



DEVELOPMENT OF EXPERIMENTAL SOLID STATE ENGINE INSTRUMENT DISPLAYS

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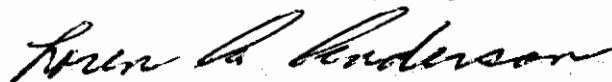
FOREWORD

This report presents the results achieved in one of a series of investigations aimed at advancing capabilities and knowledge necessary for the employment of electroluminescent phenomena in the generation of displays. The work was performed under Air Force Task 619009, "Advanced Display Generation Techniques," for which Captain B. M. Bertram served as Task Engineer. This task is an element of Project 6190 for which Mr. John H. Kearns serves as Project Engineer.

This report presents a summary of research and development accomplished during a program to design and fabricate a versatile set of solid state display components for use in engine instrument display configurations. This work was performed during the period from June 1967 to June 1968 by the Astroelectronics Laboratory, Aerospace Division, Westinghouse Electric Corporation, with Robert C. King serving as the project manager. Major contributions were made by Messrs. R. W. Wollentin, S. W. Berglin, P. F. Clarke, E. Pesout, R. D. Armstrong, W. Bertrando and J. V. Nocero. This effort was performed for the Air Force Flight Dynamics Laboratory, Directorate of Laboratories of the Air Force Systems Command, Wright-Patterson Air Force Base, under Contract F33615-67-C-1818.

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This report has been reviewed and is approved.



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ABSTRACT

The design and fabrication of a versatile set of solid state display components usable in engine instrument display configurations is described. The effort resulted in the development of plug-in electroluminescent display panels, each consisting of six columns of 125 elements at 25 lines per inch, plus scales and legends. The displays are hermetically sealed, and are green or yellow, or a combination of green and yellow. Each column is controlled by a seven bit parallel binary word. Nine display panels, three sets of logic and switching electronics, an intensity control unit, and plastic overlay scales and legends were fabricated. These components may be arranged to simultaneously display the engine parameters of revolutions per minute (RPM), exhaust gas temperature (EGT), and engine pressure ratio (EPR) for a six engine VTOL aircraft.

Distribution of this abstract is unlimited.

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L I S T O F S Y M B O L S

D	Depth
DC	Direct Current
EGT	Exhaust Gas Temperature
EL	Electroluminescent
EPR	Engine Pressure Ratio
H	Height
Hz	Hertz
LSB	Least Significant Bit
MSB	Most Significant Bit
RMS	Root Mean Square
RPM	Revolutions per Minute
V	Volts
VTOL	Vertical Take-off and Land
W	Width

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SECTION I

INTRODUCTION

The object of this research program was to design and fabricate a versatile set of solid state display components that can be used in engine instrument display configurations. Air Force interest arises because of a need to demonstrate the applicability of solid state displays in a flight simulator under realistic conditions. Experience gained in the operation of such displays will permit analysis of the presentation of continuous information with discontinuous segmented displays.

Emphasis has been placed on providing a display suitable for operation in aircraft lighting conditions, and on providing compact logic and switching electronics.

Accomplishments include the delivery of three engine instrument displays with electronics. Each instrument is of the vertical bargraph type, having six columns of 125 elements each, plus scales and legends. They are entirely electro-luminescent, and contain no moving parts. Removable overlays allow scale and legend interchangeability. The display panel is a plug-in device, and all displays will fit any of the electronics modules.

The displays have a minimum brightness of 7 foot-Lamberts, and a half-life well in excess of 1000 hours. Two colors, green and yellow, and a combination of the two, are available.

The principles and techniques presented in this report represent improvements in the state-of-the-art of displays and electronics packaging, and should be considered for future requirements.

SECTION II

DISCUSSION

A. SYSTEM CHARACTERISTICS

A solid state engine instrument display system has been designed and fabricated for use with flight simulator inputs. Versatility has been emphasized, allowing the user to change the engine parameters being displayed, the color of each display, and the brightness.

Each engine instrument consists of an electronics module, containing logic and switching functions, behind a detachable, gas filled, fast disconnect, hermetically sealed electroluminescent (EL) panel. Three electronics modules and nine EL panels have been provided. The modules may be mounted flush side by side if desired. The displays are illustrated in operation in figure 1.

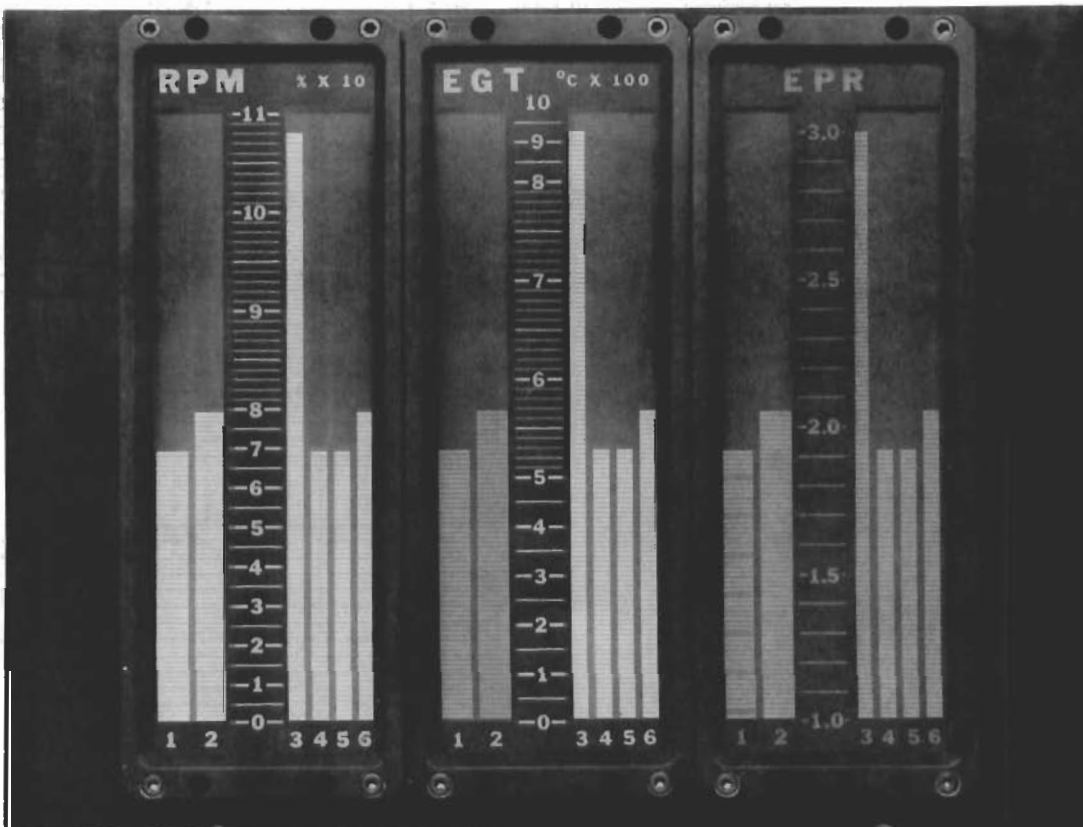


Figure 1. Solid State Engine Instrument Displays

This system has been designed for use with a simulated six engine VTOL aircraft. Therefore, each display consists of six illuminated vertical bargraphs with scale and legend markings. Each bargraph consists of 125 lighted elements having a resolution of 25 elements per inch. The EL panels and scale and legend overlays may be interchanged in such a way that three

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engine parameters may be displayed in any order, and in green, yellow, or a combination of green and yellow.

Each electronics module is approximately 2" W x 6" H x 6" D, and contains logic and switching functions to control the 750 bargraph elements of one EL panel. The logic accepts a seven bit parallel binary word for each column, while the switching controls a maximum of 600 volts.

In addition a control unit has been provided allowing the brightness of the displays to be varied individually or in unison. The control unit also contains the necessary power supplies, and requires 115 volts, 400 Hz for operation.

The complete system is shown in figure 2. Separate functions of the system are described in detail below.

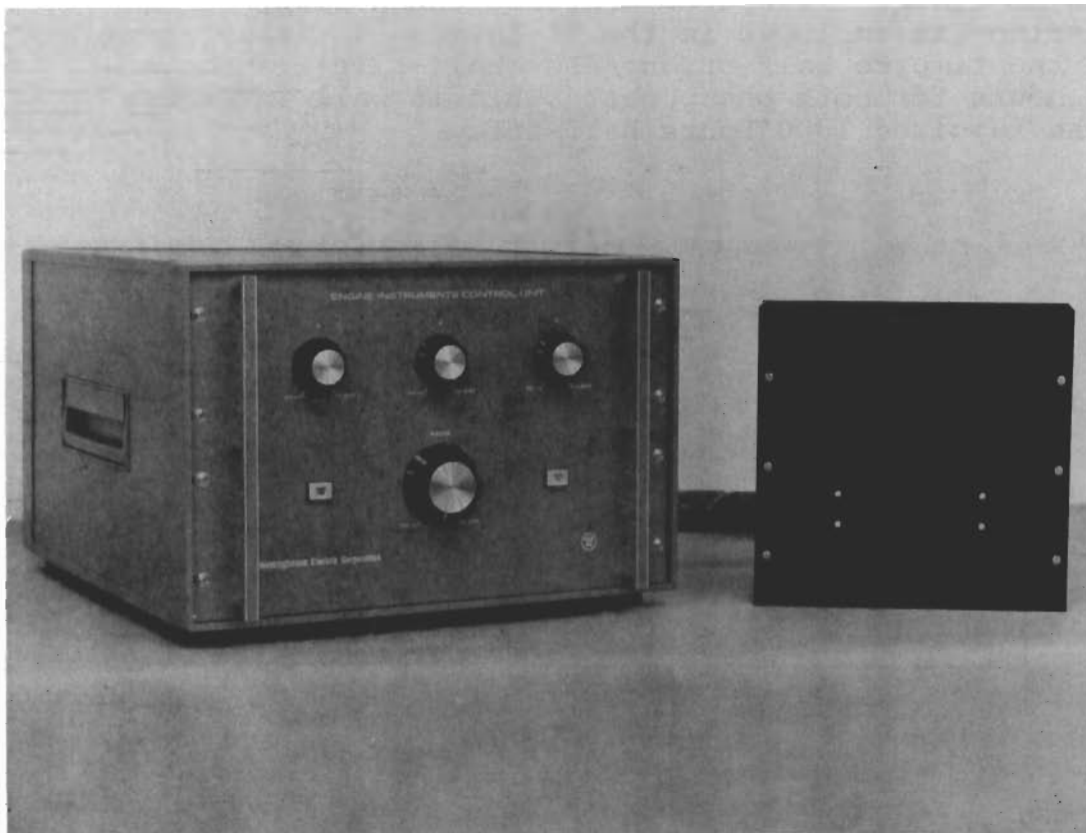


Figure 2. Solid State Engine Instruments

B. ELECTROLUMINESCENT DISPLAY PANELS

1. Phosphor

The electroluminescent phosphors employed have been optimized especially for this application. Great emphasis has been placed on the operating life of these displays,

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due to the nature of their modes of operations. During a typical simulated flight, the lower elements of the bargraph columns will be lighted almost continuously. However, the upper elements will be energized for a shorter period of time. Therefore, unless the phosphors exhibit exceptional life characteristics, there will be a perceptible difference in element brightnesses after a prolonged period of operation, where all elements are lighted.

