Reliability and the Electronic Engineer

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There is probably no more crucial issue than Reliability at the system level to both the component vendor and the systems house, and surprisingly there is very limited understanding of the mechanisms that yield to failures. This paper sets forth simply what the electronic Design Engineer needs to know with regard to calculating a given component's Mean Time Between Failure (MTBF), Failure Rate (FR), Failures In Time (FITS), and what all this jargon means.

Reliability Overview

Contrary to popular opinion, all integrated circuits begin "dying" the moment they are born, and in general, raising the average junction temperature will result in increasing the failure rate. The Arrhenius relationship which is common in many physical and chemical processes has been found to fit the failure rates in IC's as well. Equation 1 expresses the relative failure rate for temperatures, T1 and T2, and the ratio, R2/R1, is often referred to as the Acceleration Factor.

$$\frac{R2}{R1} = e - \left(\frac{EA}{KT2} - \frac{EA}{KT1}\right) \qquad \text{(EQ. 1)}$$

Where:

R = Failure Rate

EA = Activation Energy (typically 0.5eV to 1eV)

T = Absolute Temperature (°K)

K = Boltzmann's Constant (1.38×10^{-23})

One very significant issue is the assumed Activation Energy. Illustrated in Figure 1 is the Failure Rate for 0.5eV and 1eV as a function of temperature. Significantly, at junction temperatures above 100°C, the failure rate at 1eV is 1,000 times that of 0.5eV.

Reproduced in Figure 2 are the reported Activation Energies for various kinds of components. At Elantec, we use 0.8eV to 1.0eV, which is best suited to the kinds of processes that we employ.

In order to calculate MTBF we will also need to obtain reliability data from the IC vendor. Virtually all manufacturers routinely run life tests on devices which span their product line and package repertoire. Life test usually means placing devices in a burn-in oven, under power, at temperatures which are typically set at 125°C for 1,000 hours or more. Shown in Figure 3 is data taken from a slice in time for a variety of devices manufactured by Elantec. As indicated, a total of 692 devices were tested at 125°C, and the total device hours were 867,520. Failure Rate and MTBF are given by:

$$FR = \frac{\text{No. of Failures}}{\text{Total Device Hours}} \qquad \text{(EQ. 2)}$$

$$MTBF = \frac{1}{\text{Failure Rate}} \qquad \text{(EQ. 3)}$$

Since we had two failures in 867.5K hours, the FR is 2.3 per million hours, and the MTBF is 433.8K hours (at 125°C). Suppose we wanted to know what the FR and MTBF would be at 25°C. Using Equation 1 and assuming that the Activation Energy is 1eV, we calculate an Acceleration Factor of:

$$\frac{R2}{R1} = e - \left(\frac{EA}{KT2} - \frac{EA}{KT1}\right)$$

$$= e - \left[\frac{1.6E\text{-}19}{1.38E\text{-}23}\left\langle\frac{1}{398°K} - \frac{1}{298°K}\right\rangle\right]$$

$$= 17,698$$

Then we multiply the 125° MTBF of 433.8 hours by 17,698 to obtain 7.7 billion hours and corresponding FR of 0.13 per billion hours.

Another often heard term is FITS which stands for Failures in Time and is defined as the number of failures per billion hours. For the example above, FITS is equal to 0.13.

The Real World

It turns out that the foregoing analysis isn't quite right, and the reason is that our calculation was based on a relatively small sample of devices. To prove the point without thinking about it too much, suppose that we had observed zero failures in the earlier example. That would lead us to the false conclusion that the MTBF was infinite and the FR was zero. What do we do now?

Fortunately, we can turn to Poissan statistics to bail us out. And we all thought that the statistics course in school would never be of any benefit. Equation 4 predicts the probability (of failure), P(X), of finding X failures in a sample whose average failure rate is A.

$$P(X) = \frac{e^{-A}A^{X}}{X!} \qquad \text{(EQ. 4)}$$

P(X) = Probability (of failure)

X = Failures observed

A = Average number of failures

Suppose we ran a large number of such life tests (say 1,000) which actually had an average failure rate of 3.12. Figure 4 summarizes the statistics of Equation 4. The table predicts that 4.4% of the time (or in 44 life tests) we would observe no failures, 13.7% of the time we would observe one failure, 21.5% of the time we would observe 2 failures, etc. We could say that 39.6% of the time we would observe either no failures, 1 failure, or two failures. Probably a better way of looking at this data is that in 1,000 tests we would anticipate observing more than 2 failures 60.4% of the time. Therefore, if we ran only one test and observed 2 failures, we would have to say, "with a confidence level of 60.4%, that the actual failure rate is 3.12."

