HEWLETT PACKARD

APPLICATION NOTE 1017

LED Solid State Reliability

INTRODUCTION

The light emitting diode display technology offers many attractive features. Among them are ability to display information in red, yellow, green, or any combination of these colors; high performance devices readable in direct sunlight; and continuously variable intensity adjustment. One of the most common reasons that LED displays are designed into an application, however, is the high level of reliability of the LED display. Hewlett-Packard has taken a leadership role in setting reliability standards for LED displays and documenting reliability performance.

Reliability data is instrumental in choosing a device package and optimizing the performance of that device. This application note explains how to use the reliabilty data sheets published for Hewlett-Packard LED indicators and displays.

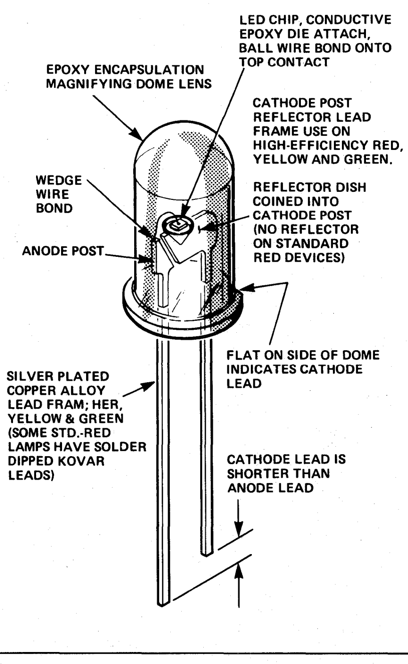

Figure 1. Construction Features of T-1 3/4 Plastic LED Lamp

The note begins with a description of LED indicator and display packages. Device failures are defined and explained. The parameters affecting useful life failure rate and mechanical test performance are discussed. As an example, the reliability of an LED display system is calculated.

HP Indicator and Display Packages

Hewlett-Packard has a wide variety of indicator and display components. Indicator products include solid state lamps, light bar annunciators, and bar graph arrays. Display products include numeric and alphanumeric devices.

Many LED devices have similar packaging and construction. T-1 3/4, T-1, rectangular, and subminiature LED lamps are epoxy encapsulated packages. Construction features of the T-1 3/4 lamp are illustrated in Figure 1. Hermetic LED lamps are air-gap devices, assembled in a TO-46 package.

Large seven segment numeric displays, light bars, and bar graph arrays are called stretched-segment packages. These devices are manufactured using the concept of stretching the light from an LED by diffusion and reflection. The LED chips are mechanically supported and electrically connected by a lead frame. The plastic housing, called a "scrambler", contains reflective cavities which act as light pipes. These cavities are filled with a diffusant loaded epoxy to provide uniform illumination at the emitting surface. Figure 2 illustrates the construction of a bar graph array.

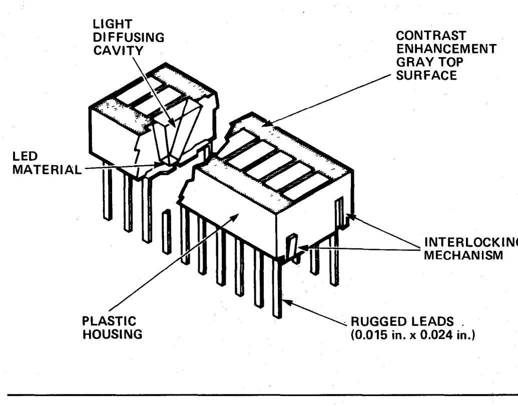

Figure 2. 10 Element Bar Graph (Cutaway)