One type of the display panel employs two colors within the same panel. Thus, it was desirable to match the life characteristics of these two colors, green and yellow, to minimize brightness differences between the two.

The life curves of the yellow and green phosphors are shown in figure 3 where no contrast enhancement or filtering was employed in the EL layer. It is apparent that the time to half brightness (half-life) is about 1400 hours for both phosphors. This is well in excess of the required 1000 hours half-life.

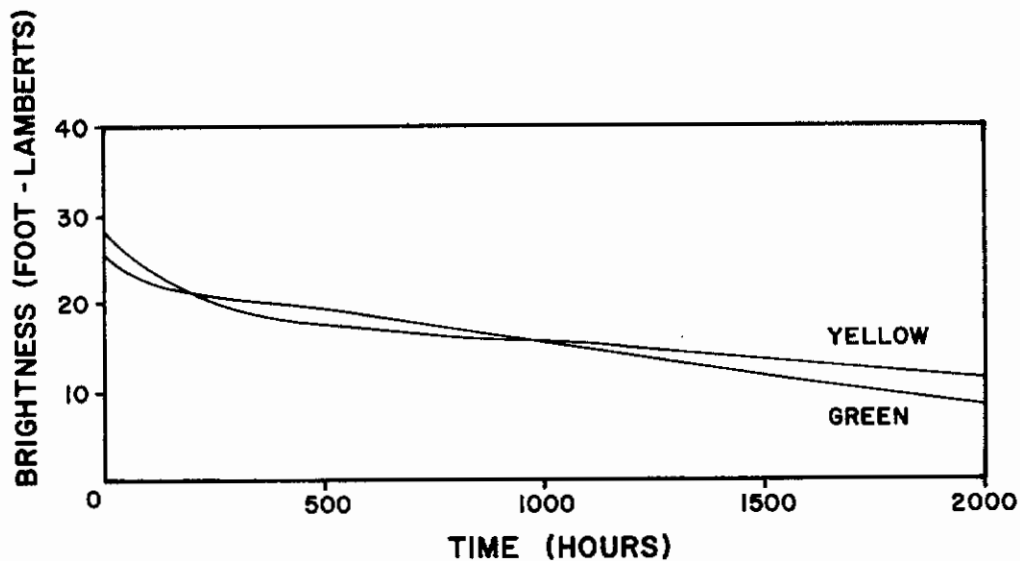


Figure 3. Phosphor Life Curves

Spectral distribution curves for the two colors are shown in figure 4. These curves have been corrected for phototube response and optical path absorption nonlinearities.

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A published paper by Dr. W. Lehmann of the Westinghouse Research Laboratories is included in the Appendix. Although the phosphors used for the bargraph displays are of a slightly different type, Dr. Lehmann's article explains the basic principles involved.

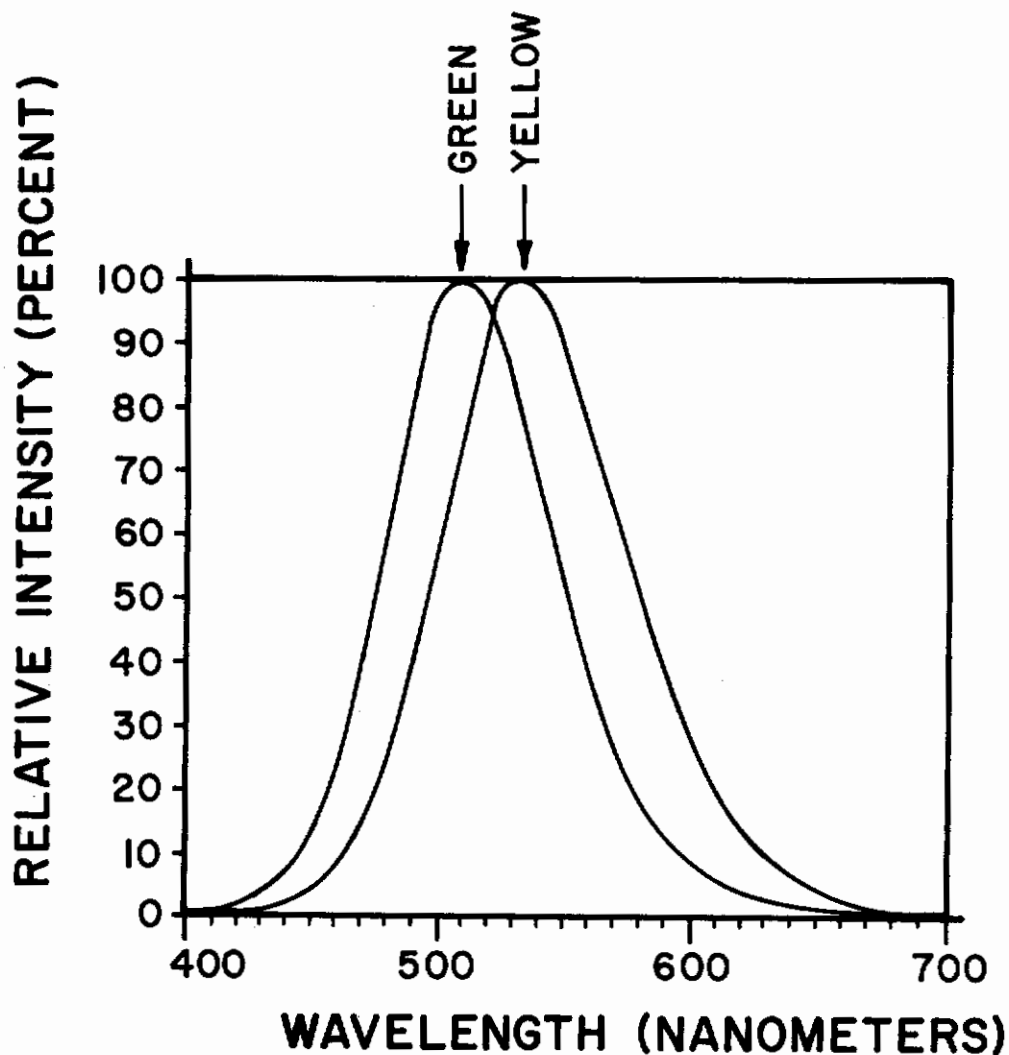


Figure 4. Phosphor Spectral Energy Distribution

2. Construction Details

Each EL display panel is a hermetically sealed, gas-filled, plug-in unit. The major components are a ceramic header containing 758 pins for electrical connection, and a glass faceplate which also serves as a substrate for the EL phosphor layers. These two parts are sealed together in such a way that the entire device is leak tight, having a maximum leak rate of 10^{-6} standard cubic centimeters of helium per second, under one atmosphere differential pressure.

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The header is illustrated in figure 5. A 96% alumina blank was machined to rough size in the unfired state, and holes for the pins and for mounting were drilled. The part was then fired, metallized, and ground to final size. Small diameter tin-plated brass pins were then soldered into the 758 holes, using tin-lead solder. These pins are flush with the inside surface of the header, and protrude from the rear to serve as the male pins of a connector. Two oxygen-free copper pinch-off tubes and two alignment pins are also soldered into the ceramic. Note that there is also a metallized band around the outside of the header. This is used to seal the faceplate to the header.

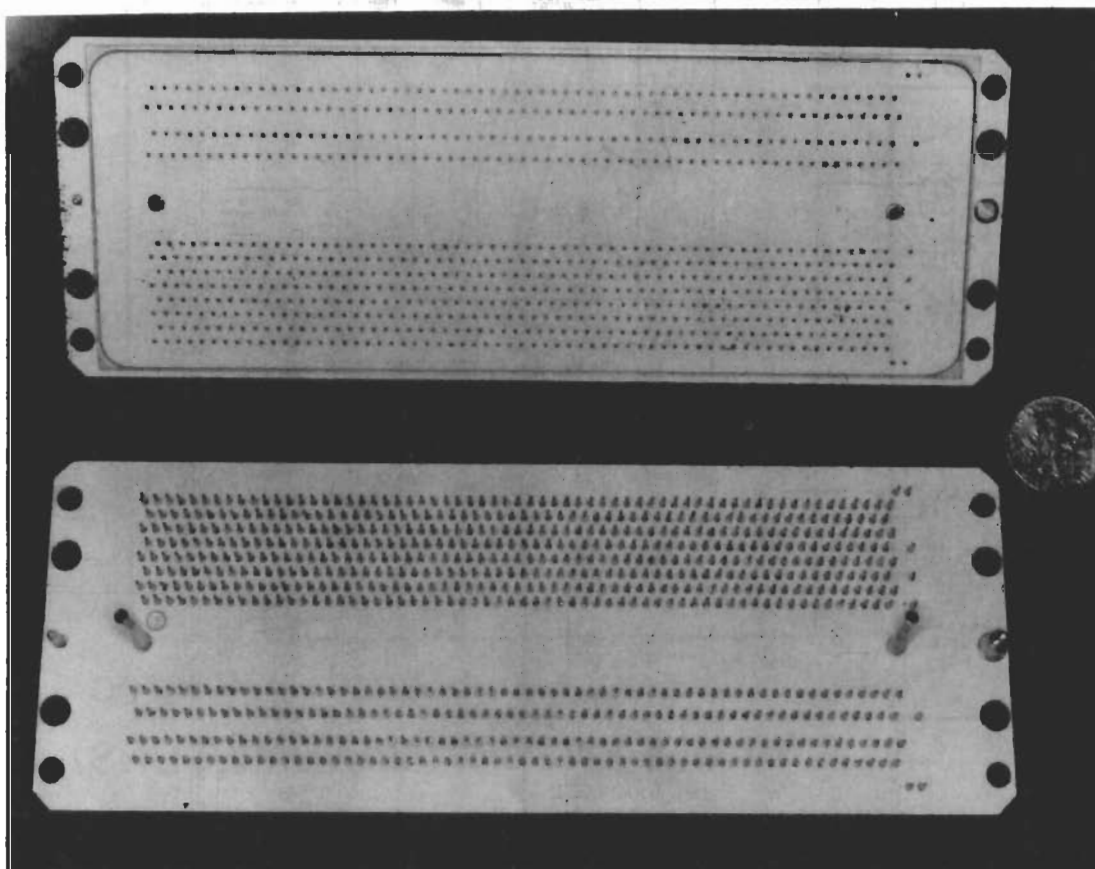


Figure 5. Ceramic EL Panel Header

A typical faceplate is shown in several stages of completion in figure 6. This assembly consists of a glass substrate having an electrically conductive surface on one side. The glass edges have been metallized, and a metal band has been soldered around the perimeter. This band is soldered to the header to effect a closure. The EL phosphor, contained in a special dielectric suspension medium, is applied to the conductive surface, which serves as an electrode of the complete device. Vacuum deposited aluminum is then deposited on the rear surface of the

phosphor-dielectric through a suitable mask. The mask defines the bargraph elements and the scale-legend element. This mask is illustrated in figure 7.



