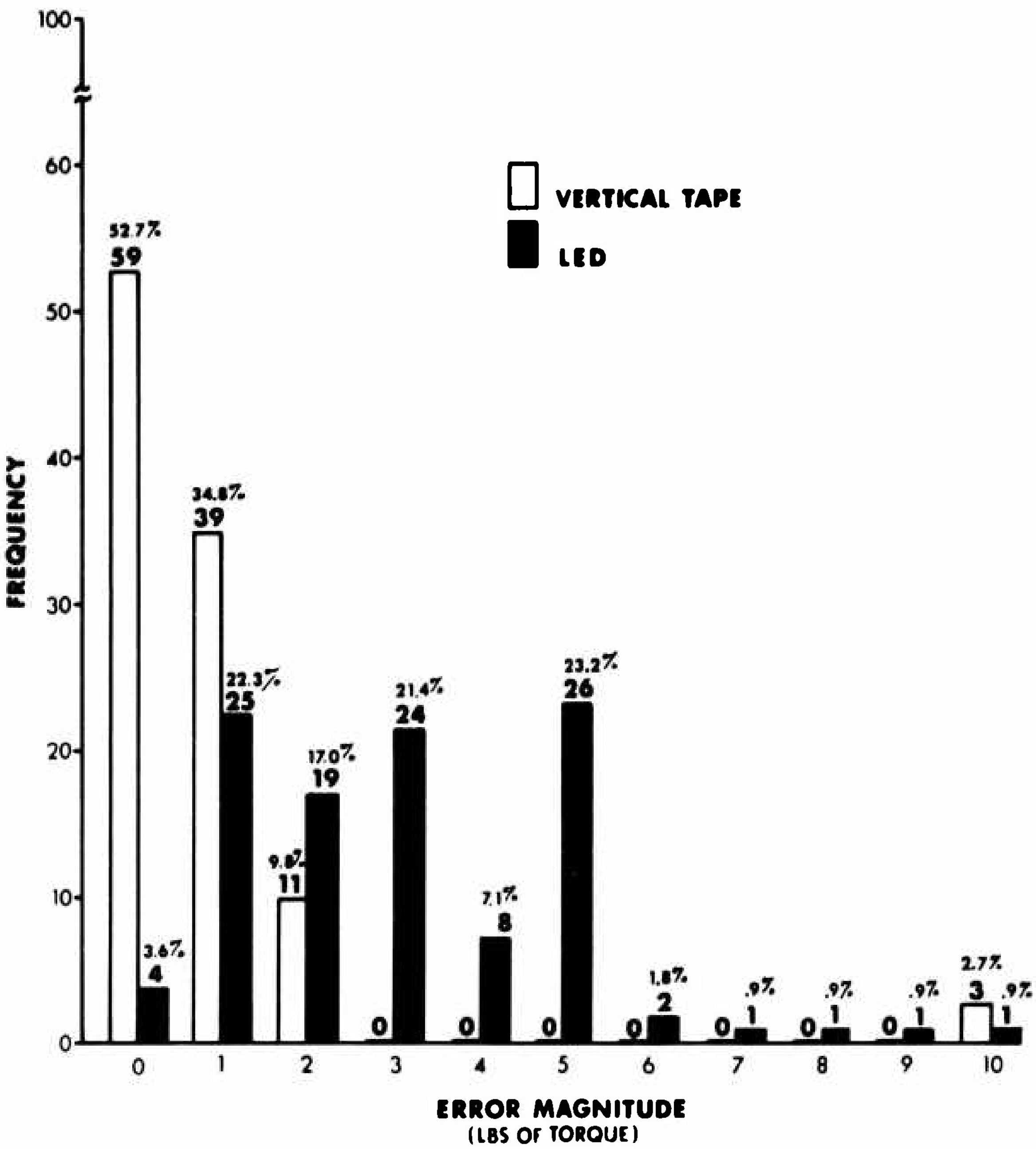
APPENDIX D-I

Distribution of Absolute Errors (Lbs of Torque)
for Subject Time, Intermediate Lighting, and 45° Viewing Angle



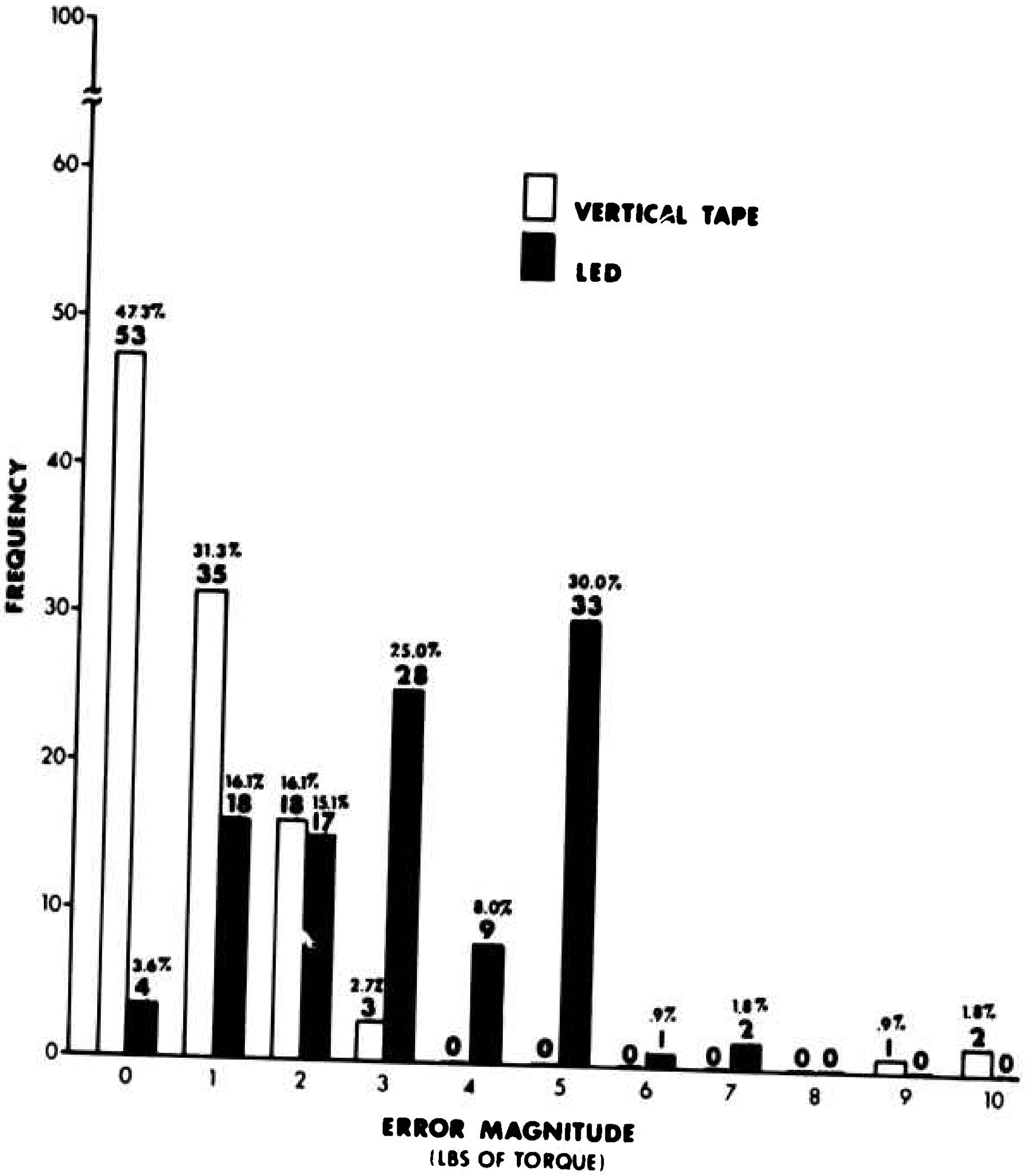
APPENDIX E-I

Distribution of Absolute Errors (Lbs of Torque)
for Subject Time, Total Darkness, and 0° Viewing Angle



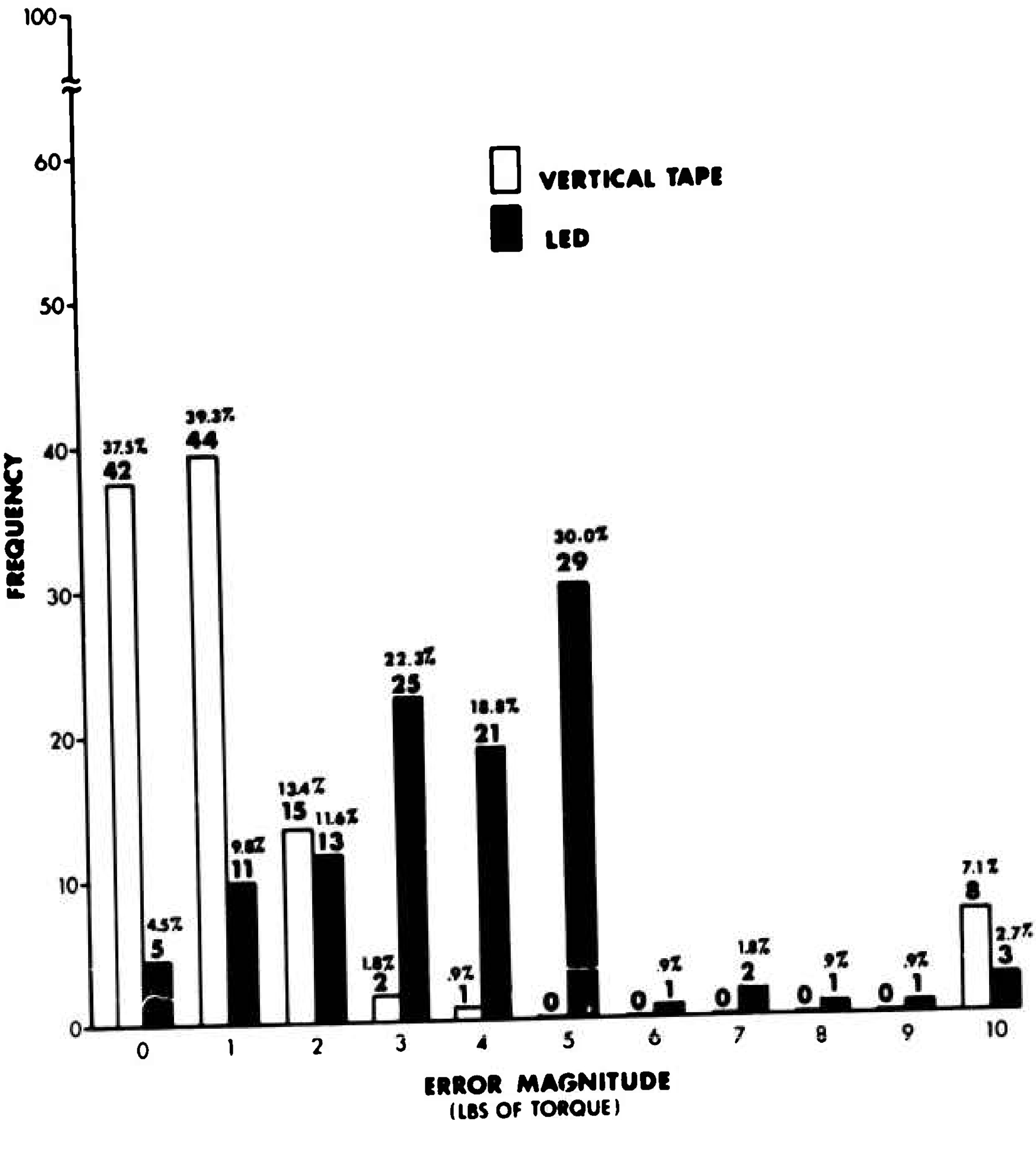
APPENDIX F-I

Distribution of Absolute Errors (Lbs of Torque)
for Subject Time, Total Darkness, and 45° Viewing Angle