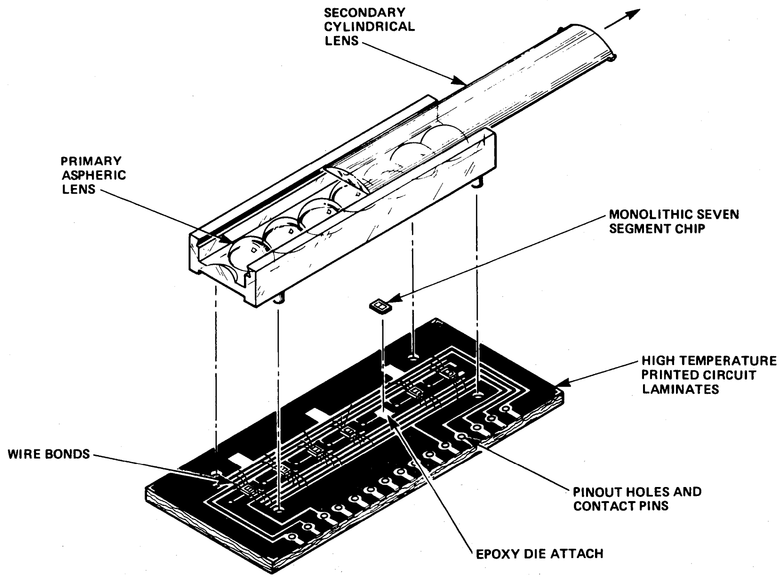

Figure 3. Mechanical Construction of a Monolithic Display Constructed on a PC Board with a Non-Immersion Lens

Monolithic displays include bargraph, numeric, and alphanumeric devices. Individual light emitting segments are formed by diffusing separate LED junctions into a single chip. In most cases, the monolithic display is magnified by an external lens. Monolithic displays can be classified into two basic categories according to whether the lens is of the immersion or non-immersion type. Immersion lenses are formed by molding an epoxy lens directly over the LED chip. Non-immersion lenses have a layer of air between the LED chip and the separately cast epoxy lens. Construction features of a monolithic display with non-immersion lens is shown in Figure 3.

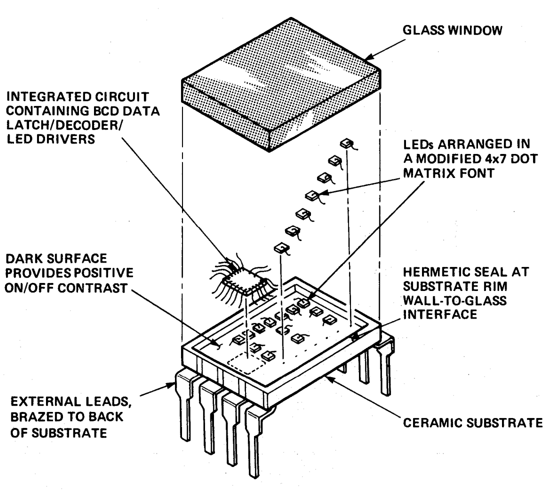

Figure 4. Construction Features of a Hermetic OBIC LED Display

Hewlett-Packard's dot matrix numeric displays have a modified 4x7 dot matrix font. This font allows both decimal numeric and hexadecimal devices. These devices feature an on-board integrated circuit (OBIC) which functions as a latch/decoder/driver. Construction features of the hermetic dot matrix numeric device are shown in Figure 4. In addition to the hermetic package, epoxy sealed and epoxy encapsulated packages are available for the dot matrix numeric displays.

The dot matrix alphanumeric display was designed by Hewlett-Packard to provide a high resolution information display subsystem. Each character of the four character package consists of a 5x7 array of LEDs which can display a full range of alphanumeric characters and other symbols (see Figure 5). Hewlett-Packard dot matrix alphanumeric displays provide on-board storage of decoded data plus constant current sinking drivers for each of the 28 rows in the four character display. These hermetic and epoxy sealed displays have construction features similar to the dot matrix numeric devices.