Figure 6. EL Panel Faceplates:
(Left to Right) Plain, Phosphor Coated, Aluminized.

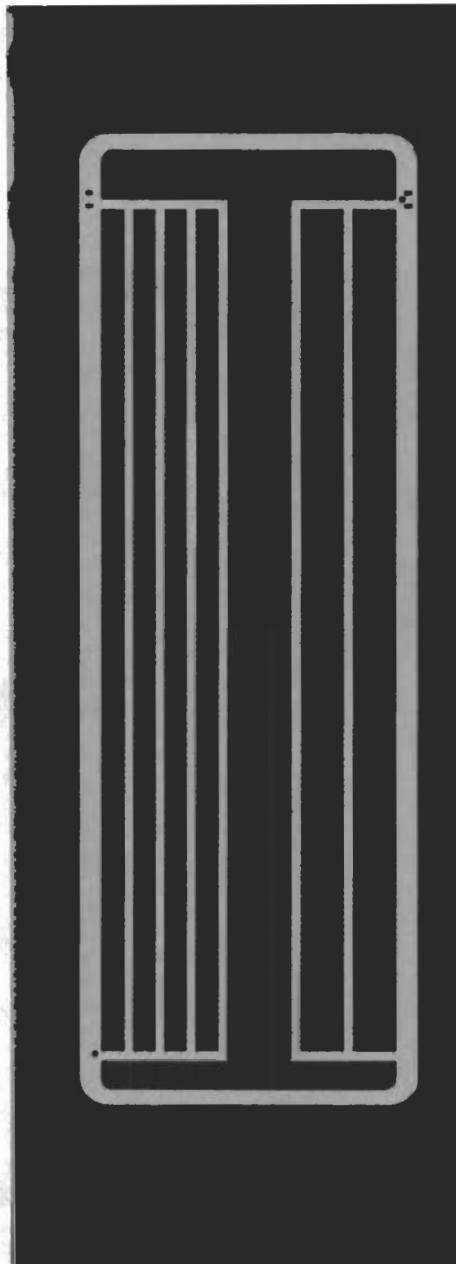


Figure 7. Display Aluminizing Mask

An electrical contact is made to each bargraph element by means of conductive silicone rubber. A small piece of this material is held captive in a hole in the end of each of the 758 header pins. The rubber piece (called a "snail") protrudes above the surface of the ceramic in the uncompressed state. As the faceplate is lowered onto the header, each "snail" contacts a single EL element. Because of the close spacings involved, very precise registration of mating assemblies is necessary.

After insuring that all elements have an electrical connection, the metal band of the faceplate is soldered to the ceramic header, using low temperature melting solder.

Finally, the assembly is gas filled with dry nitrogen containing a small percentage of helium, and the pinch-off tubes are closed. The final internal pressure is slightly less than one atmosphere at room temperature.

Interchangeable plastic overlays have been supplied which serve several purposes. First, the overlay has markings on its rear surface which show the particular engine variable being displayed, the scale numbers and index marks, and number designations for each of the six bargraphs.

Second, the overlay is a circularly polarizing filter having a transmission of about 37% for light emitted behind the overlay, in this case that produced by the EL display. Ambient light which strikes the front surface of the display is circularly polarized upon passing through the filter. This light is reflected to some degree from the surfaces of the display, but only about 1% of this reflected light can pass out to the viewer, because of having been previously circularly polarized. This increases the contrast of the display and hence the readability, under high ambient conditions.

Third, the front surface of the overlay has been treated to reduce surface reflections. This aspect, in combination with the circular polarization, results in a display having less than 5% total off-axis reflection.

C. DISPLAY DRIVING ELECTRONICS

1. Logic and Switching Functions

In order to package the electronics components necessary to control 750 EL elements in the required space, it was necessary to reduce the number of components used. This was achieved by using a unique switching and logic system, employing integrated circuits, miniature diodes, resistors, and transistors.

Figure 8 shows a basic EL element switch.

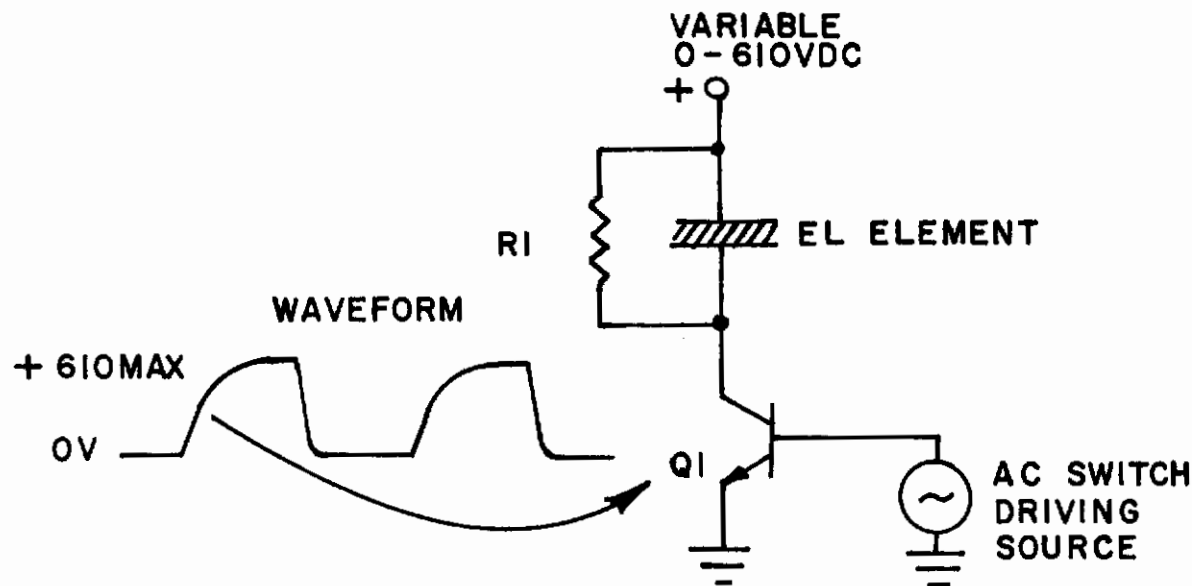


Figure 8. Basic Switch Circuit

Transistor Q1 is periodically switched on and off by a low-voltage AC driving source. This toggling action of transistor Q1 induces the waveform shown at its collector. The fall-time of this waveform is dependent on the RC time-constant created by the intrinsic resistances and capacitances of transistor Q1 and the EL element. The rise-time depends upon the capacitances of Q1 and the resistance of R1. The value of R1 has been chosen to provide a compromise between light output and power dissipation.

The number of switching elements required to drive a large number of EL elements can be greatly reduced by making use of the fact that this type of EL phosphor emits light only when in the presence of a changing electric field. Thus, if the drive signal to transistor Q1 is such that it is held continuously "ON" or continuously "OFF", the EL element will not emit light.

Continuing, a circuit such as that shown in figure 9 will also control an EL element.

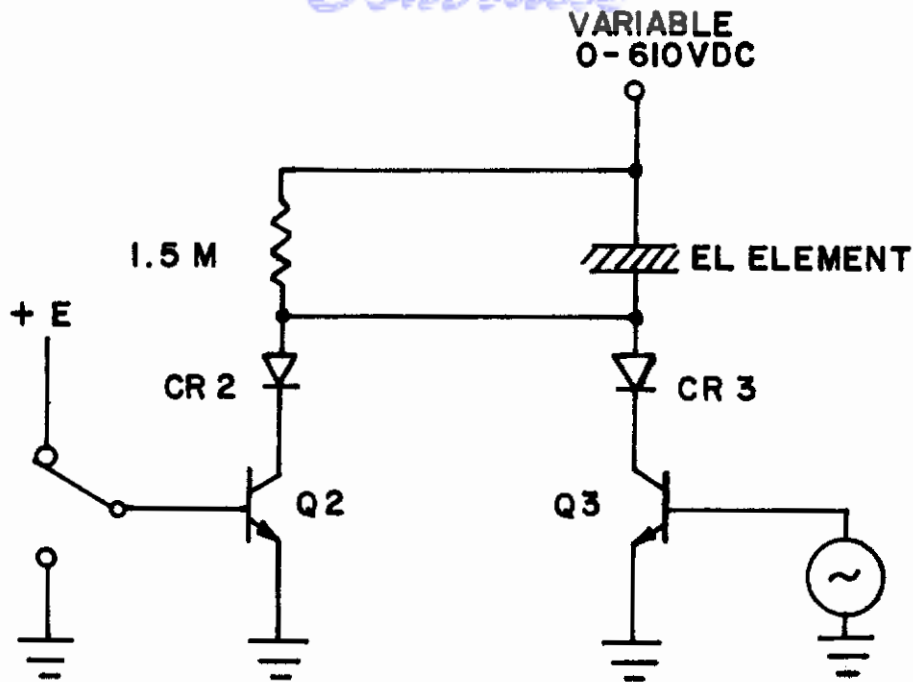


Figure 9. Diode Coupled Transistor Circuit

Two diode coupled transistors (Q2 and Q3) are used, such that when the base of Q2 is grounded, Q2 is turned off. This allows transistor Q3 to assume command of the EL element. Since Q3 is driven by an AC source, the EL element will emit light. When the base of Q2 is positively biased above ground, it will be turned on. The EL element will not emit light, regardless of the state of Q3, because the EL element is clamped to ground by Q2 and not excited by a pulsating signal.

Although the circuit of figure 9 requires more components than that of figure 2, it is possible to control two or more elements with the same transistors.

A 16 element bargraph with electronics is shown in figure 10. Using the concepts developed above, the control of this 16 element display may be explained as follows.

It should first be noted that the bargraph has been electrically divided into four groups of four elements each. Although only one resistor is shown in figure 10, each individual electroluminescent element is paralleled by a 1.5 megohm resistor. As previously shown, these resistors establish the wave shape of the square wave used for lamp excitation.

Also note that Nand gates are employed as logic functions to control the presence of the low voltage AC applied to the base of each transistor.