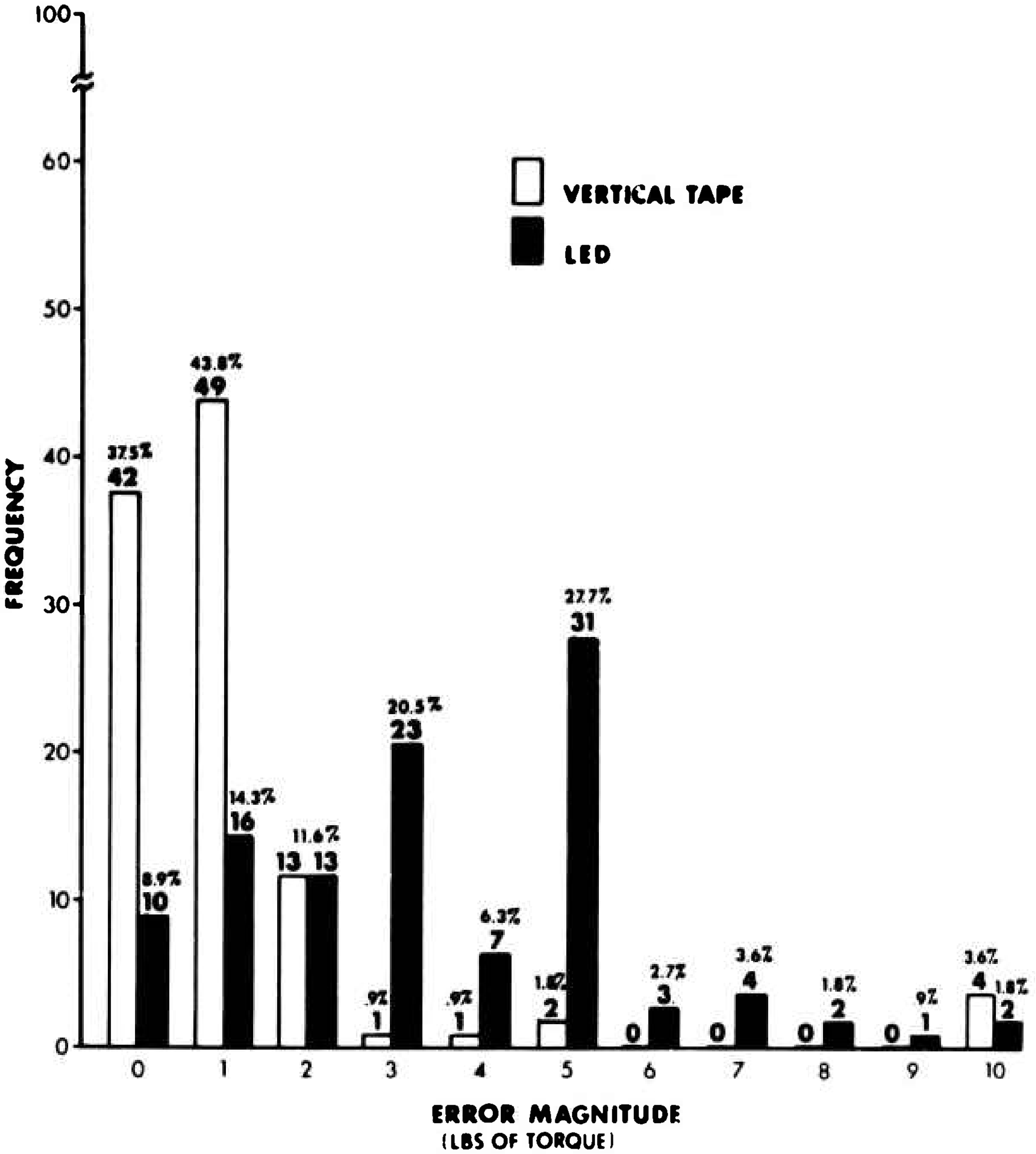
APPENDIX G-I

Distribution of Absolute Errors (Lbs of Torque)
for Forced Time, Intermediate Lighting, and 0° Viewing Angle



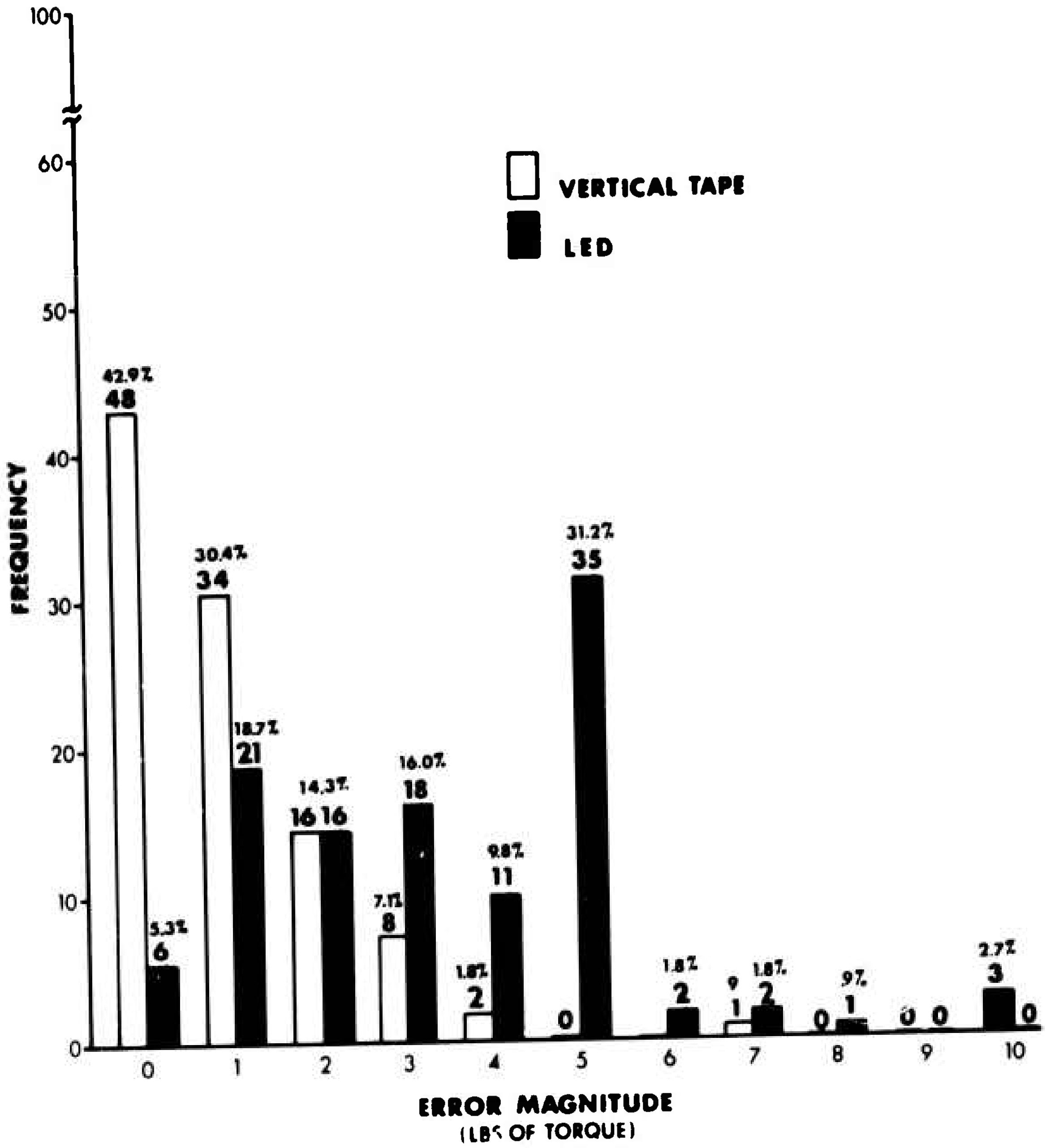
APPENDIX H-I

Distribution of Absolute Errors (Lbs of Torque)
for Forced Time, Intermediate Lighting, and 45° Viewing Angle



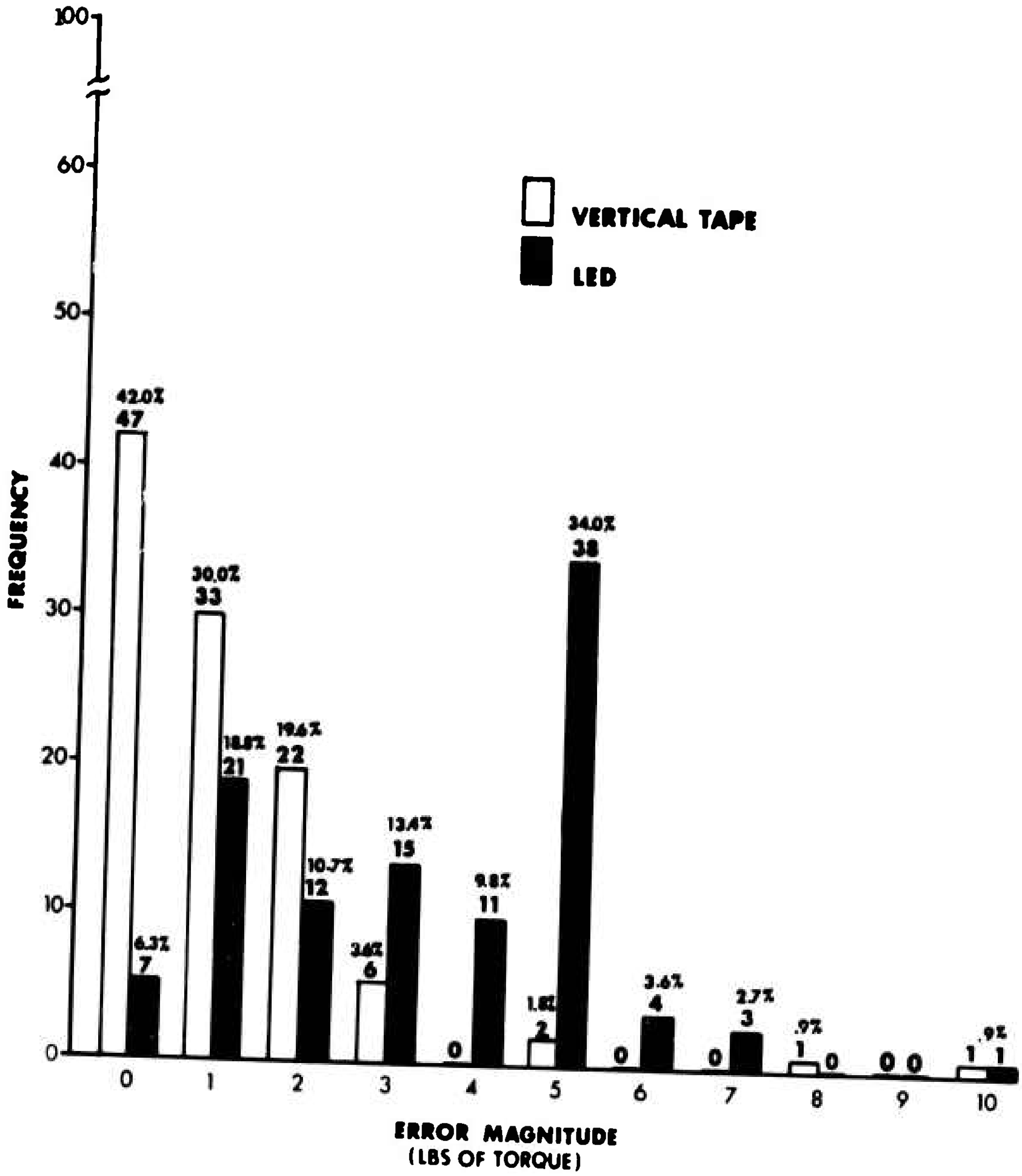
APPENDIX I-I

Distribution of Absolute Errors (Lbs of Torque) for Forced Time, Total Darkness, and 0° Viewing Angle



APPENDIX J-I

Distribution of Absolute Errors (Lbs of Torque) for Forced Time, Total Darkness, and 45° Viewing Angle



PART II

Evaluation of Human Factors Design Criteria for Four Prototype Light Emitting Diode Displays and the Current Vertical Tape Display

PURPOSE

The purpose of this evaluation was to measure certain "facial characteristics" of four prototype LED displays and a current vertical tape display. These measurements were compared to applicable military standards and relevant research studies to determine whether the characteristics of face design met size and proportion standards for optimum information transmission.

METHOD

Apparatus and Equipment

The equipment for this examination consisted of four experimental models of LED displays, and one sample of the current vertical tape display. (See Figure 1-II) All of the instruments employed were similar to the engine torque meter used on the OV-1.

Other equipment employed consisted of a vernier caliper capable of direct readings to .001 inch and interpolation to .0005 inch, and a powerfull back-lighted magnifying glass.