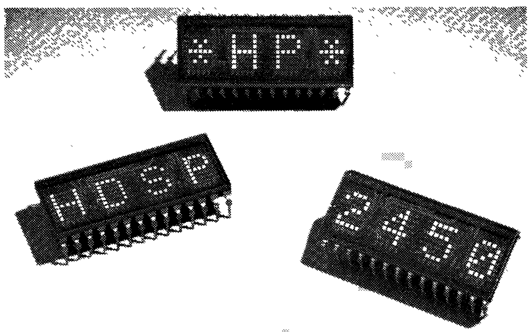

Figure 5. HDSP-2450 Series of Hermetic, Extended Temperature Range 5x7 Alphanumeric Displays

LED FAILURE RATE CHARACTERISTICS

Failure is defined as termination of the capability to perform intended functions. An understanding of how LED displays fail is essential to improving the reliability of the displays as well as that of the systems in which they are used.

LED devices can experience either parametric or catastrophic failure modes. A parametric failure occurs when the device fails to meet data sheet electrical or optical specifications. A parametric failure will not generally cause display system failure with typical drive circuits. Intensity degradation is an example of a parametric failure mode and is discussed later in this application note.

Catastrophic failures are defined as parameters exceeding data sheet limits to a degree which would cause display system failure. Catastrophic failures in lamps, stretched segment, and monolithic displays result in dim or unlit LEDs. The cause or failure mechanism for dim or unlit LEDs can be defective wire bonds, lifted LED die, cracked, or chipped LEDs. Failure mechanisms in dot matrix displays also include IC failures which result in incorrect font or input/output lines which do not meet electrical specifications.

Failure rate can be defined as the percent device failures per unit time of operation. Mean time between failure, MTBF, is simply the reciprocal of failure rate and is expressed in hours. Operating life of an LED display can be divided into three time periods each with a characteristic failure rate. Figure 6 shows the burn-in period, useful life period, and wearout period of operating life. During the burn-in or infant mortality period, failure rate decreases as weak components fall out.

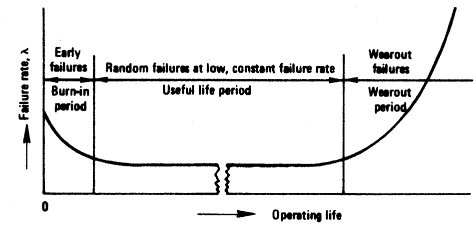

Figure 6. Typical Failure Rate Curve

During the useful life period which follows, failures occur at a low, constant rate. The failures that do occur are truly random and cannot be prevented by additional testing or burn-in of the components. Figure 7 presents useful life failure rates representative of LED lamps, stretched segment, monolithic, dot matrix numeric, and dot matrix alphanumeric displays. The format of Figure 7 is identical to the "Life Test" section of Hewlett-Packard's Reliability Data Sheets. The test conditions represent maximum allowable stress in order to generate worst-case failure rates. Total hours tested is the product of units tested times test hours/unit. The point failure rate is simply the number of failures divided by the total device hours. Units for failure rate are percent failures per 1000 hours of operation. If no failures occur during testing, the point failure rate is calculated assuming one failure.

Device	Description	Test Conditions[1]	Units Tested	Total Hours	Failed	Point Failure Rate % per 1K Hrs.[2]	90% Confidence Failure Rate % per 1K Hrs.[2]
HLMP-3750	Lamp	$T_A = 55°C$ I_F = Max.	16,270	17,275,630	1	0.006	0.023
HDSP-4830	10 Element Bar graph	$T_A = 55°C$ I_F = Max. All Seg. On	410	2,080,856	0	0.048	0.111
HDSP-6508	Monolithic Alphanumeric 8 Character Display	$T_A = 55°C$ I_F = Max. $P_{avg} = \frac{123\ mW}{Char}$	223	884,000	0	0.113	0.260
4N51	Dot-Matrix Numeric	$T_A = 100°C$ Numeric Cycle $V_{CC} = 5.0V$	576	806,000	0	0.124	0.285
HDSP-2000	Dot-Matrix Alphanumeric Four Character Display	$T_A = 70°C$ $V_{CC} = V_b = 5.25V$ $V_{col} = 3.5V$ $P_{avg} = \frac{210\ mW}{Char}$	360	870,000	3	0.345	0.768

NOTES:

1. T_A is ambient temperature during testing. I_F is the average forward current per LED. V_{CC} is the supply voltage. 5.25V is maximum recommended blanking input voltage, V_b. 3.5V is maximum recommended column voltage, V_{col}.
2. Failure rate per package.