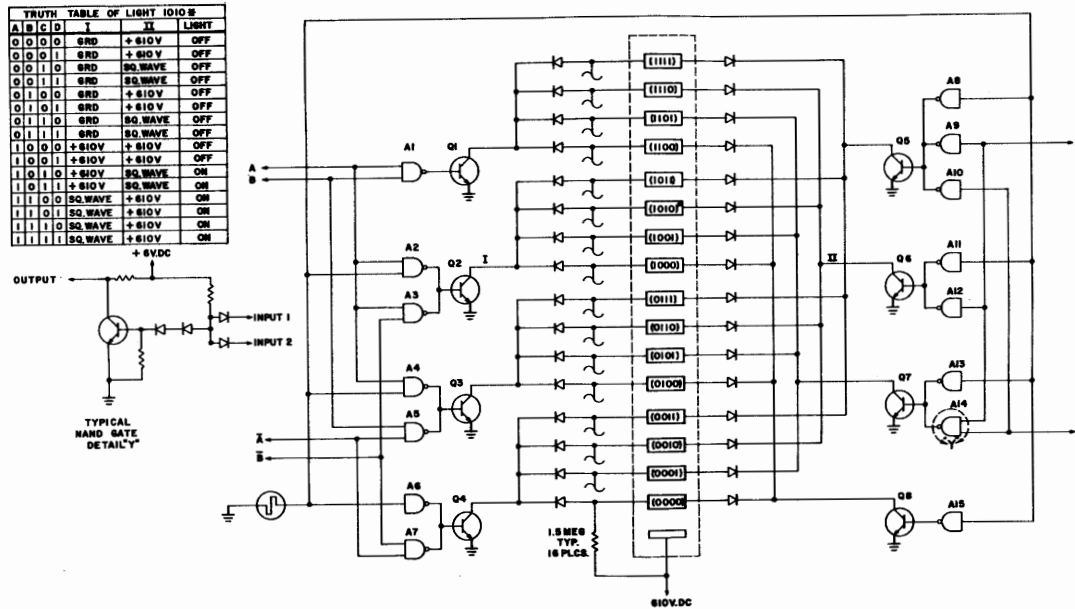
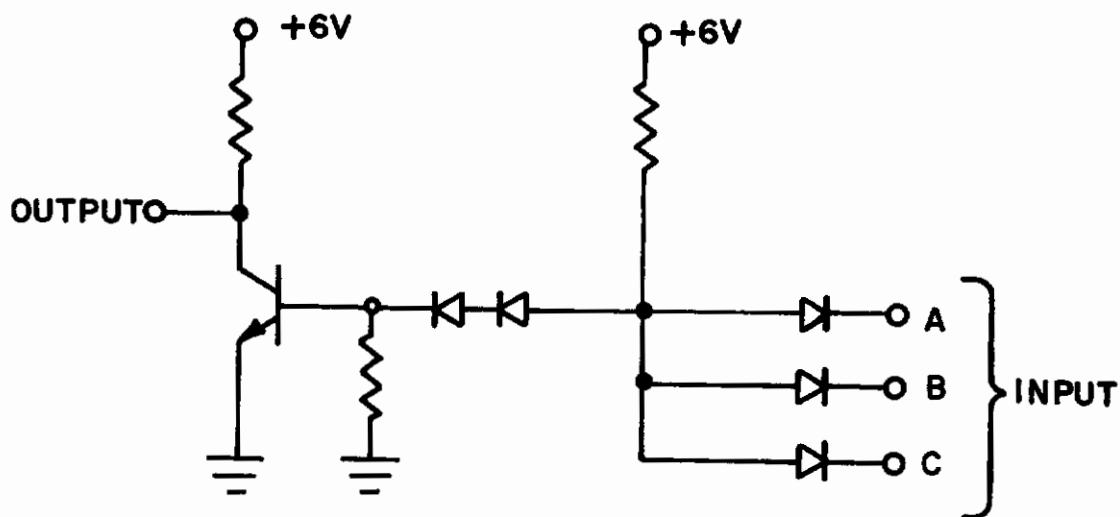


Figure 10. 16 Element Electroluminescent Bargraph Display

A Nand gate (an inverting And gate) is shown in figure 11. This particular gate has three inputs, and performs the function shown in the truth table. This table simply says that the output of a Nand gate is false (output = 0) only when all its inputs are true (A=B=C=1). Standard off-the-shelf Nand gates are available in one, two, three, four and eight input configurations with respectively six, four, three, two and one independent functions per package.



INPUT			OUTPUT
A	B	C	
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

Figure 11. Typical Nand Gate

The 16 element bargraph is controlled by a 4-bit straight binary code depicted by the symbols A, B, C, and D where A is the most-significant-bit (MSB) and D is the least-significant-bit (LSB). The binary complement of this 4-bit code is also required and is represented by the symbols \bar{A} , \bar{B} , \bar{C} and \bar{D} (read A not, B not, C not, and D not). When A is true ($A = 1$) \bar{A} is false ($\bar{A} = 0$) and vice-versa.

A truth table is shown in figure 10 for EL element 1010 (the eleventh element from the bottom). In addition to indicating when element 1010 is lighted, this truth table also lists two circuit points of particular importance to element 1010, (I) the collector of Q2 and (II) the collector of Q6. The results of each combination of the binary input code from 0000 to 1111 (decimal 00 to 15) are related below to circuit points (I) and (II) to verify the list of the truth table.

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0000: This input code combination means $A=B=C=D=0$ and $\bar{A}=\bar{B}=\bar{C}=\bar{D}=1$. $A = 0$ forces the output of both Nand gate A2 and A3 to be equal to logic one which in turn causes transistor Q2 to saturate [$(I) = \text{Grd}$] and clamp element 1010 to ground. In addition, $C = 1$ forces the output of Nand gate A12 to 0 (ground) which clamps the base of Q6 to ground regardless of the output of A11. Thus Q6 is turned off and point (II) = 610V due to the current through the common diode connected to element 0010. Element 0010 is at 610V due to the parallel 1.5 megohm resistor and the fact that Q4 is turned off because the output of Nand gate A7 is 0 (ground).

0001: Point (I) is ground because $A = 0$ and Q2 is saturated. Point (II) is 610V because Q4 and Q6 are turned off as in case 0000.

0010: \bar{C} now equals 0 so the output of A12 becomes 1 and Nand gate A11 is allowed to assume control of Q7. The input to A12 is a square wave and Q6 is caused to turn on and off in synchronism to the input square wave. This toggling of Q6 would cause element 1010 to emit light were it not being clamped to ground by Q2 (still saturated by the binary input code). Therefore, Point (I) is ground and Point (II) is a 610V zero-to-peak square wave.

0011 to 0111: Nothing happens during these combinations that cannot be explained by slight deviation of the three cases already cited.

1000: Because $A = 1$ and $\bar{B} = 1$, Q2 is turned off and Point (I) = 610V DC. Simultaneously, Point (II) = 610V DC due to $\bar{C} = 1$. Element 1010 does not see an AC signal and does not light.

1001: Same as code condition 1000.

1010: Point (I) remains at 610V DC, but Q6 can not toggle, producing a 610V square wave at Point (II). Element 1010 lights.

1011: Same as code combination 1010. Element 1010 lights.

1100 to 1111: $\bar{B} = 0$, therefore A2 assumes command of Q2 causing Q2 to oscillate in synchronism with the input square wave. For all these code combinations, Q6 is either off or toggling. Element 1010 lights.

This design concept has been further expanded to a 125 element bargraph. While a 16 element bargraph requires 8 transistors, a 128 element bargraph requires 24 transistors. The 128 elements are divided into 16 groups of 8 elements each.

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Thus 256 diodes, 128 resistors, 24 transistors, and 20 integrated circuits can control 128 bargraph elements. a 7-bit parallel, straight-binary word is required to control each column. Inversion of each binary bit, to form the complement logic signals, is accomplished by circuitry in the control unit. Logic "1" = zero volts and logic "0" = +6 volts DC.

The components for each bargraph column have been packaged on separate printed circuit cards. A typical card is shown in figure 12. Additional information about packaging will be found in Section D.

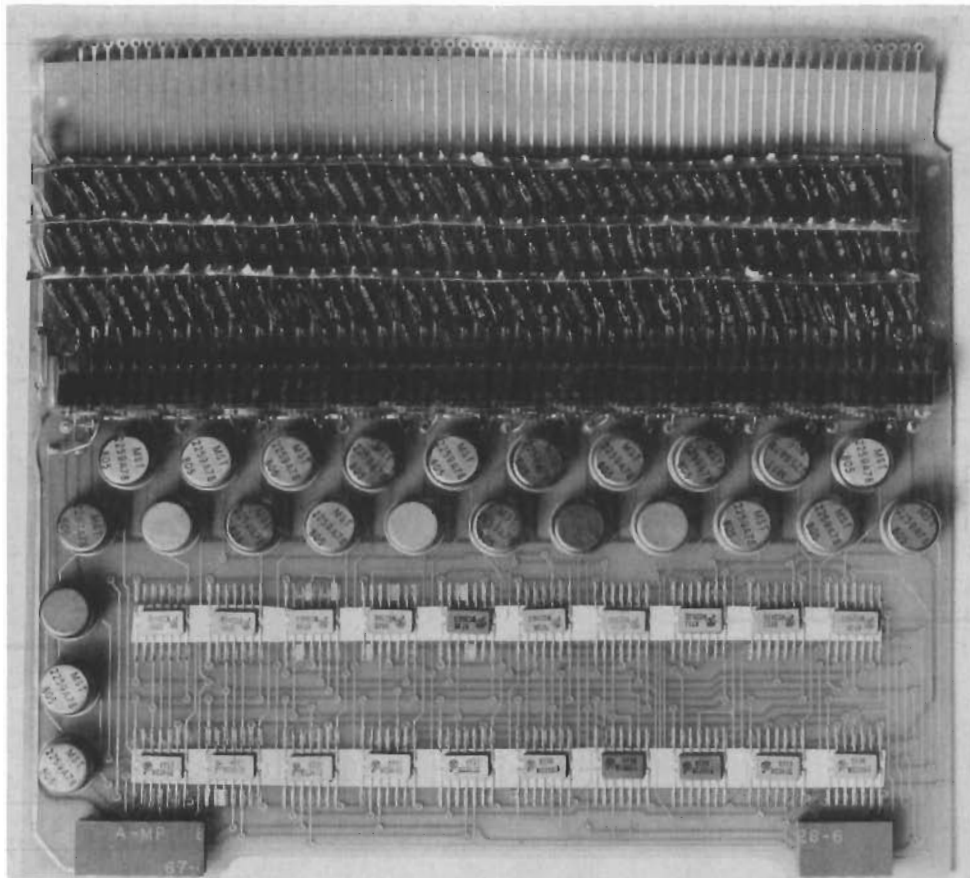


Figure 12. Logic and Switching Electronics Circuit Card

2. Control Function and Power Supply

A schematic of the Control Unit is shown in figure 13. The major components within the Control Unit are: Four variable autotransformers for intensity control, three 600 VDC power supplies for the high level logic, one 6VDC power supply for the low level logic, and a zero-to-6V peak pulse generator providing the EL driving circuit excitation. Also included are six "thyrector" diodes and two cooling fans for surge and thermal protection, respectively. Referring to figure 13, it is

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seen that the input power (115 VRMS, 400 Hertz) is applied to the Control Unit via two interlocking cooling fans. The cooling fans must be connected and operating before power will be applied to the first variable autotransformer. This transformer is located inside the Control Unit and is preadjusted and locked at a position which will allow the output power supplies to be controllable to a maximum of 610 VDC.