Procedure

Each of the five instruments was examined to determine the following characteristics:

1. Scale Characteristics

    (a) Length of graduation marks

    (b) Width of graduation marks

    (c) Minimum separation between graduation marks

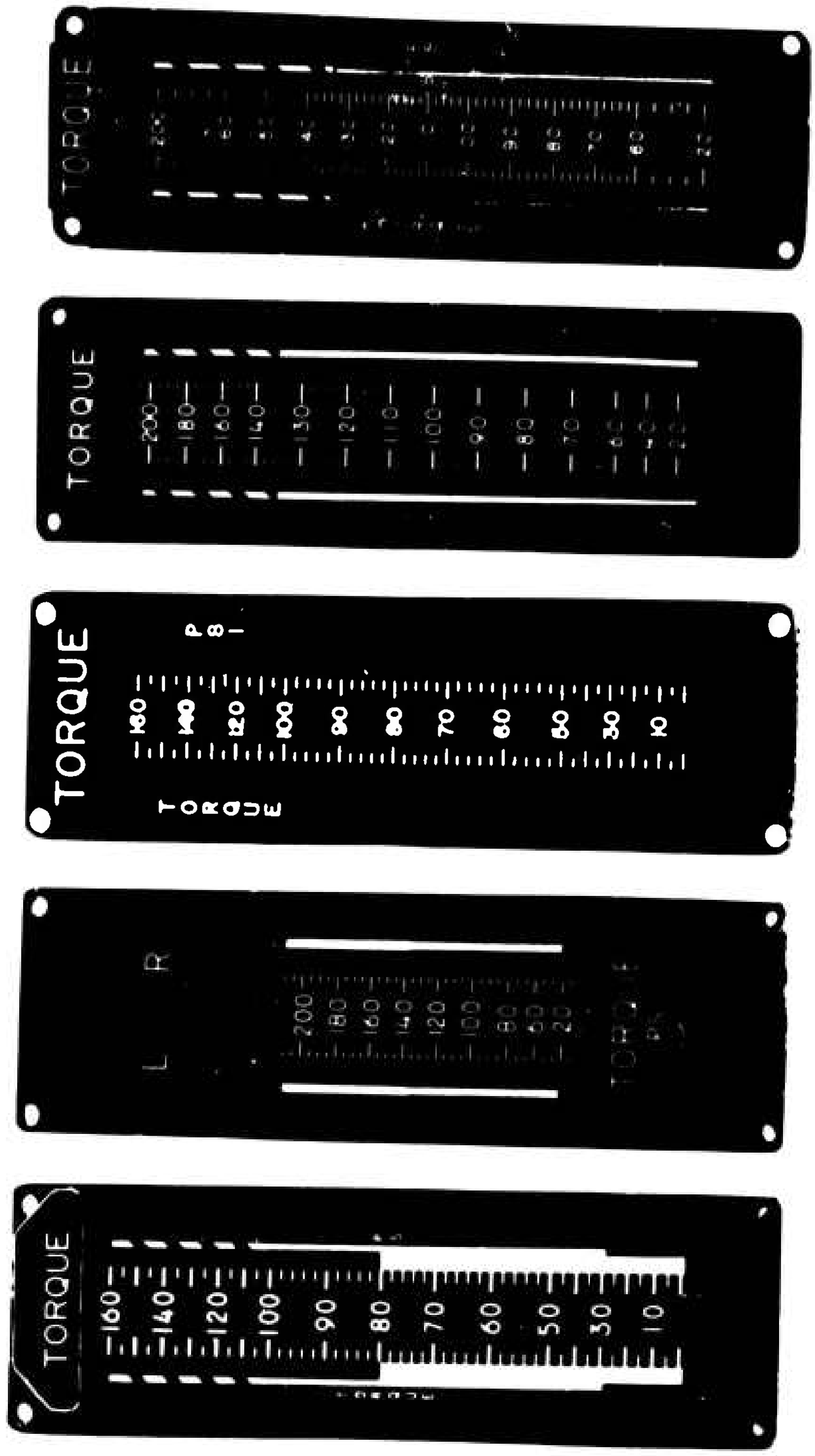


Figure 1-II
Displays: A (Vertical Tape), B, C, D, and E (Light Emitting Diode).

TABLE 1-II

INSTRUMENT DESIGN CHARACTERISTICS

SCALE CHARACTERISTICS	INSTRUMENTS: A			B	C			D			E				MILITARY STANDARD AND RECOMMENDED DISTANCE[1]
ACTUAL INTERMARK DISTANCES BY NUMBER RANGES ON THE SCALE OF EACH INSTRUMENT	0-50	50-100	100-160	20-200	0-50	50-100	100-160	20-60	60-140	140-200	20-60	60-140	140-160	160-200	
	.090	.080	.090	.065[2]	.085	.076	.085	.055[2]	.065[2]	.063[2]	.120	.055[2]	.397	.120	.070
GRADUATION MARKS (GM)															
LENGTH OF SMALLEST GM	.082[2]			.062[2]	.085[2]			.072[2]			.090[2]				.100
WIDTH OF SMALLEST GM	.029			.019[2]	.035			.015[2]			.020[2]				.025
WIDTH OF LONGEST GM	.036			.019[2]	.035			.025[2]			.020[2]				.035
LENGTH OF LONGEST GM	.137[2]			.129[2]	.135[2]			.150[2]			.155[2]				.220
NUMERAL CHARACTERISTICS															
HEIGHT	.158			.130[2]	.128[2]			.125[2]			.110[2]				.150 - .300
WIDTH	.100 (.096)[3]			.085 (.078)	.105 (.077)[3]			.085 (.075)[3]			.078 (.066)[3]				3/5 NUMERAL HEIGHT
STROKE	.030 (> .020 - < .026)[3]			.017 (> .016 - < .020)	.035 (> .016 - < .021)[3]			.020 (> .015 - < .020)[3]			.019 (> .014 - < .018)[3]				1/8 - 1/6 NUMERAL HEIGHT

1. MILITARY STANDARD BASED ON MIL-M-18012B. RECOMMENDED SPECIFICATIONS INCLUDE BAKER AND GRETHER (1954), McCORMICK (1964), WOODSON AND CONOVER (1964).
2. DENOTES VALUE IS BELOW MILITARY AND RECOMMENDED STANDARDS AS SPECIFIED IN THE LAST COLUMN.
3. FIGURES IN PARENTHESIS BESIDE THE WIDTH AND STROKE VALUES INDICATE WHAT THESE VALUES SHOULD BE, BASED ON MILITARY AND RECOMMENDED STANDARDS.

TABLE 2-II

SCALE INTERPOLATION FRACTIONS

	INSTRUMENTS														
	A			B			C			D			E		
SCALE RANGE	0-50	50-100	100-160	20-60	60-80	80-200	0-50	50-100	100-160	20-60	60-140	140-200	20-60	60-140	240-200
INTERPOLATION NECESSARY TO READ TO NEAREST ONE POUND OF TORQUE	1/5	1/2	1/5	1/13.33	1/6.66	1/5	1/5	1/2	1/5	1/5	1/2	1/5	1/10	1/2	1/10

FRACTIONS LISTED ARE THE FRACTIONS OF GRADUATION INTERVALS IN EACH RANGE WHICH THE READER MUST INTERPOLATE TO READ ONE POUND OF TORQUE (1 PSI).

2. Scale Units---the numerical progression values represented by the major and minor scale markers.

3. Interpolation---the interpolation fraction or fractions required to convert the distance between graduation marks to a value of one pound of torque.

4. Numerical Characteristics

(a) Height of numerals

(b) Width of numerals

(c) Stroke width of numerals

RESULTS AND DISCUSSION

Table 1-II presents the results of measurements taken on scale, graduation mark, and numeral characteristics for the five instruments studied. The columns headed A, B, C, D, and E (the five instruments) contain the measurements in inches ascertained for the above mentioned characteristics which are enumerated in the row headings. The last column contains military and recommended specifications for the various measurements performed.

Table 2-II shows the required interpolation fractions for regarding the various scales ranges of the five instruments to the nearest one pound of torque. As in Table 1-II, the column of A, B, C, D, and E represent the five instruments while the two row headings represent the various ranges and necessary interpolation fractions.

INSTRUMENT A

Table 1-II indicates the intermark distances and graduation marks with the exception of the length of the smallest and longest graduation marks meet or exceed the military and recommended specifications.

With regard to numerals the numeral width and stroke are slightly below military and recommended standards. Based on the numeral height of .158 inches the numeral width should be about .096 inches and the numeral stroke larger than .020 inches but not exceed .026 inches to yield proportional numerals. To make the numerals proportional based on the size of the stroke used (.030), the numeral height should be larger than .180 inches but not exceed .240 inches.

As can be seen in Table 2-II, interpolations of 1/5 or 1/2 are required to read to the nearest one pound of torque. These are acceptable interpolation requirements.[11]

INSTRUMENT B

The actual intermark distance between midpoints of the graduation marks as well as the dimensions of all graduation marks are below military and recommended specifications (see Table 1-II).

The numeral height and width did not meet either military or recommended specifications. To make the numerals proportional based on the numeral height of .130 inches, the numeral width should be about .078 inches. To make the numerals proportional based on the size of the stroke used (.017), the numeral height should be larger than .102 inches but not exceed .136 inches.

There are, on Instrument B, minor graduation marks below the number 20 and above the number 200 (see Figure 1-II). The value of these graduation marks cannot be determined without the reader making certain assumptions about these unnumbered intervals. Preferably, numerical scales start with a numbered major graduation mark and end with a numbered graduation mark to enhance readability.

The numerical scale from 20-80 has numerical progressions in fractions (e.g., 13.33, 6.66), thus degrading interpolation accuracy, a condition that should be avoided.

> There seems to be rather universal evidence that the garden variety of progression of 0, 1, 2, 3, 4, etc., is the easiest to use. This is probably because of its familiarity. Progressions by 5s or by 2s are next best, and between these there is not much advantage of one over the other. The use of 4s and 8s generally contributes to increased errors; these would be scales such as 0, 4, 8, 12, and 0, 8, 16, 24. Other progressions, such as by 3s, 6s, and 7s, and by fractional values such as 2.5, usually give such gross errors that they should be avoided except under circumstances that distinctly require them.[11]

INSTRUMENT C

Instrument C meets military or recommended standards for intermark distances, but does not meet them with the length of the smallest and longest graduation marks.

The numeral height, width, and stroke did not meet either military or recommended specifications. To make the numerals proportional based on the numeral height of .128 inches, the numeral width should be about .077 inches and the numeral stroke larger than .016 inches but not exceed .021 inches. To make the numerals proportional based on the size of the stroke used (.035), the numeral height should be larger than .210 inches, but not exceed .280 inches.

Because of the stroke width and the numeral height used on Instrument C, the numerals appear heavy and short, or "squatty" (see Figure 1-II).

To interpolate to the nearest pound of torque on Instrument C requires the reader to fractionate the intermark distance by 1/5 or 1/2. These are acceptable interpolation values for accuracy to the nearest one pound of torque.[11]

INSTRUMENT D

Table 1-II indicates that Instrument D did not meet either military or recommended specifications on intermark distances. They all are slightly below specifications. With respect to scale graduations, the length and width of the smallest and longest graduation mark do not meet the military or recommended specifications.

The numeral height and width did not meet either military or recommended specifications. To make the numerals proportional based on the numeral height of .125 inches, the numeral width should be about .075 inches. To make the numerals proportional based on the size of the stroke used (.020), the numeral height should be larger than .120 inches but not exceed .160 inches.

There are minor graduation marks below the number 20 and above the number 200 on Instrument D. The value of these graduation marks cannot be determined without the reader making certain assumptions about these unnumbered intervals. Preferably, numerical scales start with a numbered major graduation mark, and end with a numbered graduation mark which enhances readability. The numerical scale between 140 and 200 could possibly have (unnumbered) major markings at 150, 170 and 190.

As can be seen in Table 2-II interpolations of 1/5 or 1/2 of the intermark distance is required to read to the nearest one pound of torque. These are acceptable interpolation values for this accuracy.[11]

INSTRUMENT E

Instrument E has only one number range, of its four, below military and recommended specifications. However, this range is in the middle of the operating range for the instrument and, therefore, it would be highly undesirable to permit this condition to exist.

With respect to graduation marks, the length and width of the smallest and longest graduation mark do not meet military or recommended specifications.

In addition, the numeral height, width, and stroke do not meet military or recommended specifications. To make the numerals proportional based on the numeral height of .110 inches, the numeral width should be approximately .066 inches and the numeral stroke larger than .014 inches, but not exceed .018 inches. To make the numerals proportional based on the size of the stroke used (.019), the numeral height should be larger than .114 inches, but should not exceed .152 inches.

The numerical scale between 140 and 160 could possibly be read with more precision and accuracy if it contained minor markings at 145 and 155.

There is one LED per graduation mark, with none between marks. Therefore, an engine torque of 145 psi. could not be determined from Instrument E, because diodes are only present at 140, 150 and 160 psi.

SUMMARY

Four prototype LED displays and one currently employed Vertical Tape display were examined to determine adherence to recognized human factors design criteria. These design factors included scale and numeral characteristics and scale interpolation. The results show that:

1. The Vertical Tape display met military and recommended specifications on all but two of the characteristics measured.

2. All of the LED displays evaluated showed a large number of discrepancies on the characteristics studied.

3. One of the LED displays (Display B) had numbered graduation marks at 20 and 60 with two minor graduation marks between. This results in interval values of 13.33. The next numbered mark was 80 with two minor graduation marks between. This means that the three intervals within that range had a value of 6.66. The scale then changed to numbering by 20 with five intervals between resulting in a scale which is virtually impossible to read with accuracy on the low end of the scale. The other displays also change scale values from low to high ends of the scale. This practice has been found to lead to more errors in reading, and is probably not necessary for these displays.

PART III

A Photometric Evaluation of the Light Transmitting Characteristics of the Light-Emitting Diode and Vertical Tape Displays

PURPOSE

Photometric measurements were performed on each instrument to determine the maximum luminance levels under varying conditions, the uniformity of luminance throughout each array, and luminance contrast under sky brightness.