Figure 7. LED Useful Life Failure Rates

Reliability data sheets specify 90% confidence level failure rate in addition to point failure rate. LED displays like other semiconductor devices have extremely low failure rates during useful life. As a result, very few device failures are experienced during reliability testing. Statistics tell us that the more device failures that can be generated during reliability testing, the closer the experimental failure rate is to the true device population average failure rate. For instance, if no device failures are generated during reliability testing, the true device failure rate may be very different than the point failure rate. The 90% confidence level failure rate means there is a 90% probability that the actual failure rate of a device will be better than the stated value. Hence, the 90% confidence level failure rate gives more confidence in reliability calculations than the point failure rate. The 90% confidence level failure rate is based on the statistics of the distribution of failures. The assumed distribution of failures is exponential versus time. This particular distribution is commonly used in describing useful life failures in LED devices and other semiconductor components.

Figure 7 illustrates that failure rate is related to package design and package complexity. Of the epoxy encapsulated devices, the 10 element bargraphs have a point failure rate that is about an order of magnitude larger than LED lamps. However, the HDSP-4830 10 element bar graph array has 10 times as many LED die as the HLMP-3750 lamp. The 8 character HDSP-6508 air-gap package has a comparable failure rate to the epoxy encapsulated HDSP-4830 though the HDSP-6508 has 144 wire bonds and the HDSP-4830 has 10 wire bonds. The construction of the 4N51 and HDSP-2000 displays yields an impressive useful life failure rate with a comparatively large number of LED die per character. Note that the 4N51 is a single character device while the HDSP-2000 is a four character package.

FAILURE RATE PREDICTION

To obtain useful life failure rates in a reasonable amount of time, a higher-than-normal stress is applied to a sample quantity of devices known to represent the device population. This is known as accelerated life testing. The most common stress factor used is temperature. Failure rate prediction is the estimation of normal operating temperature failure rates based on maximum operating temperature failure rate.

The Arrhenius Model is an experimentally proven mathematical expression for failure rate prediction. The model includes the effect of temperature and the activation energy of a failure mechanism, permitting it to be used to predict failure rates at normal operating temperatures based on tests performed at above-normal device junction temperatures:

$$\lambda_1 = \lambda_2 e^{-\frac{E}{K}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

where λ_1 = failure rate at junction temperature T_1
λ_2 = failure rate at junction temperature T_2
T = junction temperature in °K
E = thermal activation energy in electron volts (eV)
K = Boltzman's constant (8.617×10^{-5} eV/°K)

Recall that °K = °C + 273

Application of the Arrhenius Model requires calculation of device junction temperature both for the reliability test and for the actual field operating conditions. LED junction temperature is a function of ambient temperature, power dissipated in the junction, and thermal resistance:

$$T = T_A + P_D\,(R\theta_{J\text{-}A})$$

where T = LED junction temperature in °C
T_A = ambient temperature in °C
P_D = power dissipated in LED junction in watts
$R\theta_{J\text{-}A}$ = thermal resistance junction-to-ambient in °C/W.

Activation energy is a constant which defines the dependence of failure rate on junction temperature for a failure mechanism. Several failure mechanisms exist for LED indicators and displays. Failure rate predictions on Hewlett-Packard's reliability data sheets are conservatively based on a failure mechanism with small activation energy. Using the smallest activation energy for failure rate prediction brings about the largest failure rates at any junction temperature below the tested condition. Interconnection failure mechanisms, such as defective wire bonds, have the smallest activation energy of typical LED device failure mechanisms. MIL-HDBK-217C specifies an activation energy of 0.43eV for interconnection failure mechanisms in hybrid microelectronics. A 0.43eV activation energy is used for failure rate prediction in Hewlett-Packard's reliability data sheets for indicators and displays.

Figure 8 shows the predicted improvement in failure rate and MTBF that can be realized by reducing the junction temperature of the 4N51 series of displays. The failure rate and the MTBF improve by over an order of magnitude as ambient temperature is reduced from 100° C to 30° C.