Continuing, the power flow path through the Control Unit, power is next applied to the master controllable autotransformer. The output of this transformer is divided into three identical parallel paths and directed to three smaller autotransformers. These variable autotransformers are controllable and are utilized to adjust the voltage level to Instruments A, B and C. Each of these three transformers is connected to a "Thyrector" diode which is used for surge protection and will short to ground any transient signal above 350 volts.

The power next flows from the three small autotransformers to the three output power supplies and the three output transformers. The output of each of these transformers is connected to a zener diode network which causes the outputs of the above transformers to be referenced at +300VDC; not ground. In addition the output of each transformer is connected to a "Thyrector" diode which limits surge voltages to a maximum of 770 volts.

Both the DC voltage outputs (power supplies) and the AC voltage outputs are variable by controlling the Master or Instruments A, B or C autotransformers. The DC voltage output is used as a reference and the AC voltage output is adjusted by choosing the value of voltage dropping resistors R1, R2 and R3, so that the light output of the background light is equal to the light output of the segmented columns.

In addition, the main power line of the Control Unit is also connected to a +6VDC power supply which is used as the power source for the low level logic. The main power is also supplied to a pulse generator which is used as the control excitation voltage for the electroluminescent segmented columns. The output of the pulse generator is fed to three 2-stage line drivers which provide the proper polarity and power to drive the logic in each logic electronics module.

The complete control unit/power supply is illustrated in figure 14.

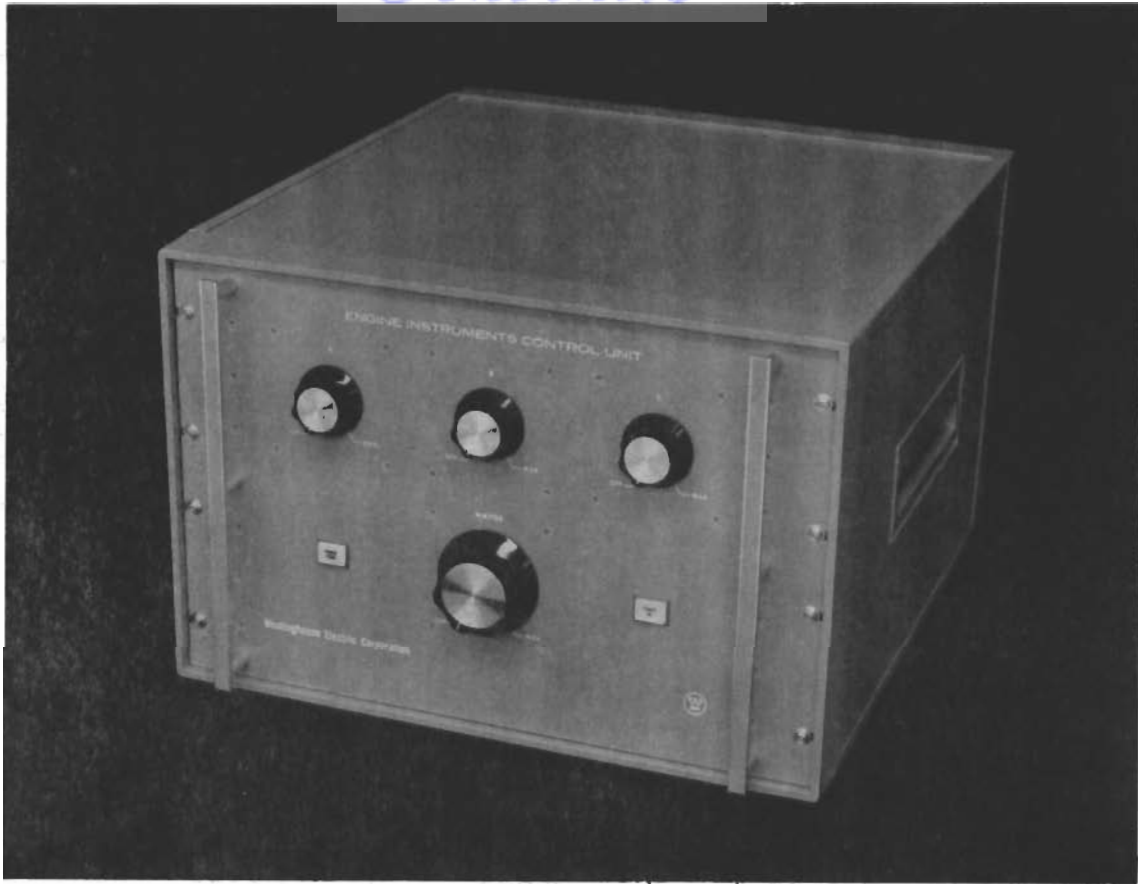


Figure 14. Control Unit and Power Supply

D. PACKAGING

1. High Density Display Connectors

A special electrical connector design was necessary to allow simple interchangeability of the EL display panels. Conventional connector designs using wiping sockets would require a great amount of insertion force for 758 pins, and an even greater withdrawal force.

This problem was solved by using conductive silicone rubber as the mating member. Phenolic blocks were drilled with the same hole pattern used in the ceramic header. See figure 15. A special female connector, consisting of a rod-shaped conductive silicone rubber insert held captive in a small diameter metal tube, was pressed into each hole. The rubber is about 1" in length, and compresses lengthwise when a header pin is placed in the socket. The electrical contact occurs between the end of the header pin and the end of the rubber insert. The dimensions of the rubber insert and its shore hardness were calculated such that the insertion force required for 758 pins would allow easy interchangeability of the EL panels using only finger pressure. The withdrawal force is nil, since the compressed rubber inserts tend to force the pins

out of the sockets.

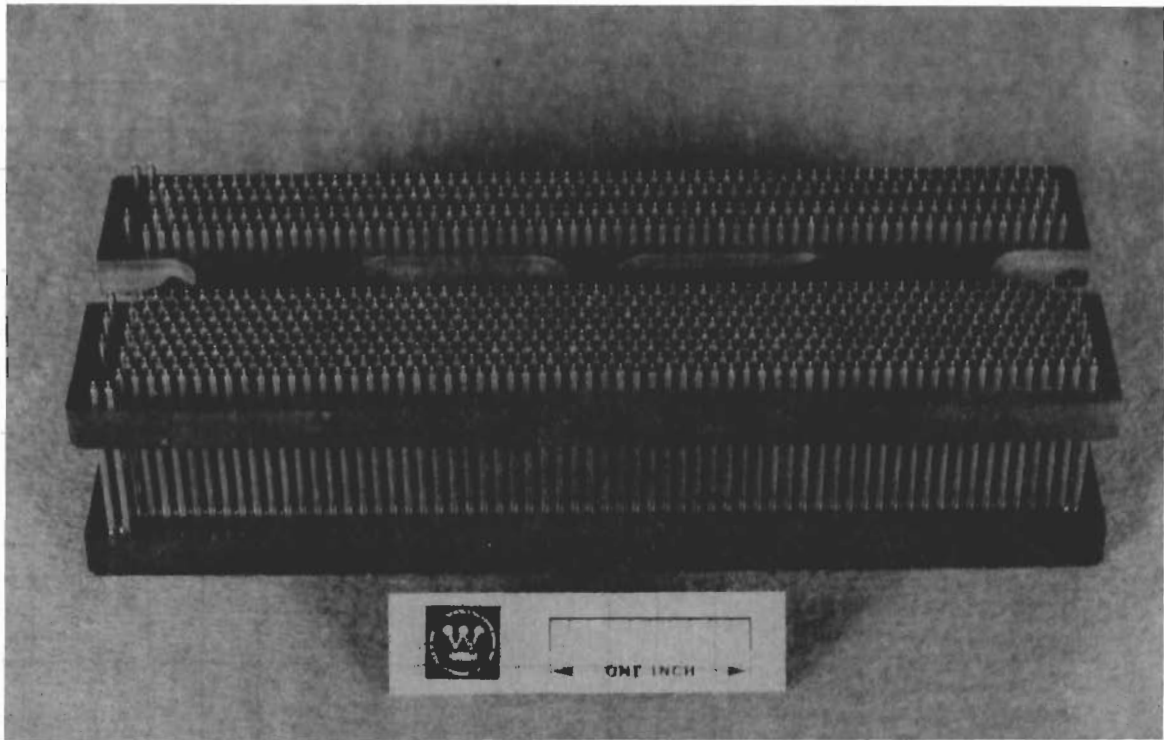


Figure 15. High Density Display Connector

Precautions have been taken to prevent voltage breakdown between adjacent connector sockets. The ends of the sockets are recessed into the phenolic block to lengthen the creepage path. All other adjacent metal areas are varnished with a high dielectric strength electronic varnish.

In its completed form, the connector is enclosed in a metal shell, which also acts as a mount for the EL panel. Alignment holes accept the two alignment pins protruding from the ceramic header, and guide the header into the connector. Threaded holes are provided for screws which hold the EL panel, together with a plastic overlay and bezel, firmly in place. Additional holes are provided for mounting the instrument into the aircraft instrument panel.

2. Electronics Packaging

Successful packaging of the engine instruments was accomplished by solving several problems. These were:

- a. Packing 120 integrated circuits, 144 transistors, 750 resistors, 1500 diodes, and 72 connector pins

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and sockets into 60 cubic inches. This is a packing density of 44 components per cubic inch.

b. Designing the circuitry layout to operate at 610 volts DC without voltage breakdown.

c. Allowing sufficient air flow between components to dissipate heat generated.

d. Maintaining rigid mechanical integrity.

After considering several approaches, it was decided to mount all the components for a single bargraph on one double sided circuit board with plated-through-holes. Thus, each engine instrument requires 6 boards. A board without components is shown in figure 16. Note that the board consists of a rigid epoxy-fiberglass board, to which a flexible cable has been bonded on each side. These flexible cables serve to connect the circuit board to the rear of the EL panel receptacle.