We should use 3.12 average failures in all of our calculations instead of our 2 observed failures, and we should always add, "to a 60% confidence level" to all the numbers we quote. So, our experimental data from Figure 3 boils down to an MTBF of 867,520 hours divided by 3.12 or 278,051 hours at 125°C to a 60% confidence level.

Fortunately, we don't have to go through all this convoluted reasoning each time we want to make calculations because the statisticians have calculated fudge factors for us which are summarized in Figure 5.

Note that this solves our "zero observed failure problem" by assigning 0.916 average failures to the case of zero observed failures to a 60% confidence level.

On the other hand, 60% confidence level doesn't sound very confident. If we wanted to be more conservative, we could use a fudge factor from a 90% confidence level. Now our 3.12 average failures become 5.3, and that makes our failure rate and MTBF look a lot worse. Most semiconductor manufacturers have historically used 60% confidence levels.

The Bottom Line

To ascertain the system level FR and MTBF, we must perform a thermal analysis for a given device to calculate average junction temperature. We will then use the Arrhenius Relationship and the IC manufacturer's reliability data and Activation Energy to predict FR and MTBF. For example, an EL2044 packaged in a plastic DIP is operated from 15V rails at an ambient temperature of 70°C. The output voltage is 2V and the load, R_L, is 150Ω; the feedback resistor, R_F, is 300Ω. The quiescent power, Pq, is simply:

$$Pq = (V+ - V-)(Is) \qquad \text{(EQ. 5)}$$

The power dissipated due to load, Pl, is:

$$P1 = (V - V_{OUT})\left(\frac{V_{OUT}}{R_L \parallel R_F}\right) \qquad \text{(EQ. 6)}$$

The total power is given by:

$$Pt = Pq + Pl \qquad \text{(EQ. 7)}$$

From the datasheet, we obtain an Is of 7.6mA, so Pq is 228mW. Pl is 260mW, and Pt is equal to 488mW.

$$T_J = (Pt)(\theta_{JA}) + T_A \qquad \text{(EQ. 8)}$$

θ_{JA} obtained from the datasheet is 95°C per watt which results in a junction temperature of 116°C. The datasheet states that the maximum allowable junction temperature is 150°C, so the application is okay from that point of view.

The life test circuit for the EL2044 indicates that the test is done with 15V supplies and essentially no load at 125°C under "ambient" conditions; hence, the life test data reported by Elantec would be under these conditions. The average power dissipation using Equation 5 would be 228mW, and the corresponding junction temperature per Equation 8 would be 147°C.

We can now examine the predicted impact on MTBF and FR resulting from operating the junctions at 116°C. Using the Arrhenius Relationship we derive an Acceleration Factor of:

$$AF = \frac{R2}{R1}$$

$$= e - \left[\frac{1.6E\text{-}19}{1.38E\text{-}23}\left(\frac{1}{389°K} - \frac{1}{420°K}\right)\right]$$

$$= 9.0$$

The corrected (for finite sample size) MTBF with a 60% Confidence Factor that we calculated earlier was 278K hours. To obtain the "worst case" MTBF, simply multiply by 9.0 to obtain 2.5 million hours with a corresponding Failure Rate of 0.4 per million hours.

2.5 million hours seems like a long time, but presumably there could be many devices in the system. If, for example, there were 100 amplifiers, we would expect an MTBF of about 34 months.

The moral of the story is that heat is the implacable enemy of integrated circuits. In order to insure the system reliability, junction temperature must be minimized by every available means. This might mean putting a heat sink on the package or reducing the power supply voltages, or increasing the load resistance, or all of the above.