Ambient Temperature - °C	**Junction Temperature - °C**	**Point**	
		MTBF - Hours	**Failure Rate/ 1K Hours Operation**
100	130	806,000	0.124%
90	120	1,108,000	0.090%
80	110	1,549,000	0.065%
70	100	2,205,000	0.045%
60	90	3,200,000	0.031%
50	80	4,745,000	0.021%
40	70	7,199,000	0.014%
30	60	11,201,000	0.009%

Figure 8. Failure Rate Prediction for LED Dot Matrix Numeric Displays

Reducing the product of power dissipated and thermal resistance can have effects on reliability similar to reducing ambient temperature. Blanking the display wherever possible can reduce junction temperature significantly. Junction-to-ambient thermal resistance is the sum of junction-to-case plus case-to-ambient thermal resistance. Junction-to-case thermal resistance is defined by the display package design and is specified on the device data sheet. The display system designer, however, has control over case-to-ambient thermal resistance. For devices such as lamps, stretched-segment, and monolithic devices, the primary thermal path from the LED junction is through the device cathode leads. Providing a maximum printed circuit board trace width to the cathode lead is one way to reduce thermal resistance in these devices. Heat-sinking the substrate of dot matrix devices is a technique that will improve their reliability.

DISPLAY SYSTEM RELIABILITY

Reliability is defined as the probability that a device will perform its intended function for a specified period of time under stated conditions. When failure rate remains constant, as in the useful life period, display system reliability may be predicted by the exponential distribution:

$$R = e^{-t(\lambda_1 + \lambda_2 + \lambda_3 + \ldots)}$$

where R = reliability or probability of survival
t = mission time or actual utilization time[1]
λ_i = component (i) useful life failure rate

As an example, the useful life reliability of the LED display system in Figure 9 will be calculated. This eight digit numeric display uses Hewlett-Packard's 4N51 series of dot matrix displays. The on-board-integrated-circuitry on these devices minimizes display system component count. On-board circuitry includes a latch, a BCD to dot matrix decoder, and LED drivers.

For this example let us assume that the display system in Figure 9 will be operational 8 hours/day and 5 days/week for 5 years. Mission time can then be calculated:

$$t = \left(\frac{8 \text{ hrs.}}{\text{day}}\right)\left(\frac{5 \text{ days}}{\text{week}}\right)\left(\frac{52 \text{ weeks}}{\text{year}}\right)(5 \text{ years})$$

$$t = 10.40\text{K hrs.}$$

Let us also assume that the display system will be used in ambient temperature of 55° C. The next step is to calculate the sum of the individual component failure rates. From Figure 8 the point failure rate for each of the 4N51 series displays is 0.026% per 1000 hours of operation at 55° C ambient. Point failure rate for each of the LSTTL components is .007% per 1000 hours of operation.[2] Point failure rate for the microcomputer is .043% per 1000 hours of operation.[3] The sum of individual component failure rates, λ_{total} is then:

$$\lambda_{total} = (.043\%/1\text{K hrs.}) + 2(.007\%/1\text{K hrs.}) + 8(.026\%/1\text{K hrs})$$

$$\lambda_{total} = .265\%/1\text{K hrs.}$$

The probability of survival of the 8 digit LED display system is then:

$$R = e^{-t(\lambda_{total})} = 97\%$$

[1]Mission time cannot exceed the useful life of any component when calculating system reliabilty.
[2]1981 cumulative data for LSTTL components from Texas Instruments. A .43 eV activation energy is assumed.
[3]Data taken from Intel reliability report RR-25, December, 1979. A .3 eV activation energy is assumed.