METHOD

Apparatus

1. A Spectra Pritchard Photometer equipped with a two-minute aperture mirror and a four-inch focal length PD-62 Spectar objective lens. The aperture (measuring surface) subtended .0041 inches at four inches.

2. A nine footlambert standard light source with a NBS number 3215-1-5 IPL limit red filter.

3. Four light-emitting diode instruments with power supplies (see Figure 1-II, Part II, Page 29).

4. A thermostatically-controlled oven having a temperature variation of ± two degrees.

Procedure

1. Photometric measurements were performed under the following conditions:

a. In the Laboratory with ordinary fluorescent lighting and at room temperature.

b. Outdoors under sunny, clear sky (ambient temperature 91 degrees F).

c. Inside an oven with a stabilized temperature of 60 $\pm$ two degrees centigrade. Light transmission through the oven window was 91.34 percent, and this factor was considered in the data pertaining to these measurements.

2. The photometer was aligned and focused both perpendicular and at 45 degrees to the surface of each diode being measured in room lighting. In some cases, this eccentric viewing angle had to be reduced due to mechanical blockage of the diode. The measurements outdoors and in the oven were only recorded perpendicular to the surface.

3. Sky brightness levels were photometrically measured at 45 degrees elevation north, south, east and west, as well as directly overhead. These are shown in Table 1-III.

4. Not all diodes of a particular unit were measured. Only a representative sample of the brightest and dimmest were evaluated to determine ranges of variation, within a single instrument. An attempt was made to select an equal number to be measured from each display bank.

5. To reduce errors, a scanning technique was employed to determine the luminance for each diode. The highest measurement found over the entire diode surface was recorded.

6. Measurements outdoors were made with the instrument face toward the sun to maximize the reduction in contrast. Direct reflections from the sun were avoided throughout this procedure. An attempt was made to reproduce viewing problems that might possibly be encountered in-flight.

7. Display A was not photometrically evaluated.

8. Contrast was determined during the outdoors evaluation only. Contrast is defined by the equation:

$$C = \frac{B^2 - B^1}{B^1}$$

Where C is the contrast, B^1 is the background luminance, and B^2 is the average lamp brightness. A positive contrast indicates that the lamp is brighter than the darker surround, while a negative contrast would be the reverse.

Table 1-III

Clear Sky Luminosity Measurements

Time: 2:00 P.M.

Position of Photometer	Footlamberts
Perpendicular to Earth's Surface	4500
45° East	1700
45° West	5700
45° South	2250
45° North	3000

RESULTS AND DISCUSSIONS

INSTRUMENT B

Right Bank - Viewing Diodes Perpendicular to the Surface. (See Appendix A-III)

	Range	Average	Contrast
Indoor	54 - 100 fL	76 fL	
*Outdoor	48 - 64 fL	55 fL	62% (Positive)
Oven (60° C)	15 - 45 fL	34 fL	

*NOTE: Black instrument background = 34 fL

Left Bank - Viewing Diodes Perpendicular to the Surface. (See Appendix B-III)

	Range	Average	Contrast
Indoor	80 - 300 fL	176 fL	
*Outdoor	160 - 320 fL	225 fL	56% (Positive)
Oven (60° C)	49 - 210 fL	111 fL	

*NOTE: Black instrument background = 34 fL

Right Bank - Viewing Diodes 35° from the Normal to the Surface. (See Appendix C-III)

	Range	Average
Indoor	3.2 - 9.4 fL	5.1 fL

Left Bank - Viewing Diodes 35° from the Normal to the Surface. (See Appendix D-III)

	Range	Average
Indoor	1.8 - 9.6 fL	4.3 fL

The diodes were hidden from view at an angle greater than 35° from normal to the surface in this instrument. Intensity appeared to drop off rapidly as the viewing angle was changed horizontally and vertically from the normal to the surface. In addition, some diodes in the right bank appeared as horizontal rather than round lines. Diode Number 27 (from the top) in the right bank was inoperative. A wide range of brightness differences were found on the left bank of the instrument.

Contrast measurements for the left bank of diodes outdoors appears acceptable. However, the instrument could not be accurately read subjectively under these high luminance conditions. It is possible that the measurements (160-320 fL) included some reflections from the instrument cover glass surface.

INSTRUMENT C

Right Bank - Viewing Diodes Perpendicular to the Surface. (See Appendix E-III)

	Range	Average	Contrast
Indoor	36 - 140 fL	86 fL	
*Outdoor	100 - 160 fL	130 fL	35% (Negative)
Oven (60° C)	62 - 92 fL	79 fL	

*NOTE: Black instrument background = 200 fL

Left Bank - Viewing Diodes Perpendicular to the Surface. (See Appendix F-III)

	Range	Average	Contrast
Indoor	64 - 120 fL	82 fL	
*Outdoor	140 - 180 fL	160 fL	20% (Negative)
Oven (60° C)	75 - 98 fL	87 fL	

*NOTE: Black instrument background = 200 fL

Right Bank - Viewing Diodes 45° from the Normal to the Surface. (See Appendix G-III).

	Range	Average
Indoor	12 - 52 fL	28 fL

Left Bank - Viewing Diodes 45° from the Normal to the Surface. (See Appendix H-III)

	Range	Average
Indoor	14 - 30 fL	23 fL

There was no change in apparent brightness when these diodes were viewed at different angles from the normal to their surfaces. However, luminosity values measured 45° from the normal were considerably lower than those measured perpendicular to the surface under similar conditions. A negative contrast was measured under a bright clear sky. A wide variation of luminosity differences existed between diodes. All diodes were functioning when photometric measurements were taken; however, a section of diodes in both the left and right banks (diodes 15 through 29, counting from top of the scale) have since failed to operate. These diodes give the appearance of short vertical lines.

INSTRUMENT D

Left Bank - Viewing Diodes Perpendicular to the Surface. (See Appendix I-III)

	Range	Average	Contrast
Indoor	60 - 180 fL	114 fL	
*Outdoor	120 - 200 fL	156 fL	30% (Positive)
Oven (60° C)	28 - 103 fL	64 fL	

*NOTE: Black instrument background = 120 fL.

Left Bank - Viewing Diodes 45° from the Normal to the Surface. (See Appendix J-III)

	Range	Average
Indoor	38 - 78 fL	53 fL

All diodes in the right bank failed to light up. The left bank was composed of 99 rows with four diodes in each row. Sixty diodes were not functioning at all and several rows produced a noticeable flicker. Apparent brightness was not affected by a change in viewing angle. Also, a wide range of luminosity differences was found in this instrument.

INSTRUMENT E

Right Bank - Viewing Diodes Perpendicular to the Surface. (See Appendix K-III)

	Range	Average	Contrast
Indoor	16 - 60 fL	34 fL	
*Outdoor	16 - 200 fL	115 fL	4.2% (Negative)
Oven (60° C)	10 - 68 fL	37 fL	

*NOTE: Black instrument background = 120 fL

Left Bank - Viewing Diodes Perpendicular to the Surface. (See Appendix L-III)

	Range	Average	Contrast
Indoor	22 - 84 fL	40 fL	
*Outdoor	120 - 300 fL	174 fL	45% (Positive)
Oven (60° C)	17 - 83 fL	37 fL	

*NOTE: Black instrument background = 120 fL

Right Bank - Viewing Diodes 45° from the Normal to the Surface. (See Appendix M-III)

	Range	Average
Indoor	18 - 46 fL	34 fL

Left Bank - Viewing Diodes 45° from the Normal to the Surface. (See Appendix N-III)

	Range	Average
Indoor	14 - 50 fL	25 fL

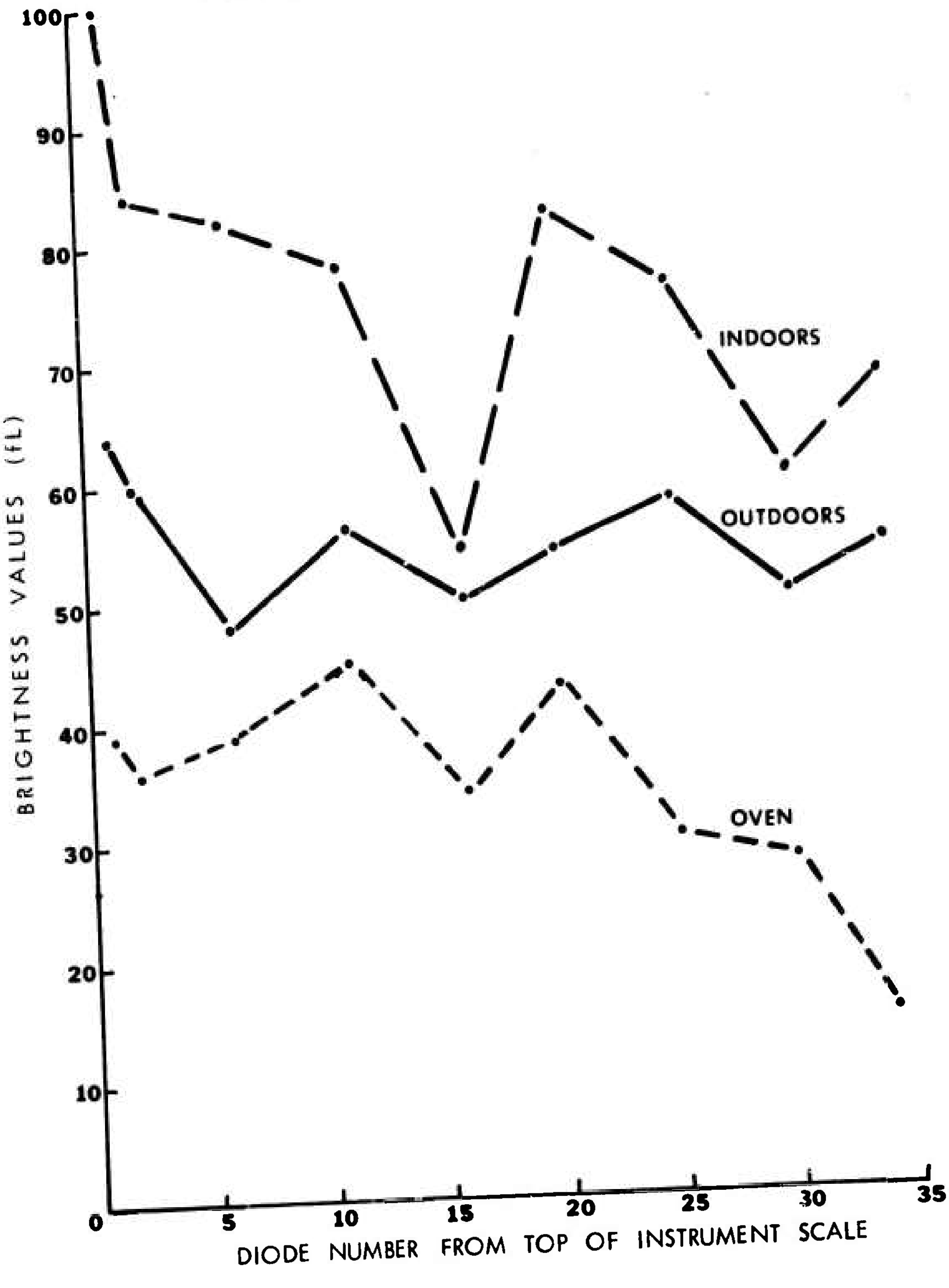
Apparent brightness changes varied little as the viewing angle was shifted from the horizontal and vertical planes of the instrument. However, in all cases and under all conditions of testing, the luminosity difference between the brightest and dimmest diodes was greater than fifty percent, and in some cases, as much as seventy-five percent. Four diodes on the left bank became inoperative when the intensity was turned to maximum.

SUMMARY

A photometric evaluation was determined for four vertical tape aircraft instrument displays incorporating light-emitting diodes. They were measured under room lighting (both perpendicularly and at 45 degrees eccentricity) in an oven, and outdoors under high ambient light. The results indicate rather large luminance differences between diodes even within the same display. Viewing at oblique angles (up to 45 degrees) showed rather large differences between instruments, with even the best display being considerably dimmer at this angle. Luminance measurements while subjecting the diodes to high (60° C) heat showed relatively little degradation in light output. Readability of all instruments in bright sunlight was found to be unacceptable as evidenced by low contrast measurements and subjective evaluation.