In summary, in order to calculate MTBF or FR in a system, we need to determine the device's average junction temperature in our system, obtain the Activation Energy and Failure Rate data from the vendor, calculate the Acceleration Factor for our specific application, and correct the failure rate for finite sample size at a Confidence Factor commensurate with the system's needs.

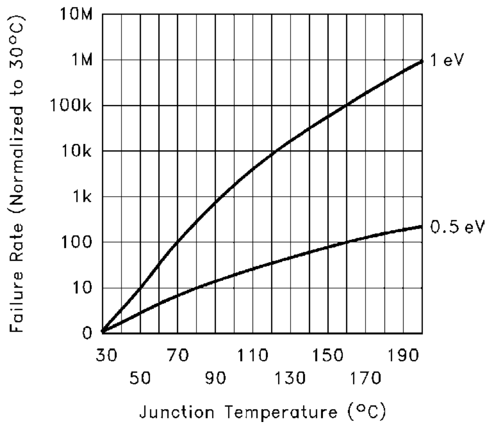

FIGURE 1.

Activation Energy

COMPONENT AND MECHANISM	REPORTED EA (EV)	
	MAIN POPULATION	WEAK POPULATION
Silicon Semiconductor Devices		
Silicon Oxide and Si/Sio2 Interface		
Surface Charge Accumulation, Bipolar	1.0	
Surface Charge Accumulation, MOS	1.2	
Slow Trapping Charge Injection	1.3–1.4	
Metalization		
Electro-Migration	0.5–1.2	
Corrosion (Chemical, Galvanic, Electrolytic)	0.3–0.6	
Bonds		
Intermediate Growth Al/Au	1.0	
N-Channel Si Gate Dynamic RAM		
Slow Trapping	1.0	
Contamination	1.4	1.4
Surface Charge	0.5–1.0	
Polarization	1.0	
Electro-Migration	1.0	
Oxide Defects	0.3	0.3
FAMOS Transistors		
Charge Loss	0.8	

Source: Burn-In, F. Jensen, N. Petersen, Wiley and Sons, New York, 1982

Partial Summary of Elantec Reliability Data

DEVICE TYPE	QUANTITY	FAILURES	HOURS	DEVICE-HOURS
EL2020CN	45	0	1,000	45,000
EL2020CN	45	0	1,000	45,000
EL2028J	105	1	1,000	105,000
EL2020J/883	105	0	1,000	105,000
EL2030CN	77	1	1,234	95,020
EL2033CN	105	0	1,000	105,000
EL2037CM	105	0	2,500	262,500
EL2190L/883	105	0	1,000	105,000
TOTALS	692	2	9,732	867,520

Poisson Distribution Table

X	AVERAGE = X!	3.12 P(X)	SUM (P(X))
0	1	0.044157	0.044157
1	1	0.137770	0.181927
2	2	0.214921	0.396849
3	6	0.223518	0.620367
4	24	0.184344	0.794712
5	120	0.108790	0.903503
6	720	0.056571	0.960074
7	5040	0.025214	0.985289
8	40320	0.009833	0.995123
9	362880	0.003409	0.998532
10	3628800	0.001063	0.999595
11	39916800	0.000301	0.999897
12	4.8E+08	0.000078	0.999975
13	6.2E+09	0.000018	0.999994
14	8.7E+10	0.000004	0.999998
15	1.3E+12	0.000000	0.999999

Average Failures Confidence Level

NUMBER OF FAILURES	50%	60%	70%	80%	90%	95%
0	0.693	0.916	1.204	1.990	2.305	2.990
1	1.678	2.022	2.439	2.990	3.890	4.740
2	2.674	3.120	3.615	4.280	5.300	6.300
3	3.672	4.160	4.762	5.500	6.700	7.750
4	4.671	5.250	5.891	6.700	8.000	9.150
5	5.970	6.300	7.005	7.900	9.250	10.50
6	6.669	7.350	8.111	9.100	10.55	11.85
7	7.669	8.400	9.209	10.25	11.75	13.15
8	8.669	9.450	10.30	11.40	13.00	14.45
9	9.668	10.50	11.38	12.50	14.20	15.70
10	10.66	11.55	12.47	13.65	15.40	16.95