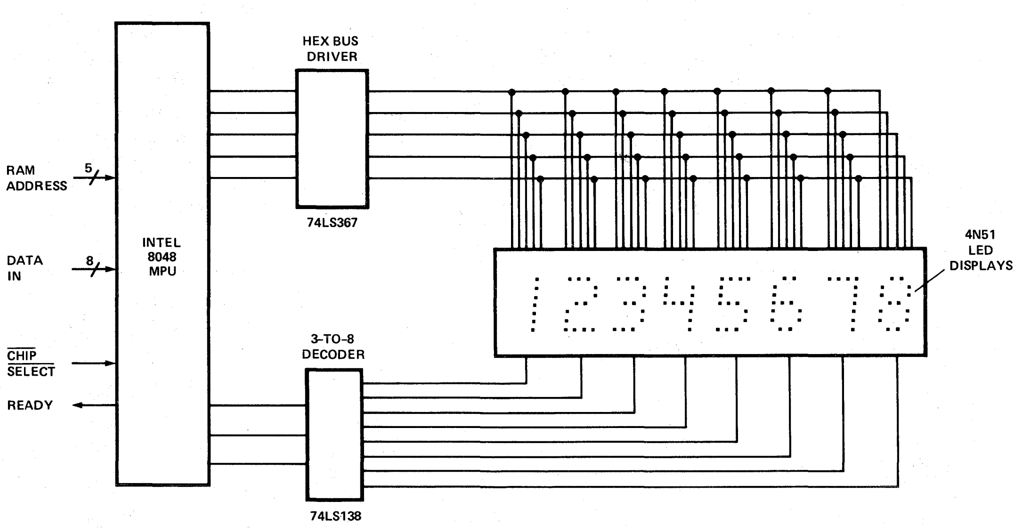

Figure 9. 4N51 Display System

INTENSITY DEGRADATION

Intensity degradation is a long term wearout mechanism in LED displays. Hewlett-Packard defines a 50% reduction in intensity as a parametric failure mode. A 50% change in intensity is one that the human eye can easily recognize. Figure 10 presents normalized luminous intensity vs. stress time for red LED displays. Figure 10 represents averaged data because the rate of intensity degradation is not identical for all LEDs. The logarithmic stress time axis implies that the rate of intensity degradation decreases as time increases. Even curve D, which represents operation at 200% of maximum ratings, does not bring about noticeable degradation after 10,000 hours stress time. Curves A and B indicate that increased current density results in more rapid degradation. Curves B and C indicate that junction temperature has little effect on rate of degradation. Curve C represents degradation at absolute maximum drive levels. Curves A through D are for direct drive of LEDs. Strobed operation brings about approximately equal rates of degradation for equal average currents. When Hewlett-Packard displays are driven at maximum rated current, the rate of high efficiency red and green degradation is about the same as the rate of red. Yellow degradation is about two times the rate of red.

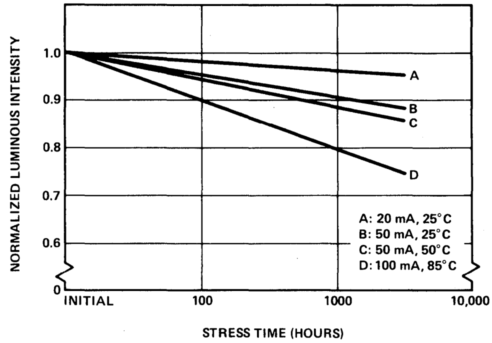

Figure 10. Intensity Degradation vs. Stress Time

MECHANICAL AND ENVIRONMENTAL TESTS

Reliability data sheets for Hewlett-Packard's standard products include life test data, failure rate prediction, mechanical, and environmental test performance. Tests are performed in accordance with the latest revisions of MIL-STD-750 and MIL-STD-883. Mechanical and environmental test data for the Hewlett-Packard 5082-7350 dot matrix numeric display is given in Figure 11. The 5082-7350 is an epoxy sealed, air-gap package.

Mechanical tests are performed to insure package integrity. Solderability determines the ability of the device to be soldered via conventional techniques. With no preparatory cleaning the device leads are immersed in flux for 5 to 10 seconds, then into molten solder which has been stabilized to 260° C. After immersion in a solder bath for the specified time and cooling for 5 minutes, devices are examined using 10X magnification. Pinholes and voids must not be concentrated in one area and must not exceed 10% of the total area.