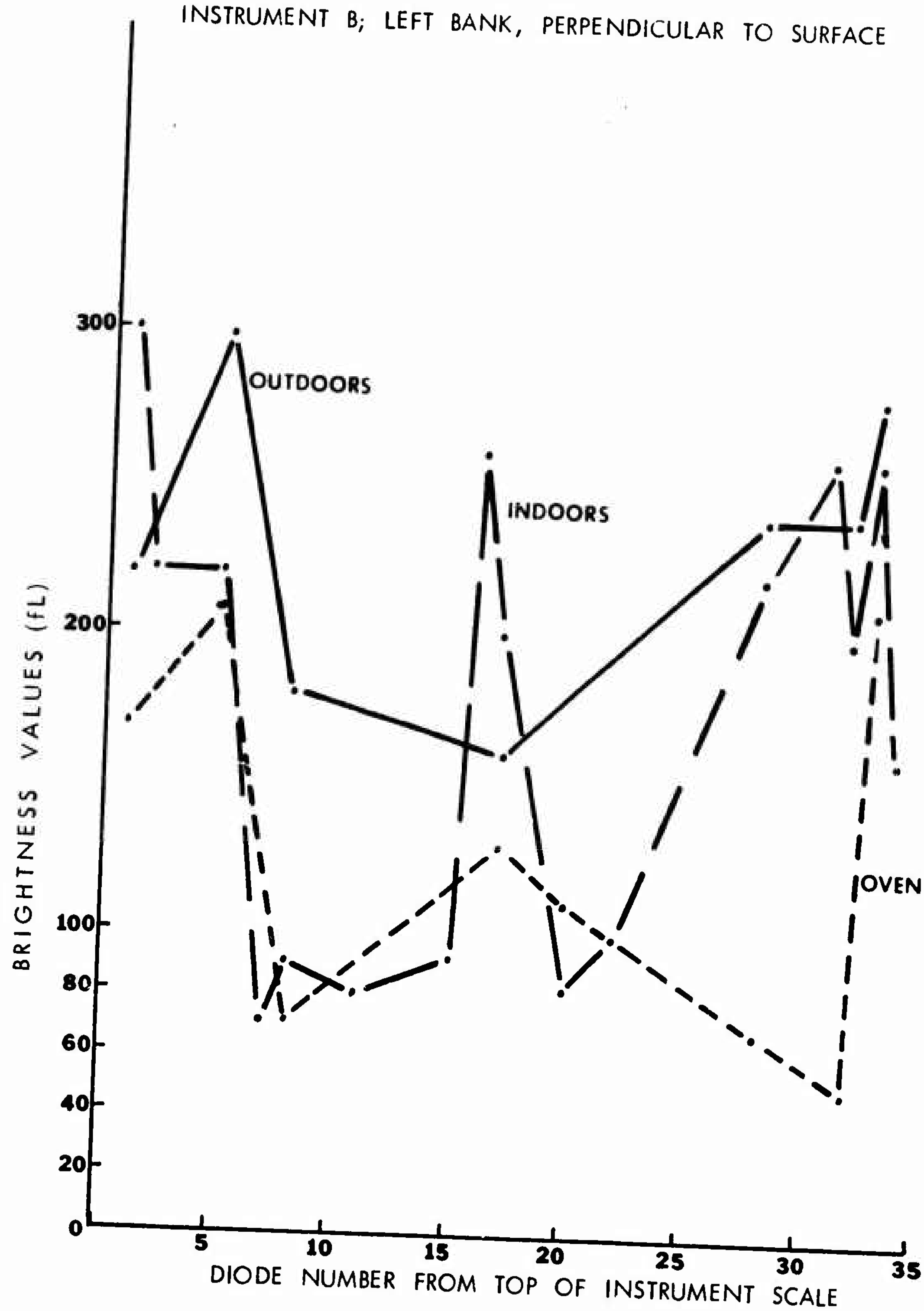
APPENDIX A-III

INSTRUMENT B; RIGHT BANK, PERPENDICULAR TO SURFACE



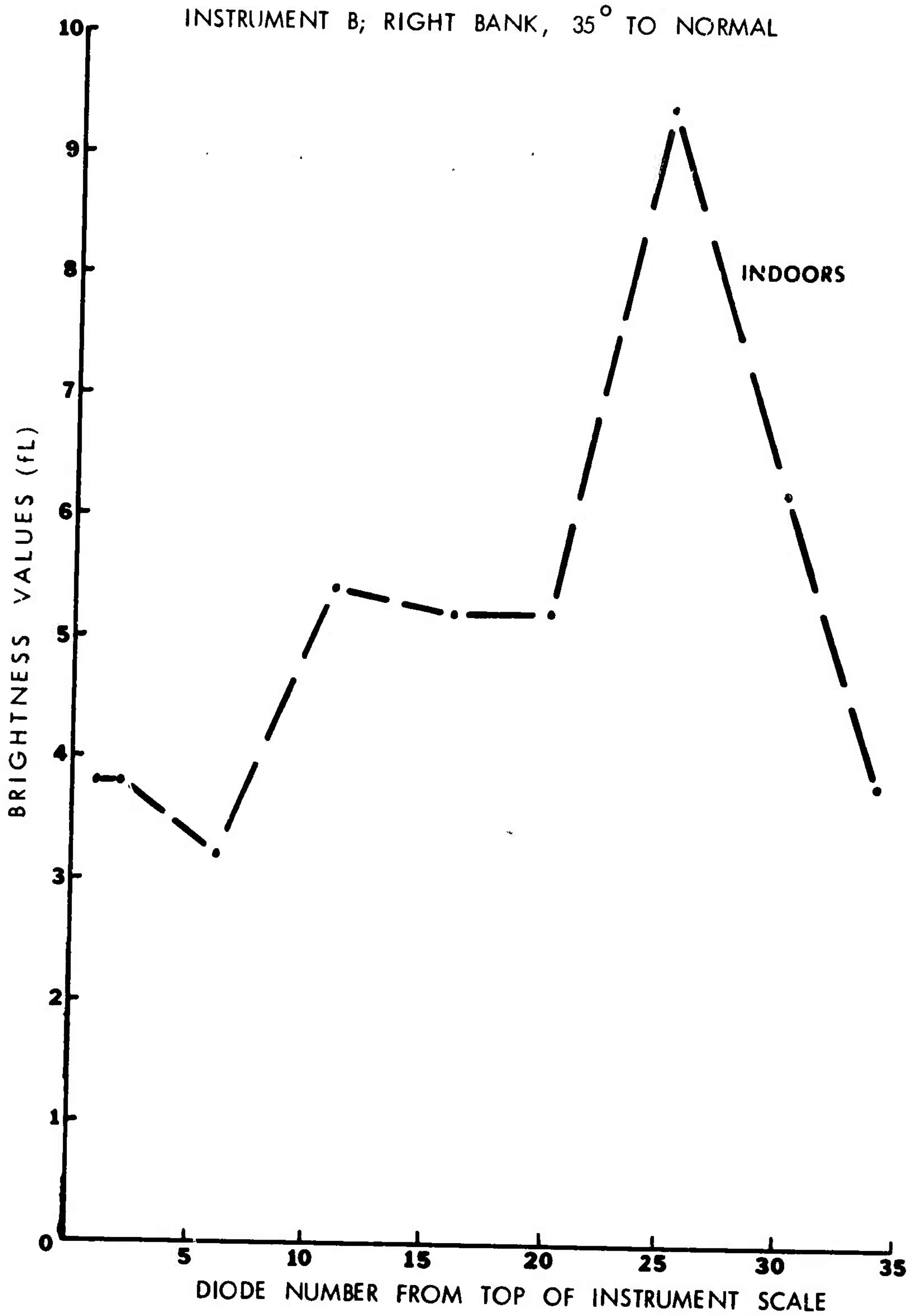
APPENDIX B-III

INSTRUMENT B; LEFT BANK, PERPENDICULAR TO SURFACE

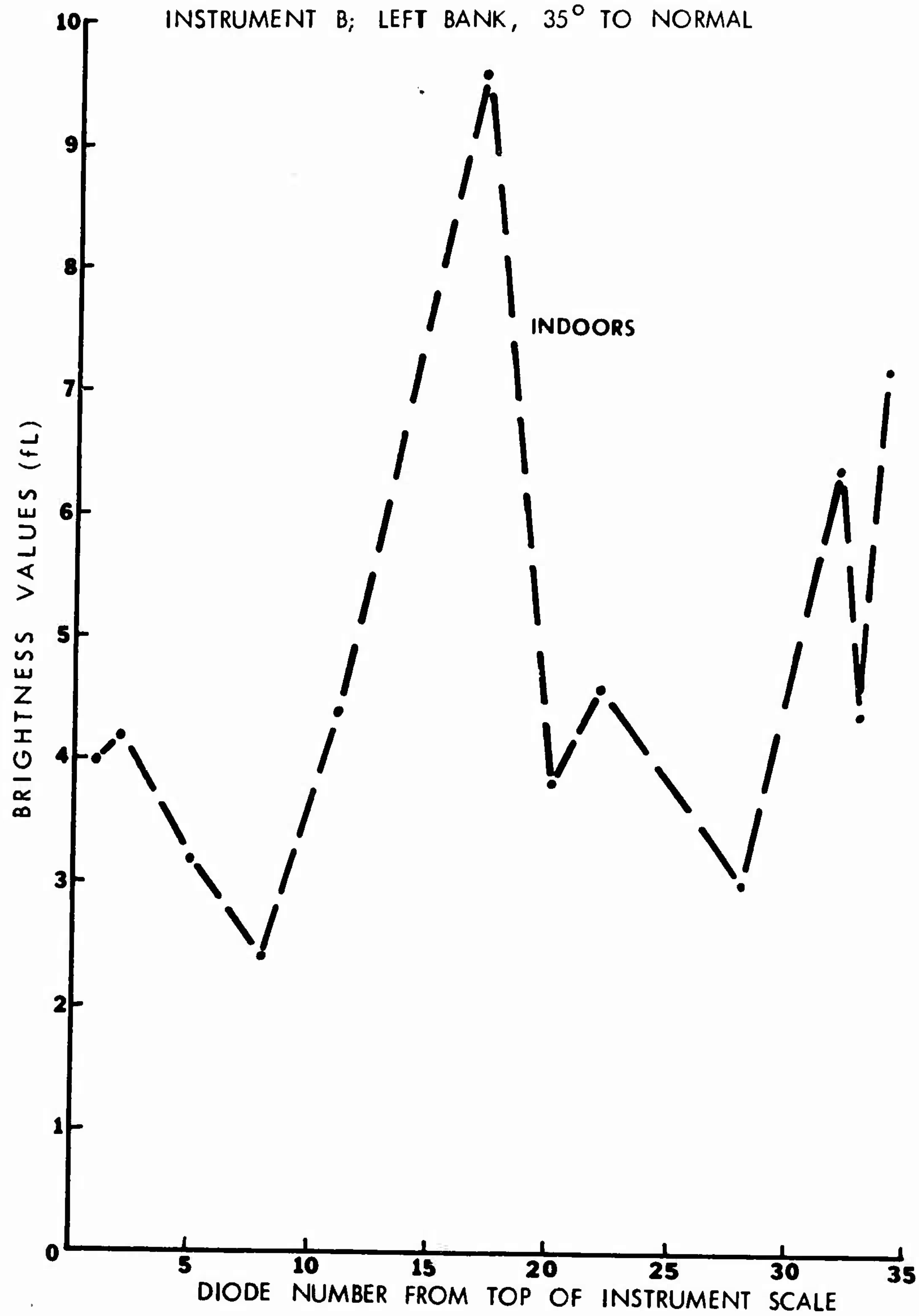


APPENDIX C-III

INSTRUMENT B; RIGHT BANK, 35° TO NORMAL

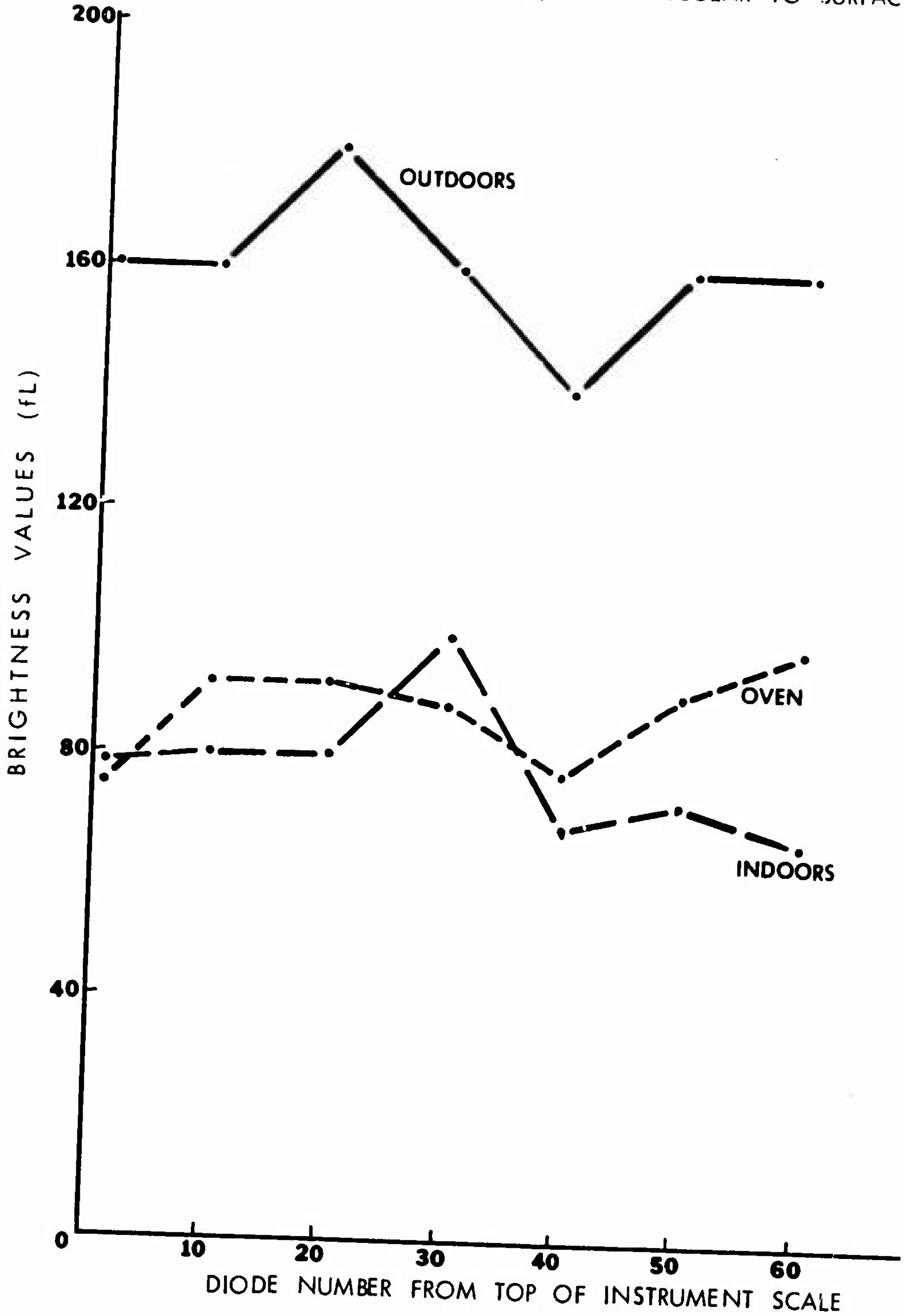


APPENDIX D-III



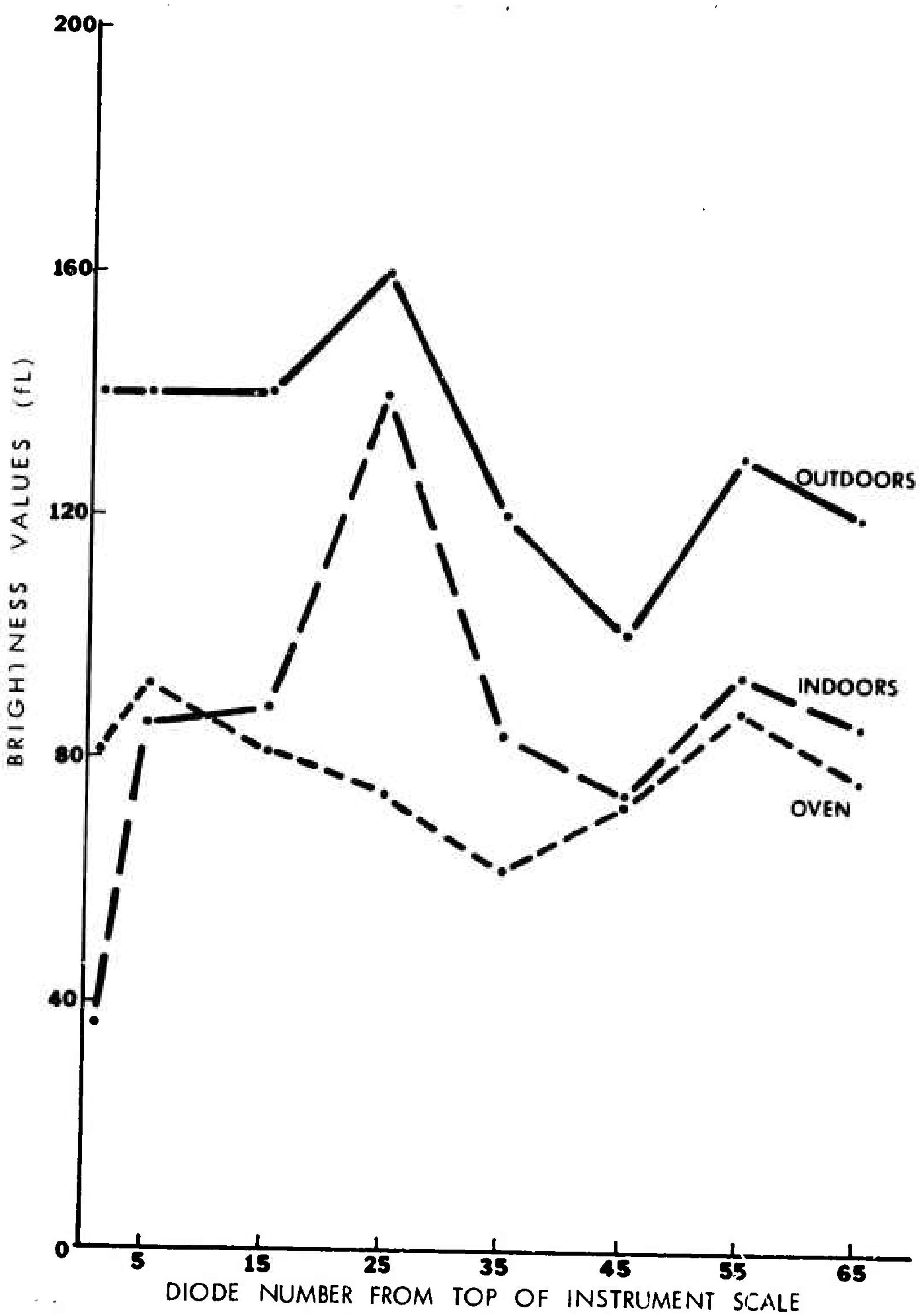
APPENDIX E-III

INSTRUMENT C; LEFT BANK, PERPENDICULAR TO SURFACE



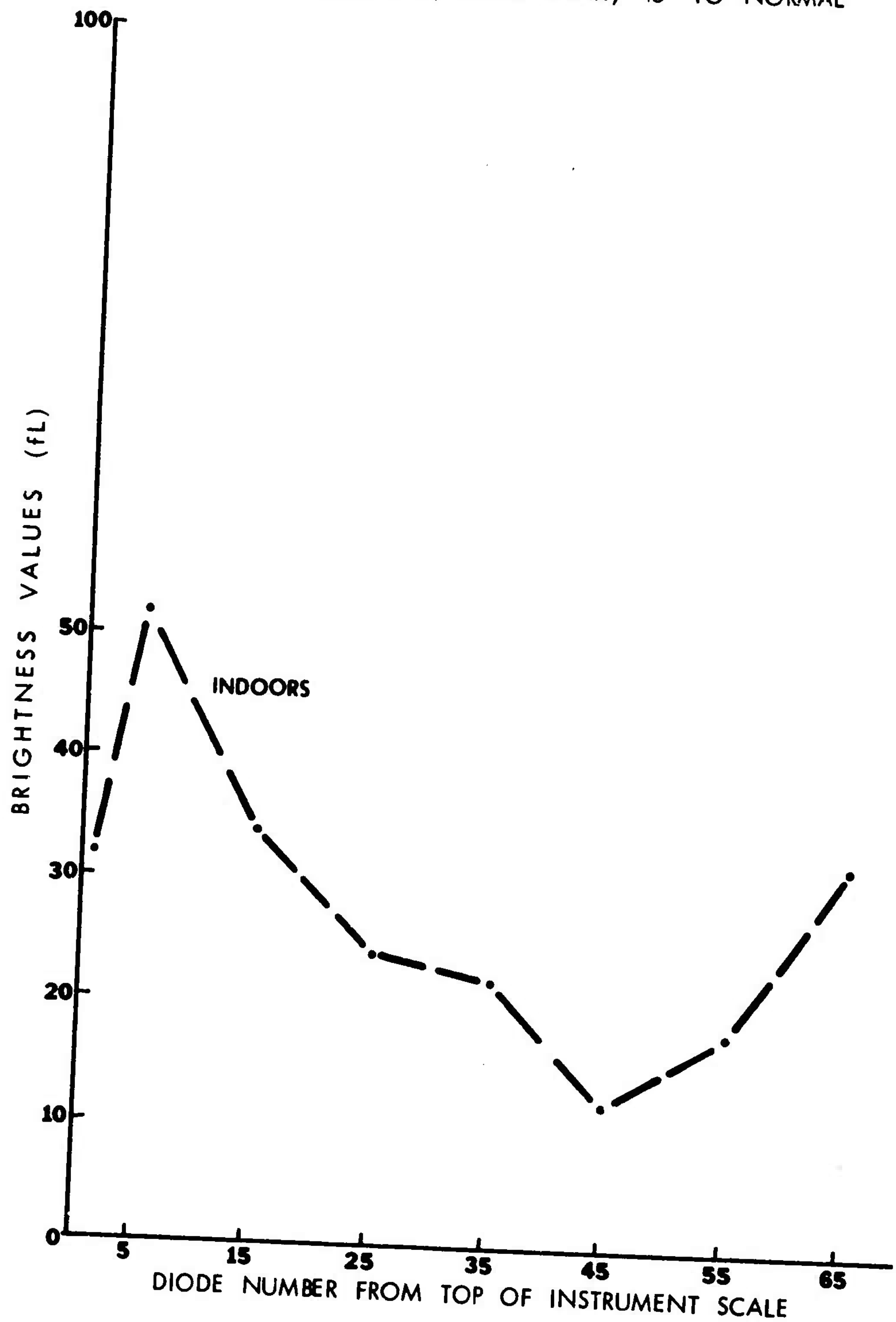
APPENDIX F-III

INSTRUMENT C, RIGHT BANK, PERPENDICULAR TO SURFACE



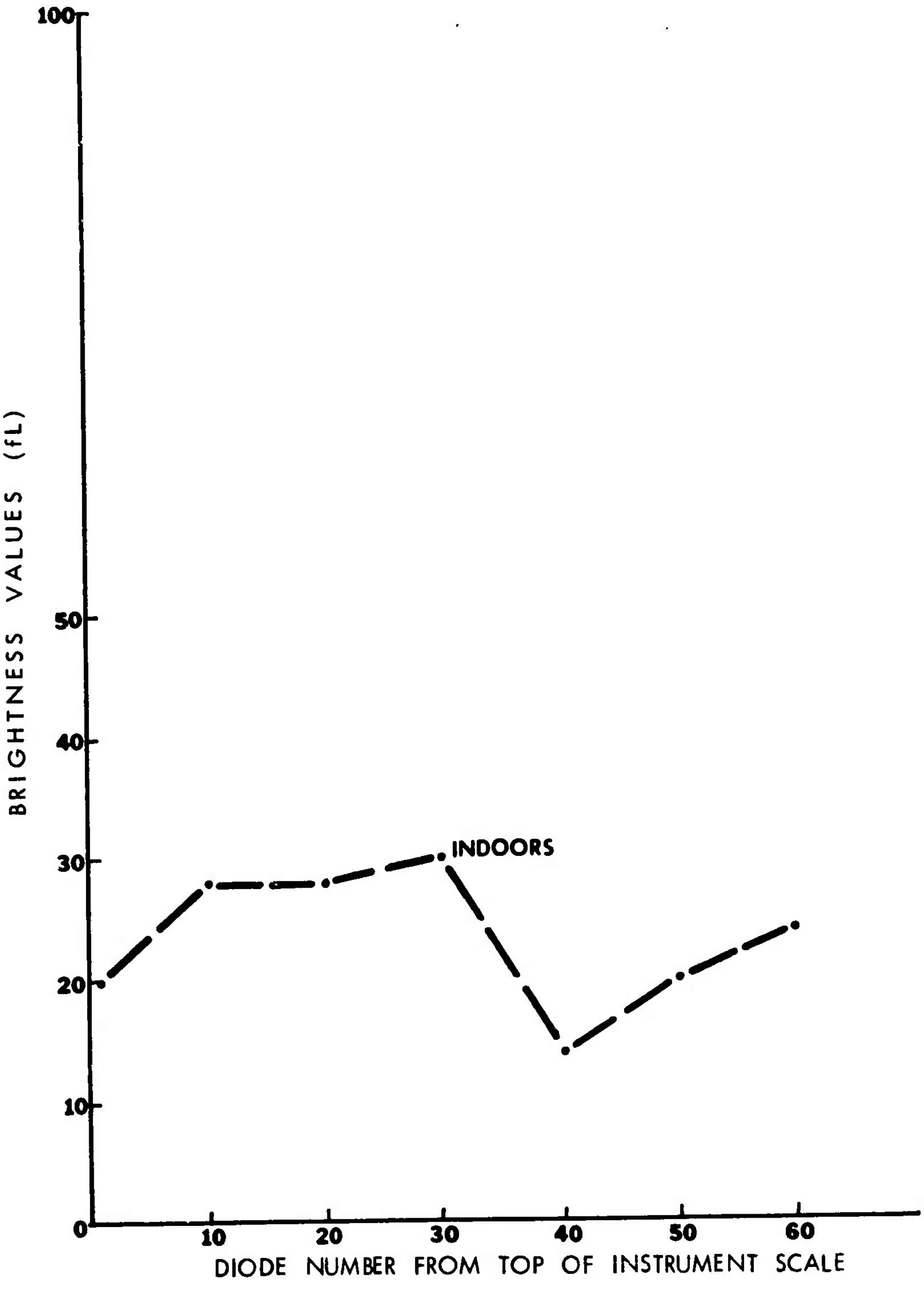
APPENDIX G-III

INSTRUMENT C; RIGHT BANK, 45° TO NORMAL



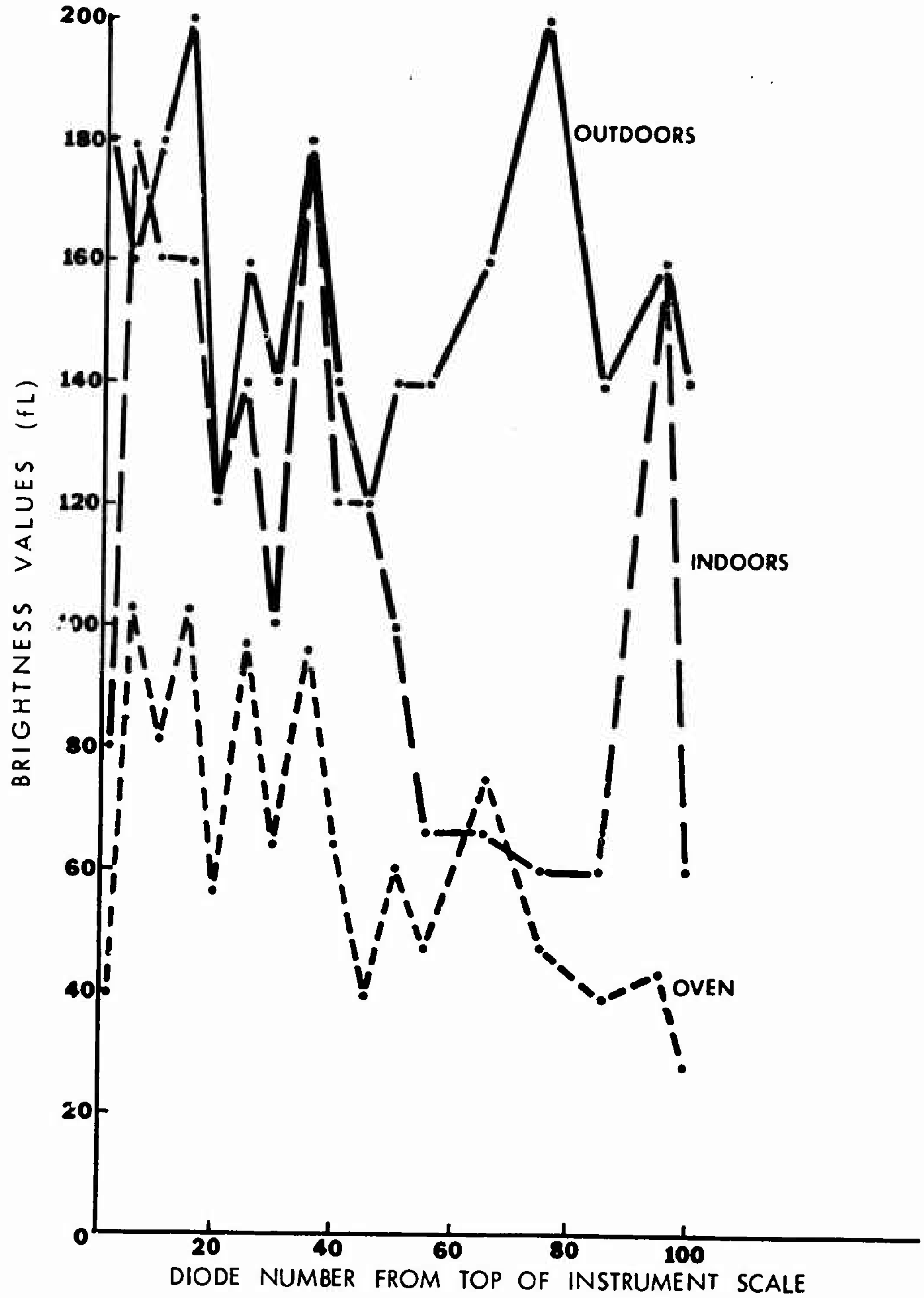
APPENDIX H-III

INSTRUMENT C; LEFT BANK, 45° TO NORMAL



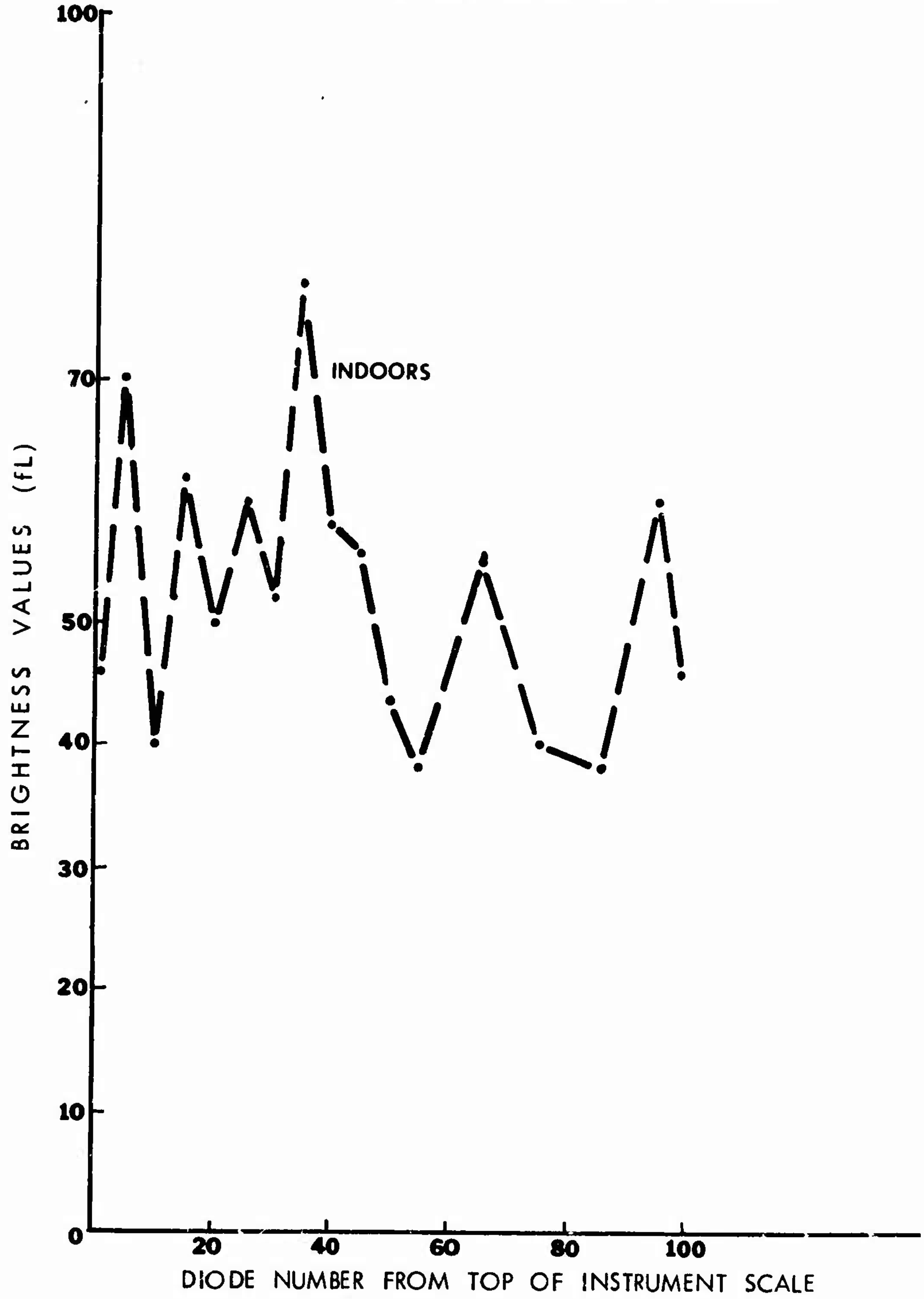
APPENDIX I-III

INSTRUMENT D; LEFT BANK, PERDENDICULAR TO SURFACE



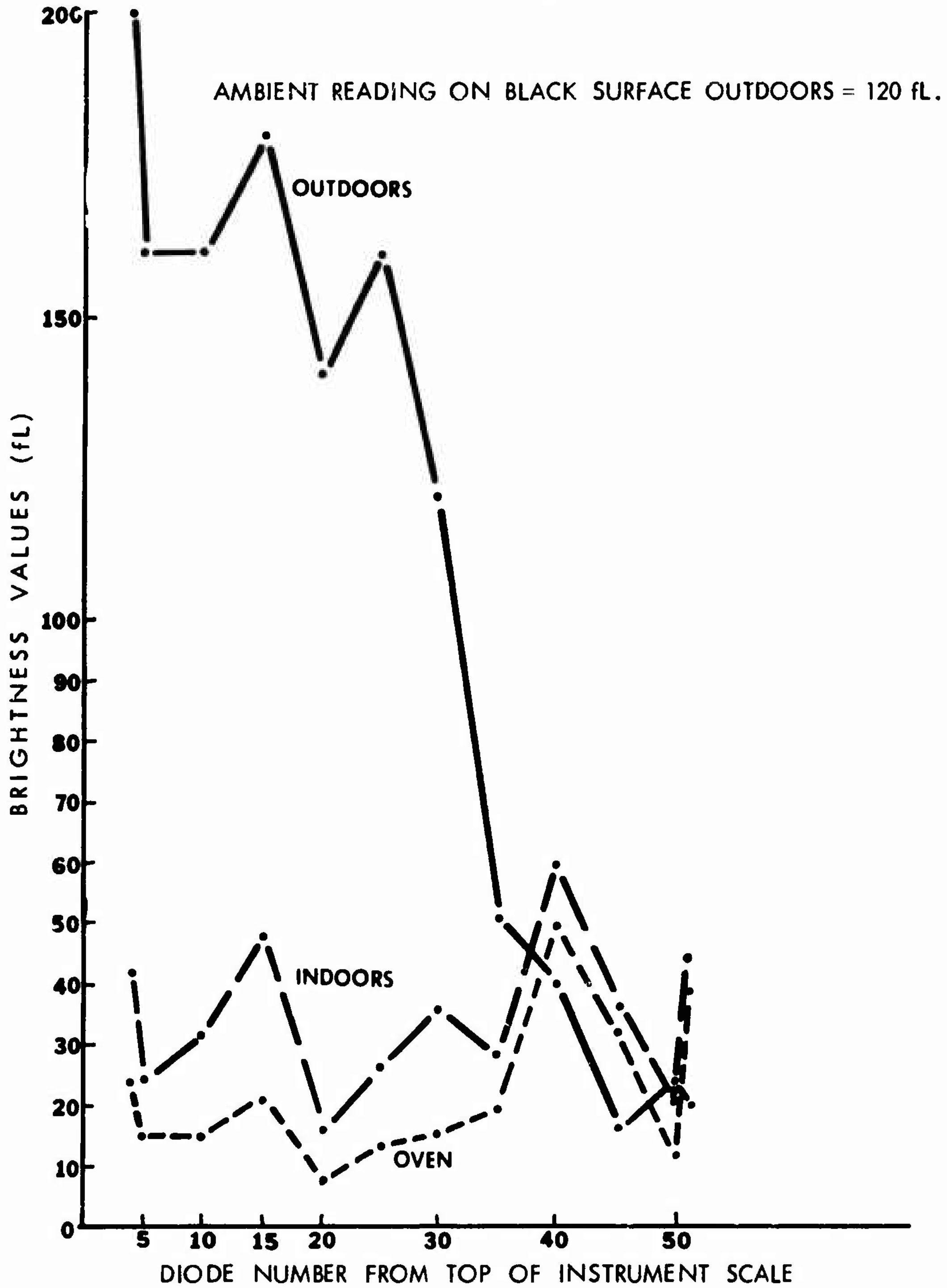
APPENDIX J-III