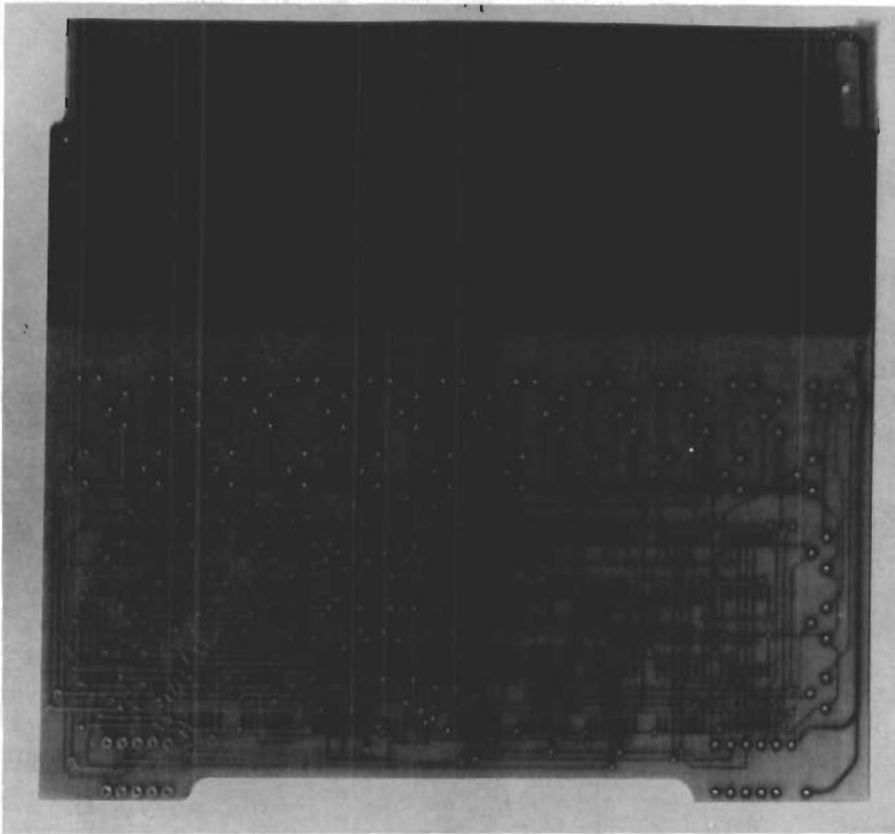


Figure 16. Logic Circuit Board
With Flexible Cables

A completed board with components is shown in figure 12. All components are mounted directly on the board, with the exception of the 250 diodes. These were pre-assembled into a single welded module, illustrated in figure 17.

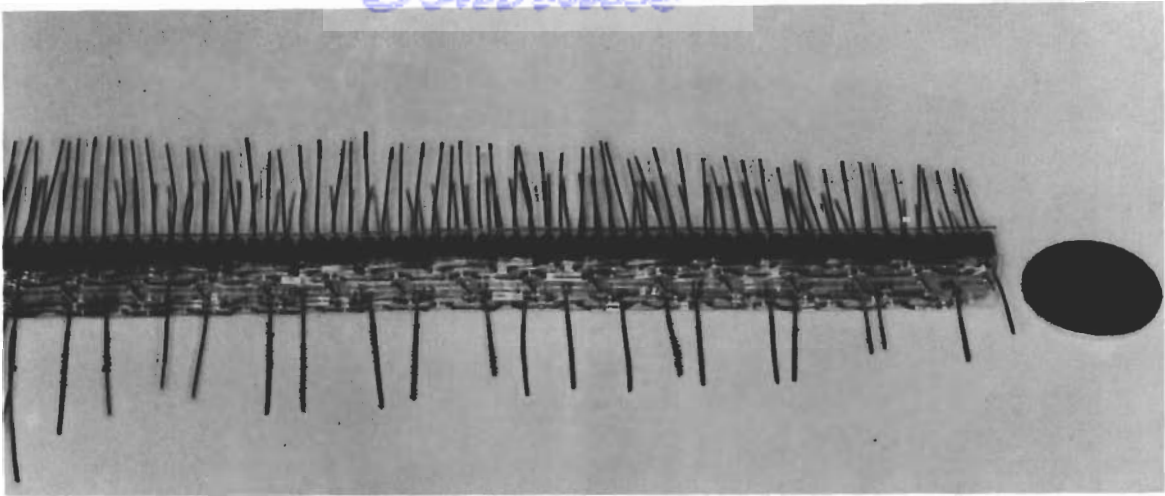


Figure 17. Welded Module Containing 250 Diodes

When assembled on the EL panel receptacle, the six circuit boards appear as in figure 18. The boards are free to flex on their flexible cables, allowing access for repair. A mother board plugs into the rear of the six boards, providing electrical access and mechanical rigidity. The final assembly is shown ready to insert into the enclosure in figure 19.

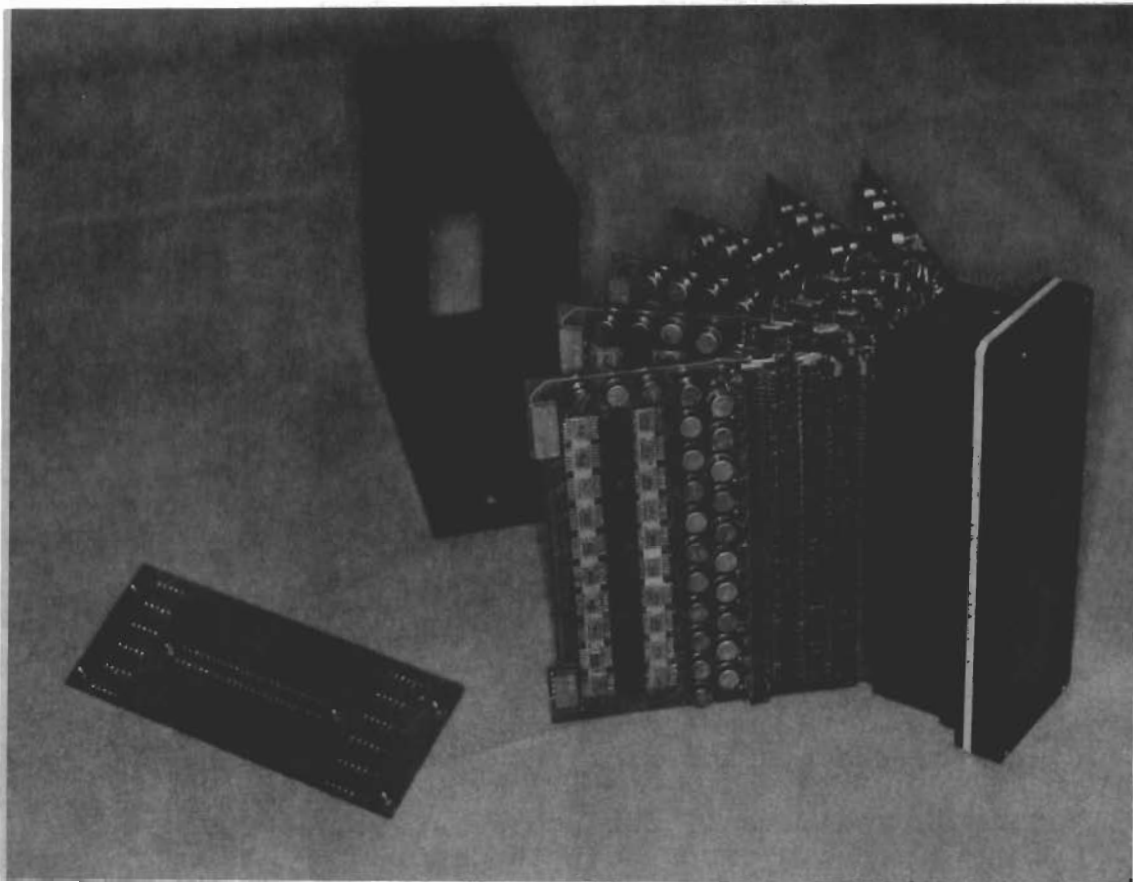


Figure 18. Electronics Module Showing Flexible Cable Feature

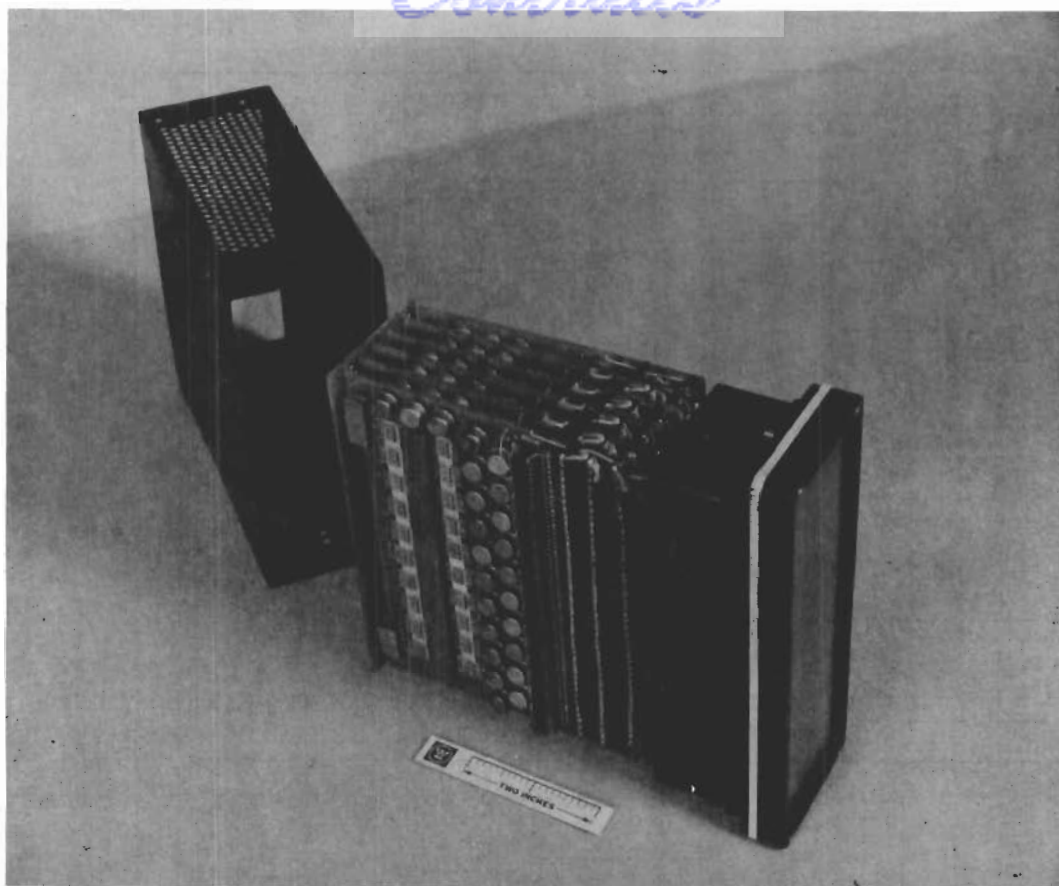


Figure 19. Assembled Electronics Module

The electronics modules are designed to allow interchangeability and flush side-by-side mounting. Three modules are shown mounted in this manner in figure 20.

3. Thermal Considerations

The components were arranged on the board so that adequate cooling could be provided. At the same time, the arrangement had to provide for the flow of information across the board. Information progresses from the mother board, through the integrated circuits, transistors, diodes, and resistors, in that order.

Maximum operating temperatures and heat dissipation also increase from the IC end to the resistor end. The warmest components, the resistors, were mounted as far as possible from the most sensitive components, the IC's. In addition, the mass of the EL panel connector serves to restrict heat flow from the resistors to the EL panel.