Test	MIL-STD-883 Reference	Test Conditions	Units Tested	Total Failed
Solderability	2003	Sn 60, Pb 40 Solder at 260° C for 5 sec.	25	0
Temperature Cycling	1010	500 cyc., -55 to 100° C electrical & leak failures	45	0
Thermal Shock	1011	50 cycles, 0 to 100° C, 3 sec transfer	25	0
Moisture Resistance	1004	10 days, 90-98% RH, -10 to 65° C, non-op	25	0
Shock	2002	5 blows each X1, Y1, Z1 axis 1500g .5 msec.	25	0
Vibration, Variable Frequency	2007	3, 4 min cycles each X, Y, Z axis at 20g min 20 to 2000 Hz	25	0
Constant Acceleration	2001	20,000 g's, Y1 axis, 1 minute	25	0
Terminal Strength	2004	Condition B2, 3 bends > 15°	25	0
Salt Atmosphere	1009	35° C fog for 24 hours	25	0
Electrostatic Discharge	3015	5 discharges each pin 1000V, 500Ω, 300 pF	5	0

Figure 11. Mechanical Tests 5082-7350 Series Displays

Temperature cycling tests are performed to define a thermomechanical life. Various parts of the optoelectronic device are in contact such as the substrate, LED die, and bond wires. If coefficients of thermal expansion are not well matched, temperature changes are accompanied by physical strain. The magnitude of the physical strain increases as the magnitude of the temperature excursion increases. Probability of failure increases with the number of temperature cycles. Seven segment displays have less than 1% failure after 500 cycles from -40 to +85° C. Air-gap packages such as the 5082-7350 offer improved temperature cycling performance over epoxy encapsulated displays. With no encapsulant epoxy, there is less physical strain on wire bonds and die attachments.

The thermal shock test exposes devices to alternate extremes in temperature. Parts are transfered from liquid at 0° C to liquid at 100° C. Airgap packages can withstand a larger number of thermal shocks than epoxy encapsulated devices.

If the device package material is not impervious to the diffusion of water vapor, long term exposure to high humidity will eventually subject the active elements to high humidity. Humidity can lead to failure from corrosion of the active elements or from increased surface leakage currents. The moisture resistance test achieves accelerated effectiveness through temperature cycling. Temperature cycling provides alternate periods of condensation and drying which accelerate the development of corrosive processes.

Hermetic LED displays are packaged using a glass to metal or glass to ceramic seal. These products are impervious to moisture and meet hermeticity testing to prescribed levels. In addition, Hewlett-Packard makes displays which have an epoxy seal such as the 5082-7350 and the dot matrix alphanumeric displays. These displays are also capable of passing fine and gross leak hermeticity tests.

The shock test determines the ability of LED components to withstand shock of the same severity as that produced by collision impacts, near-miss gunfire, or underwater explosions. A 1500 G shock would be approximately equal to the shock that a device would experience if it were mounted to a rigid, 40 pound enclosure and dropped from three feet onto a concrete floor.

Vibration and acceleration tests expose parts to the predominant frequency ranges and magnitudes that may be encountered during field service.

In addition to standard LED display products, Hewlett-Packard offers a high-reliability product line. Special electrical and mechanical testing is performed on standard Hewlett-Packard displays to comply with the requirements of the U.S. Military qualified parts list, Hewlett-Packard defined specifications, or customer defined specifications. The special testing can be performed on a lot qualification basis, 100% screen, or a combination of lot qualification and 100% screen. Based on estimates in MIL-HBDK-217C, lot qualification testing can improve useful life failure rates by as much as five-fold. One hundred percent screening is designed to eliminate infant failures.

Display components can have significant impact on the reliability of an electronic system. System reliability is a function of the sum of individual component failure rates. It takes a combination of good design, quality pieceparts, and tightly controlled production processes to yield reliable display components. Components which appear to have the same design may have very different mechanical and operating life performance characteristics. Hewlett-Packard has reliability data sheets available for indicator and display products from your local field sales office.