INSTRUMENT D; LEFT BANK, 45° TO NORMAL



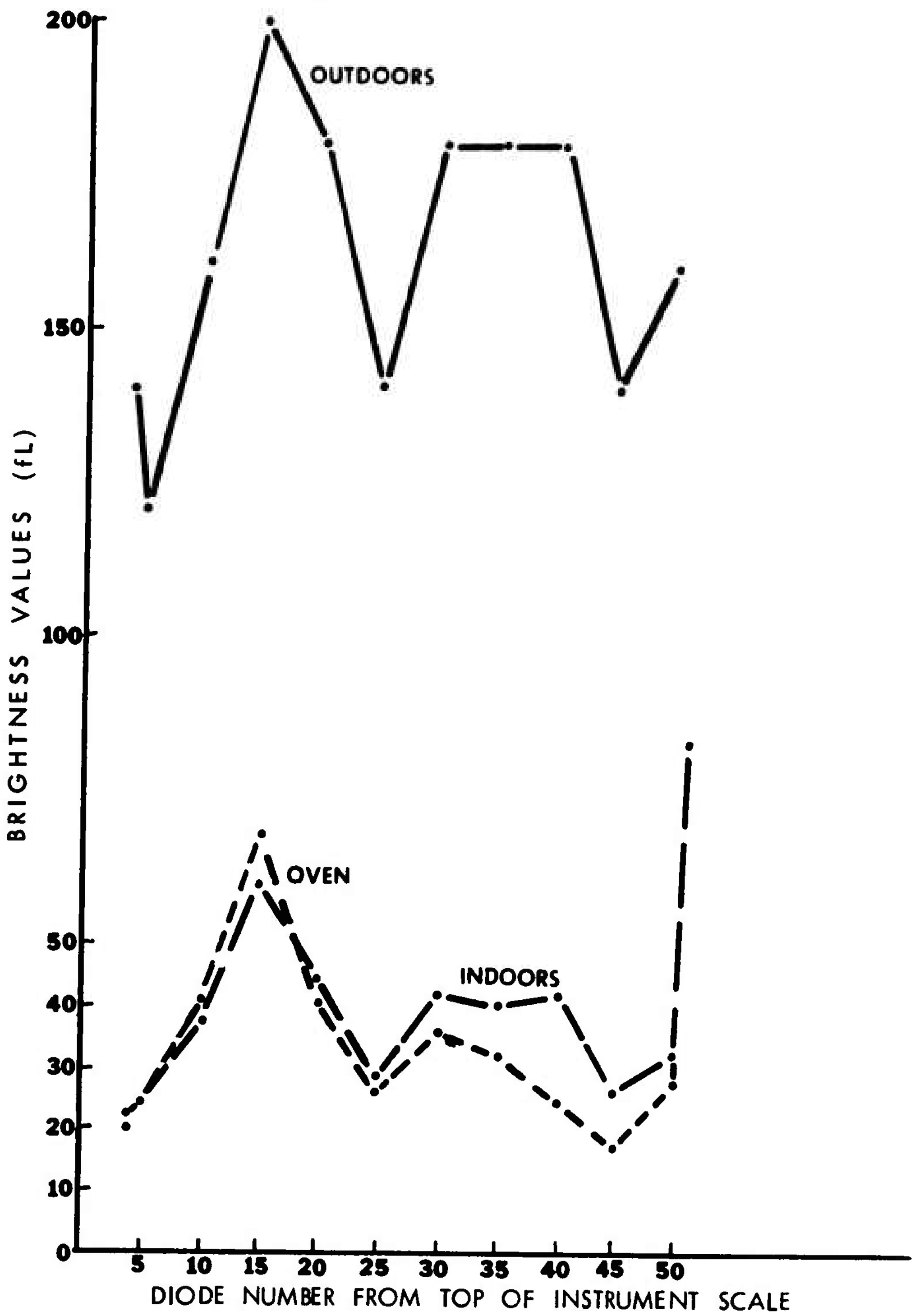
APPENDIX K-III

INSTRUMENT E; RIGHT BANK, PERPENDICULAR TO SURFACE



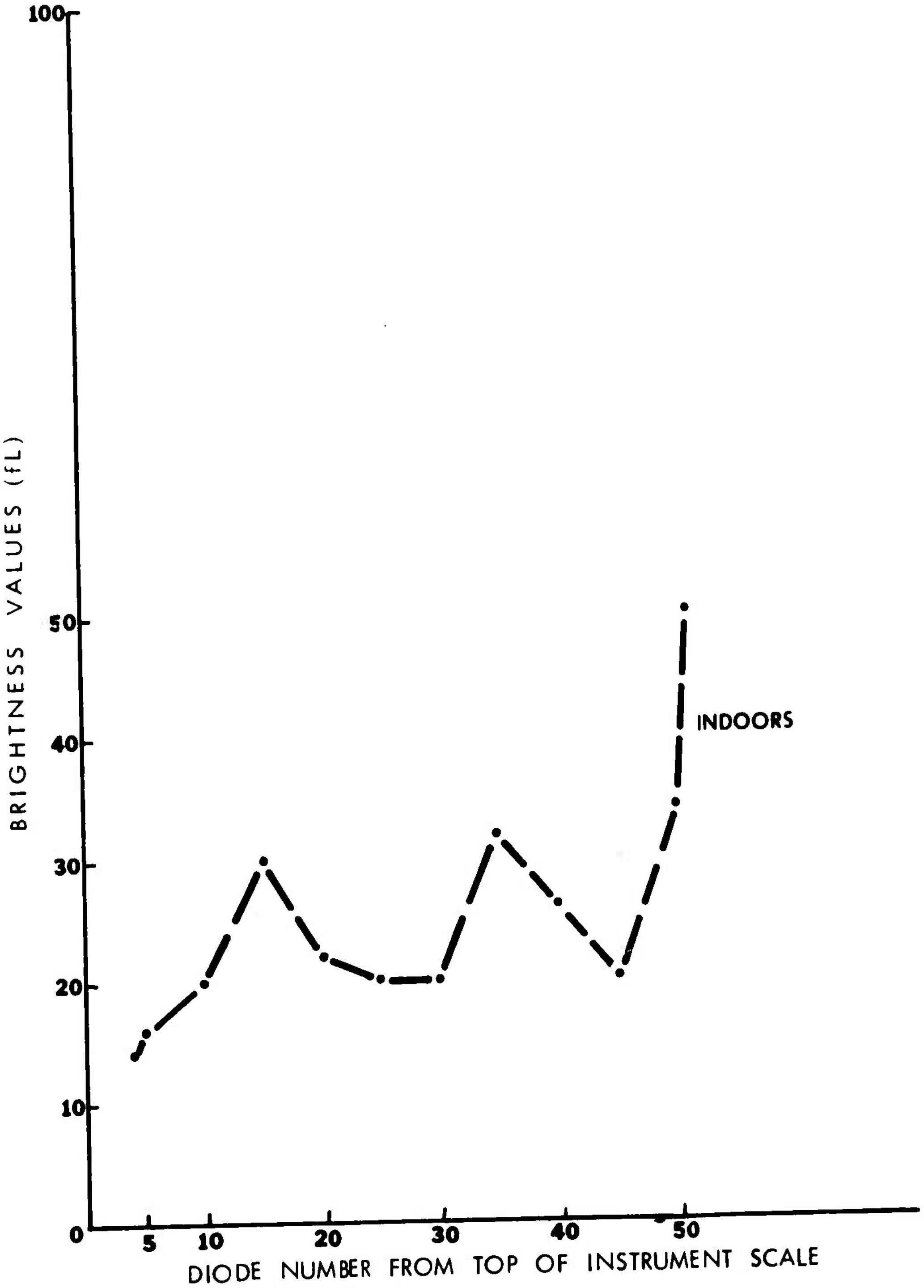
APPENDIX L-III

INSTRUMENT E; LEFT BANK, PERPENDICULAR TO SURFACE



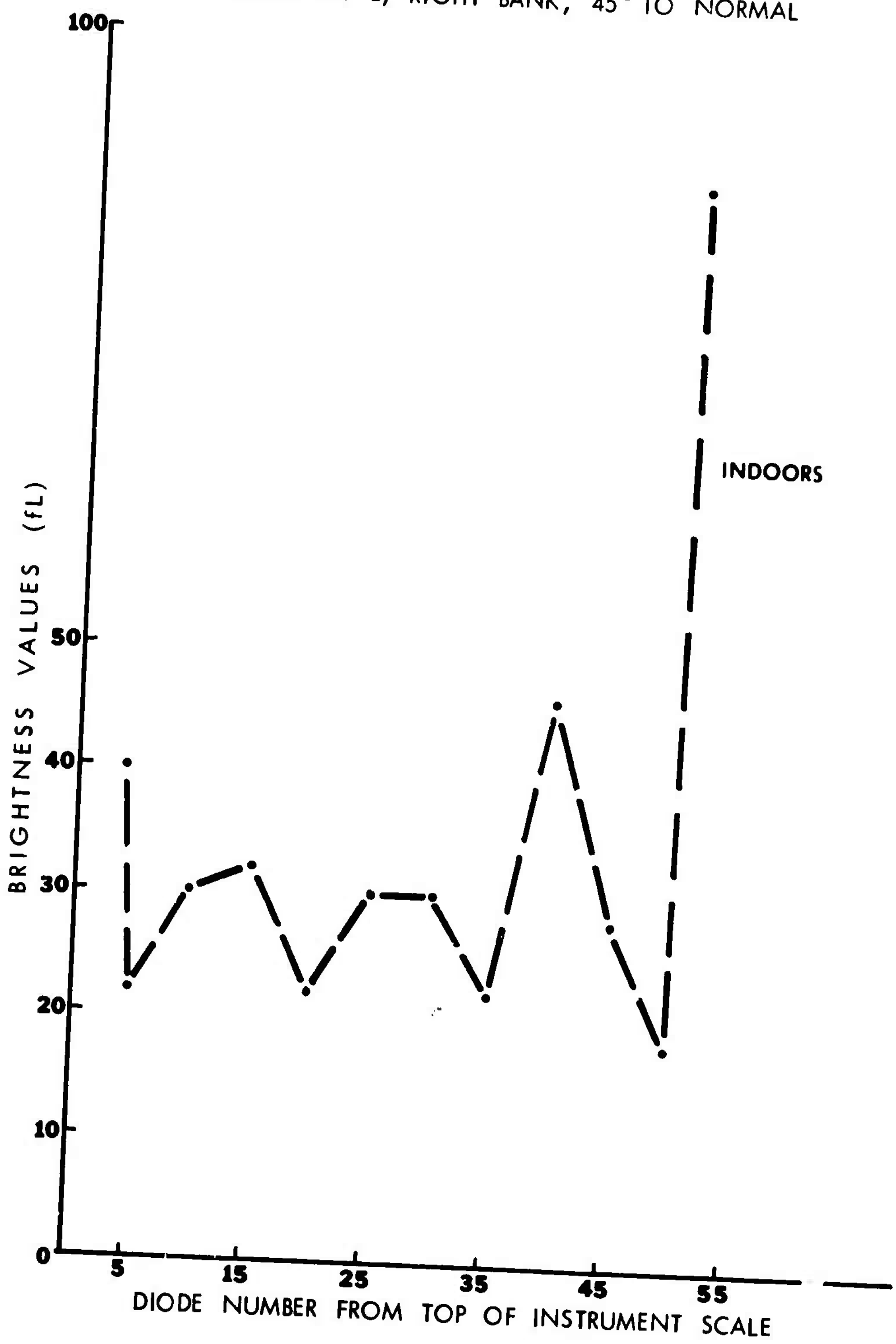
APPENDIX M-III

INSTRUMENT E; LEFT BANK, 45° TO NORMAL



APPENDIX N-III

INSTRUMENT E; RIGHT BANK, 45° TO NORMAL



PART IV

Overall Summary of Parts I, II and III

A light emitting diode display (see Figure 3-I) was selected for comparison with the currently used vertical tape display for reading accuracy and speed. The following results were obtained:

1. The LED display showed a significantly higher error rate than the vertical tape display. The mean absolute error for the LED display was 3.5 "points" compared to 1.2 for the vertical tape display.

2. The LED display was consistantly over-estimated by about three "points" while the vertical tape display was under-estimated by about one-half "point."