A thermal analysis of this configuration was completed prior to construction, both theoretically and empirically. It was apparent immediately that natural convection cooling would be inadequate or marginal. Consequently, a forced

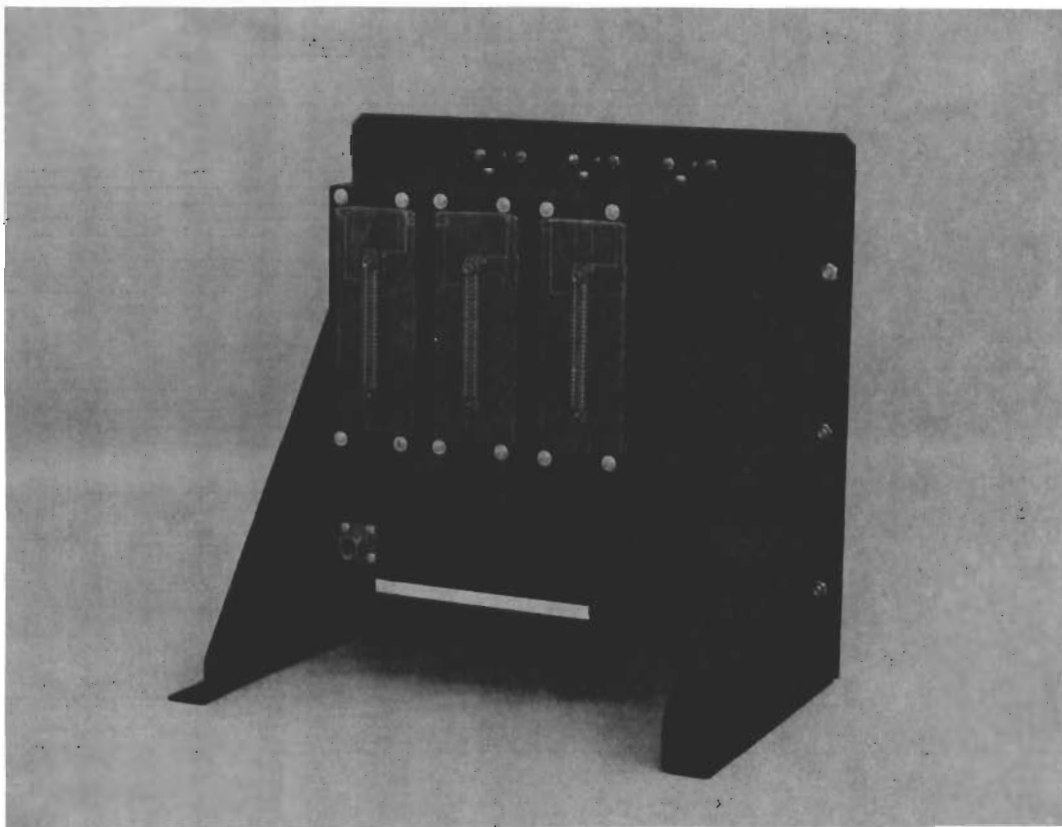
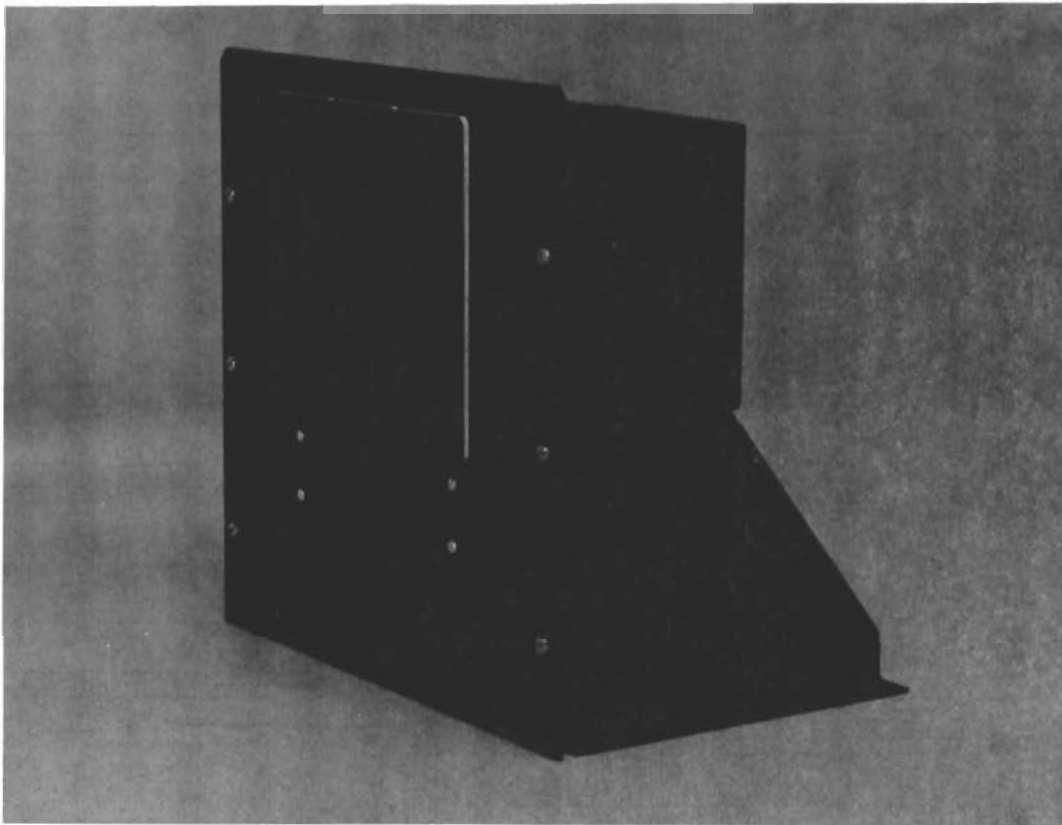


Figure 20. Mounted Engine Instruments

air system consisting of a small fan, plenum chamber, and filter has been incorporated. This unit mounts directly below the three engine instruments, and may be seen in figure 20. Electrical interlocks prevent system operation unless power is being supplied to this fan.

After construction, a thermal test was run under worst case operating conditions. (Maximum power is dissipated in the electronics when all EL elements are turned off). This test indicated that all components are adequately protected from thermal failure.

SECTION III

SUMMARY AND RECOMMENDATIONS

This development program has resulted in the successful fabrication of displays which have extended the state-of-the art in several areas. Several 750 element plug-in display panels and mating connectors were constructed which may be inserted and withdrawn with only finger pressure. The controlling electronics have been packaged in a space considerably smaller than that required by an equivalent mechanical device. The useful life of the display has been extended by the use of special phosphors. The overall result represents an important step forward toward the implementation of solid state displays for aircraft use. Human factors studies performed using these displays will provide much needed data concerning the usefulness of this type of information presentation. However, additional work should be undertaken toward further improvement.

Continuing improvement in electroluminescent phosphors should be sought to increase the useful life of displays. Current materials research clearly indicates that lifetimes of many years are achievable through careful investigation of light producing mechanisms. By deliberately eliminating competing mechanisms one by one, so that most of the input energy is available to produce light, very significant improvements will appear within the next few years. Phosphors which operate at low DC voltages may also become available which will greatly simplify the switching electronics.

Incorporation of these improvements as they become available should lead to general application of EL displays for military and commercial use.

Contrails

Hyper-Maintenance of Electroluminescence

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ABSTRACT

Electroluminescent ZnS:Cu becomes extremely deterioration-resistant after firing or refiring in pure sulfur. Additional air bake is permissible. The emission does not deteriorate toward zero, but toward a finite equilibrium which, in best cases, may be more than 50% of the original intensity. These "hyper-maintenance" phosphors permit high brightness (by excitation with high frequency) to be maintained over long time. The deterioration is considered to be due to sulfur vacancies diffusing from the particle surfaces into the interior.

The electroluminescence of powdered ZnS or (Zn, Cd)S phosphors embedded in an insulating medium and excited by an alternating electric field usually deteriorates with a rate which is nearly inversely proportional to the frequency, but which depends little or not on the amplitude of the exciting field (1). Therefore, it has become customary to characterize the maintenance behavior of a phosphor by the number of cycles required to deteriorate the emission intensity to 50% of its original value. This half-life is in the order of 10^7 to 10^8 cycles of continued operation in case of an ordinary ZnS:Cu,Cl phosphor embedded in a plastic dielectric and operated in dry air at room temperature. Thornton improved this half-life by a factor of roughly two to ten, i.e., up to about 10^8 to 10^9 cycles, by means of air baking (2). A similar improvement is achieved if the phosphor is embedded in a ceramic (instead of a plastic) dielectric. Jaffe observed that replacement of the chlorine by bromine resulted in another improvement by a factor of 5 or more (3) which extended to obtainable half-life up to 10^9 to 10^{10} cycles.

We discovered that green emitting ZnS:Cu,Br or corresponding (Zn,Cd)S phosphors become extremely deterioration resistance if they are fired, or refired, in an atmosphere consisting of approximately 100% sulfur vapor provided only that the phosphor is in actual contact with the sulfur when it cools down after firing. The latter condition is essential. If the phosphor is fired and cooled in sulfur, the maintenance is good. If it is fired in sulfur but cooled in nitrogen or argon, the maintenance is poor. If it is fired in argon but shortly refired and cooled in sulfur, the maintenance is good. It is permissible also to use Thornton's air bake procedure on sulfur-fired phosphors and, in fact, this combination gave the longest living phosphors.

The emission intensity of an electroluminescent phosphor so prepared usually does not deteriorate with time to zero but to a finite level and, in some cases, this finite level may be higher than 50% of the zero-hour intensity so that the "half-lives" of these phosphors appear to be infinitely long. This behavior was called "hyper-maintenance." The investigation on hyper-maintenance of electroluminescence is as yet not considered to be complete. Nevertheless, some observations and conclusions may be communicated.

Life tests on hyper-maintenance phosphors naturally require much time and, in contrast to ordinary electroluminescent phosphors, cannot be accelerated by excitation with a higher frequency since their deterioration is not inversely proportional to, but almost or

completely independent of, the exciting frequency. For this reason, hyper-maintenance phosphors show their best performance at high frequency (typically in the order of 10 kcps) where ordinary phosphors would deteriorate within a relatively short time. It is thus possible with hyper-maintenance phosphors excited with high frequency to maintain substantial brightness over long times. However, an accelerated deterioration of hyper-maintenance phosphors with increasing electric field strength was observed, also in striking contrast to the behavior of ordinary electroluminescent phosphors whose maintenance is almost or completely independent of the field strength.

The zero-hour brightness of a good hyper-maintenance ZnS:Cu phosphor usually is somewhat lower (roughly between 50 and 100%) than that of a standard ZnS:Cu phosphor. However, several per cent of the ZnS may be replaced by CdS (4) which, beside the well-known color shift of the emission, causes all traps to become somewhat shallower (5) and, therefore, an extension between the approximate proportionality between emission intensity and frequency up to higher frequencies. Hence, hyper-maintenance is most successfully combined with (Zn,Cd)S phosphors to be excited by high frequencies and, under this condition, even the zero-hour brightness of a hyper-maintenance phosphor may be better than that of a standard ZnS phosphor. Typical data are compared in Table I.

Some deterioration curves measured on (Zn,Cd)S:Cu phosphors are shown in Fig. 1 and 2. The phosphors corresponding to Fig. 1 are fired in sulfur and air baked. They differ only in their CdS concentration (and, hence, somewhat in their emission color) but not in their maintenance (exceeding the unavoidable limit of accuracy of the measurements). Each curve in Fig. 2 is the average of measurements on four phosphors containing Cl, Br, or I, respectively. All samples containing Cl and Br are green emitters while the four iodine containing samples emit blue. The superiority

Table I. Zero-hour emission intensity of a hyper-maintenance ZnS(90%), CdS(10%):Cu,Br phosphor compared with a standard ZnS:Cu,Cl phosphor

Phosphor	(Zn,Cd)S:Cu,Br (hyper-maintenance)		ZnS:Cu,Cl (standard)	
Frequency (cps)	60	5000	60	5000
Brightness (ft-L)	2.2	230	3.2	140
Quanta (arb. units)	3.1	320	5.3	300
Emission color	Yellow-green		Green	

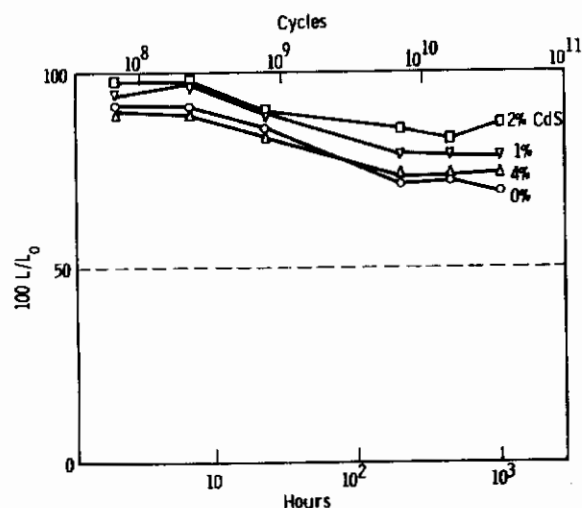


Fig. 1. Deterioration curves measured on several (Zn,Cd)S:Cu,Br phosphors, all sulfurized and air baked, operated in dry air at room temperature, 10 kcps.

of Br over Cl and I is clearly to be seen, and the approach of the curves corresponding to Br containing phosphors to finite and rather high brightness levels after long time of operation is quite obvious.

The observed effect of sulfur and air (i.e., oxygen) on the maintenance of electroluminescence gives a clue as to a possible mechanism of deterioration. It is assumed that the phosphor deteriorates because of a creation of deep traps due to sulfur vacancies which, under the combined action of temperature and electric field, diffuse from the particle surface into the interior. This assumption is in agreement with many observations:

(A) Indications are that a commonly observed glow peak at about -125°C is due to sulfur vacancies (5, 6). However, the latter must be expected to be double donors producing two glow peaks. Although considerable uncertainty still exists, the second level may be the one responsible for a frequently observed glow peak at about -50° to -20°C which was observed by Jaffe (3) to increase strongly during deterioration.

(B) The deterioration effect is temperature dependent and proportional to $\exp(-E/kT)$ where E is some

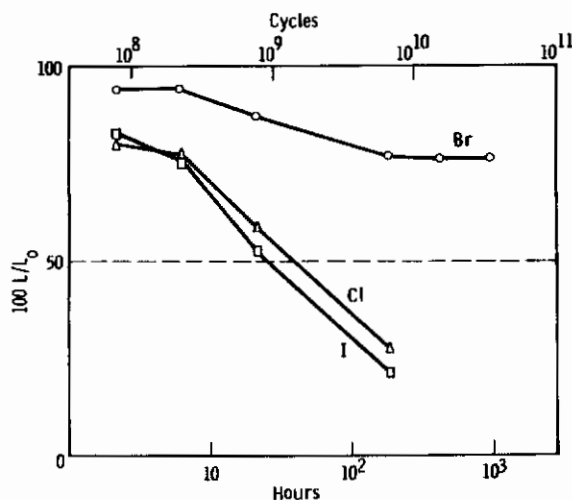


Fig. 2. Average deterioration curves (each 4 samples) measured on (Zn,Cd)S:Cu phosphors made with Cl, Br, or I, respectively. The phosphors are sulfurized and air baked, operated in dry air at room temperature 10 kcps.

energy (1). This indicates some kind of diffusion process involved, as already assumed by several workers.

(C) Maintenance improves with the particle size of the phosphor (1). Hence, an influence of a competition between particle surface (or surface-near parts) and the volume is indicated. Since glow peaks do build up during deterioration, a diffusion of something responsible for the additional glow peaks from the surface into the volume seems to take place.

(D) The most obvious way to improve the maintenance is to take care that little or no sulfur vacancies are available at the surface of a phosphor particle ready to diffuse into the volume, i.e., the surface atoms of each particle shall be mostly sulfur rather than zinc atoms. Such a phosphor particle has only a limited number of sulfur vacancies available ready to diffuse into the volume, so that its emission does not deteriorate toward zero but toward a finite level. The particle has then used up all available sulfur vacancies from its surface and remains at a finite brightness level without any further deterioration provided only that no new sulfur vacancies are created at the surface.

(E) Sulfur vacancies may be occupied also by other anions, e.g., by oxygen. Hence, a bake in oxygen [or in air (2)] improve the maintenance considerably while a bake in a neutral atmosphere (e.g., argon) has little or no effect.

(F) ZnSe phosphors can be expected to contain fewer anion vacancies on their particle surfaces than ZnS because selenium is less volatile than sulfur. Hence, the life time of electroluminescence of ZnSe phosphors can be expected to be better than that of ZnS phosphors, in general agreement with experience.

(G) Water may cause a break of the Zn-S bond between surface atoms of a ZnS crystal so that, originally, equimolar amounts of Zn and S are effectively removed from the crystal. The reaction requires a certain energy which may be supplied by ultraviolet irradiation or, in case of electroluminescence by the same electric field which excites the phosphor. Various, and not too well understood, further reactions between the liberated Zn, the S, and the surrounding (e.g., the water) are possible. These secondary reactions seem to cause a desulfurization of the particle surfaces. At least, liberated zinc frequently appears during exposure to ultraviolet (Lenard), or during electroluminescence in the presence of water (7), and can be observed visually as a very thin, dark deposit on the particle surfaces. Free surface zinc is identical to sulfur vacancies on the particle surfaces, ready to diffuse into the particles.

The proposed deterioration mechanism is accessible to a semiquantitative analysis. Let the time-average of steady-state emission be $L = \beta/M$ where M is the concentration of deep traps in the particle volume, and where β represents all other parameters. It must be supposed that the traps denoted by M are deep enough that a captured electron has little chance of escape during one cycle of the applied frequency. The concentration of sulfur vacancies at or near the surface may be C . When they diffuse into the volume, they decrease at a rate proportional to C which gives

$$C = C_0 \exp(-\alpha t) \quad [1]$$

where C_0 and α are constants, and t is the time. Simultaneously, the concentration of deep traps in the volume increases with the same rate

$$dM/dt = -dC/dt = \alpha C_0 \exp(-\alpha t)$$

which gives

$$M = M_0 + C_0 [1 - \exp(-\alpha t)] \quad [2]$$

Hence, the emission intensity at any given time, normalized to the "zero-hour" intensity L_0 , is

$$L/L_0 = M_0/M = \{1 + (C_0/M_0)[1 - \exp(-\alpha t)]\}^{-1} \quad [3]$$

This is a function of the ratio L/L_0 on the variable αt with one parameter, the ratio C_0/M_0 . The function is

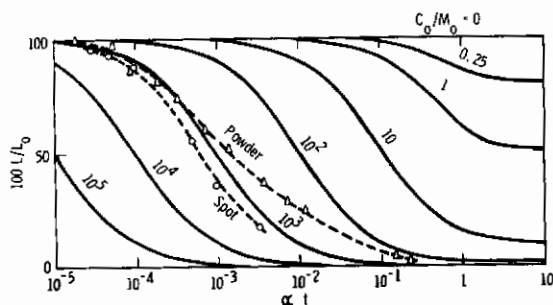


Fig. 3. Function of Eq. [3] for various values of C_0/M_0 (solid curves). Experimental values measured on a powder (standard ZnS:Cu,Cl, dashed curve) and at a single emitting spot in a phosphor particle (dotted curve) are plotted on an arbitrary time scale.

shown in Fig. 3 where the curves with the lowest ratios of C_0/M_0 , i.e., those representing the best maintenance, do approach rather substantial values of L/L_0 for $\alpha t \rightarrow \infty$. In contrast, the curves with high values of C_0/M_0 , representing poor maintenance, do not only go down very soon, they also approach finite values of L/L_0 very close to zero. In this case of $C_0 \gg M_0$, Eq. [3] reduces to $L/L_0 = 1/(1 + t/\tau)$ where $\tau = M_0/(C_0\alpha)$ which is the hyperbolic decay first reported by Roberts (8).

These equations represent ideal cases only. In practice, the situation most certainly is obscured by many complications so that a more detailed calculation seems to have little sense. One complication is the fact that all real phosphors contain particles of many different sizes and, hence, different deterioration rates. If the deterioration curve of such real phosphor containing a wide particle size distribution is analyzed, one finds that the curve becomes somewhat shallower but never steeper than the ideal curves described by Eq. [3]. This is also in agreement with experiment. Figure 3 shows the deterioration curve measured on a real

phosphor (a standard ZnS:Cu,Cl) which, indeed, is shallower than the ideal curves. The other experimental curve in Fig. 3 is that measured on a single emitting spot inside of one particle [measured by Haberland (9)]. One may safely assume that we are much closer to ideality in this case than in the case of a phosphor containing many particles and, indeed, the experimental curve follows the ideal ones very closely.

The proposed mechanism of a sulfur vacancy migrating from the particle surface into the volume is, of course, still a very crude approach to reality. Other atomic or ionic diffusions may occur besides those of sulfur vacancies. It is also possible that the assumption of only the outermost surface of a particle to be of influence is too extreme and that, in reality, surface-near layers several atoms deep are involved. These and other questions are still to be answered.

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Any discussion of this paper will appear in a Discussion Section to be published in the December 1966 JOURNAL.

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13. ABSTRACT The design and fabrication of a versatile set of solid state display components usable in engine instrument display configurations is described. The effort resulted in the development of plug-in electroluminescent display panels, each consisting of six columns of 125 elements at 25 lines per inch, plus scales and legends. The displays are hermetically sealed and are green or yellow, or a combination of green and yellow. Each column is controlled by a seven bit parallel binary word. Nine display panels, three sets of logic and switching electronics, an intensity control unit, and plastic overlay scales and legends were fabricated. These components may be arranged to simultaneously display the engine parameters of revolutions per minute (RPM), exhaust gas temperature (EGT), and engine pressure ratio (EPR) for a six engine VTOL aircraft. Distribution of this abstract is unlimited.			

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