3. Neither of the illumination levels employed, nor the viewing angles employed had any effect on the error rates between the two instruments.

4. The over-estimation of the LED display tested was attributed in part to a "spill-over" effect which was pronounced not only in this instrument but all of the LED displays observed.

5. Because of the glare and "spill-over" observed in the LED displays, the accuracy with which these displays can be read (with the present diodes) is a function of the scale characteristics. Since the "spill-over" amounted to a couple of diodes in height---about 1/16 inch, the reading precision would be determined by the distance between graduation marks, and the value of these marks.

A human factors design criteria evaluation was performed with the following overall results:

1. All instruments were found to be deficient in meeting military or recommended standards with respect to facial design characteristics.

2. The vertical tape display violated fewer facial design criteria than the light-emitting diode displays.

A photometric evaluation of the four LED displays led to the following conclusions:

1. Contrast measurements and subjective responses show that the LED displays evaluated are unacceptable for viewing under high ambient light conditions.

2. For the LED displays evaluated there were gross luminance differences between individual diodes within the same display.

3. Eccentric viewing at 45° was either not possible due to mechanical blockage or showed large luminance loss.

4. A large number of individual diodes failed during the evaluation. The cause of these failures is unknown.

5. Several of the individual diodes demonstrated non-uniformity of brightness when viewed under high magnification.

6. Luminosity measurements taken under artificially high temperature (60° C) remained relatively stable.

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