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Methods for Calculating Failure Rates in Units of FITs

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Introduction

The calculation of failure rates is an important metric in assessing the reliability performance of a product or process. This data can be used as a benchmark for future performance or an assessment of past performance, which might signal a need for product or process improvement. Reliability data are expressed in numerous units of measurement. This document uses the units of FITs (Failures-In-Time), where one FIT is equal to one failure occurring in 10^9 device-hours. These methods are assembled here to provide a reference to the way failure rates are calculated in FITs.

Most of these methods only apply to constant failure rates. They assume that a χ^2 distribution is a reasonable approximation of the failure distribution over time. The examples given use failures that exhibit an Arrhenius behavior. Other failure models can also be applied to these methods, but care must be used for those models that do not simulate a constant failure rate.

Please note that the methods described in this document represent simplified ways of calculating failure rates using various forms of data. More detailed methods exist in other publications, such as EIA/JESD63 Standard Method for Calculating the Electromigration Model Parameters for Current Density and Temperature and JESD37 Standard for Lognormal Analysis of Uncensored Data and of Singly Right-Censored Data Using the Persson and Rootzen Method.

METHODS FOR CALCULATING FAILURE RATES IN UNITS OF FITs

(From JEDEC Board Ballot JCB-01-02, formulated under the cognizance of the JC-14.3 Subcommittee on Silicon Devices Reliability Qualification and Monitoring.)

1 Scope

The methods described in this document apply to failure modes and mechanisms whose failures exhibit a constant failure rate, e.g., an Arrhenius behavior characterized by an activation energy for failure. If data on the distributions of failure with time exist, these activation energies can be assumed from prior knowledge or failure analysis signatures. If the default activation energies are not known or can't be determined, an activation energy can be used as a default. Refer to JEP122 Activation Energies for Failure Mechanisms to obtain initial estimates.

The purpose of this method is to provide a reference to the way failure rates are calculated in FITs.

2 Terms and definitions

probability density function of the time-to-failure; mortality function [f(t)]: The probability of failure at a given instant of time t. F(t)dt is the probability of failure in the interval t to t + dt.

cumulative distribution function of the time-to-failure; cumulative mortality function [F(t)]: The probability that a device will have failed by time t or the fraction of units that have failed by time t. It is the integral of f(t).

cumulative reliability function [R(t)]: The probability that a device will function at time t or the fraction of units surviving to time t. $R(t) = 1 – F(t)$

instantaneous (or hazard) failure rate [h(t)]: The rate at which devices are failing referenced to the survivors. $h(t) = f(t) / R(t)$

cumulative hazard function [H(t)]: The integral of h(t).

FIT (failure in time): The number of failures per 10^9 device-hours. Typically used to express the failure rate. Similarly, it can be defined as 1 PPM per 1000 hours of operation or one failure per 1000 devices run for one million hours of operation.

population failure distributions: The frequency of occurrence of failures over segments of time. Typically seen failure distributions are Normal, Lognormal (wearout), Weibull and Exponential.

2 Terms and definitions (cont'd)

bathtub curve: A plot of hazard rate versus time that exhibits three phases of life: infant mortality (initially decreasing failure rate with time), intrinsic or useful life (relatively constant failure rate) and wearout (increasing failure rate with time).

acceleration factor (AF): A multiplier relating failure times during an accelerated life test versus those during useful life application conditions, assuming the same cumulative percent failures and sigma for the two different stress conditions.

activation energy (E_A): The excess free energy over the ground state that must be acquired by an atomic or molecular system in order that a particular process can occur. Examples are the energy needed by the molecule to take part in a chemical reaction, by an electron to reach the conduction band in a semiconductor, or by a lattice defect to move to a neighboring site.

apparent activation energy (E_A'): Activation energy that is calculated using the principles of the physical relationship between stress and failure rate but is not directly related to a basic change in physical processes. It may be based on too many possible physical "effects" that, when stressed as a unit, produce a cumulative effect. It is similar to the concept of activation energy but measures the probability of not exceeding some measurable attribute. A plot of the reciprocal or absolute temperature (1/T(K)) versus the log of percent failed is linear.

3 Methods for calculating failure rates

The methods detailed below are arranged in an order such that an increasing amount of detail regarding the failure data is available for each successive model

3.1 Case I: Single activation energy procedure for constant failure rate distributions

Assumptions:

- NO TEST INTERVALS (single read point of 2000 hours)
- UNKNOWN FAILURE MECHANISMS
- NOMINAL VOLTAGES DURING STRESS TEST

This method assumes knowledge of the number of failures in a known sample size from a life test with a single stress temperature and single end point test. The failures have not been segregated or analyzed to determine the applicable failure mechanism, so an apparent activation energy is assumed for all failures.

3.1 Case I: Single activation energy procedure for constant failure rate distributions (cont'd)

3.1.1 Summarize the data

- f = # of failures = 15
- ss = sample size = 500
- T_{STRESS} = stress temperature = 125 ºC
- T_{USE} = use temperature = 55 ºC
- E_A (avg) = apparent activation energy = 0.7 eV
- Very low power consumption during life test (negligible self heating)
- Apparent activation energy may or may not be an average.

3.1.2 Calculate the acceleration factor

Using the Arrhenius equation (1), calculate the acceleration factor for the failures at the given stress and use temperatures.

$$AF = \exp\left[\left(\frac{E_A}{k}\right)\cdot\left(\left(\frac{1}{T_{USE}}\right)-\left(\frac{1}{T_{STRESS}}\right)\right)\right] \quad \mathbf{(1)}$$

$$= \exp\left[\left(\frac{0.7eV}{8.6\cdot 10^{-5}eV/K}\right)\cdot\left(\left(\frac{1}{(55+273)^\circ K}\right)-\left(\frac{1}{(125+273)^\circ K}\right)\right)\right]$$

$$= 78.6$$

Usually devices draw power during life test. Junction temperature can be derived from the ambient temperature, power dissipation and the thermal impedance, and should be used for accurate estimation of the acceleration factor. The self-heating in a device is package-dependent. The thermal dissipation property of a package (Theta ja, θja) determines the amount of self-heating for the package. θ_{ja} is a function of the air velocity around the package body. A good rule of thumb is that θ_{ja} is reduced by as much as 30% for moving air compared to still air. As an example, if we were to assume that θ_{ja} were 60 °C/watt, the power dissipation were 0.1 watt at 125 °C, and 0.12 watts at 55 °C, then there would be 7.2 °C (60*0.12) difference between junction temperature and ambient at 55 °C and 6 °C (60*0.1) difference at 125 °C. Thus, the acceleration factor would be calculated based on 131 °C as stress temperature vs. 62.2 °C as the actual use temperature. The net effect of the self-heating would reduce acceleration factor to 62.5, compared to 78.6 calculated earlier without a self -heating consideration.

Some mechanisms such as oxide and inter-layer dielectrics may also be accelerated due to the applied electric fields. Appropriate models may be used to calculate acceleration due to voltage applied. Refer to JEP122 for the most commonly used models.

3.1 Case I: Single activation energy procedure for constant failure rate distributions (cont'd)

3.1.3 Calculate the point estimate of the failure rate

$$\lambda_{POINT} = \frac{f \cdot 10^9}{t \cdot ss \cdot AF}$$

$$= \frac{15 \cdot 10^9}{2000h \cdot 500 \cdot 78.6}$$

= 190.84 **~191 FITs**

3.1.4 Calculate the upper confidence bound of the failure rate

$$\lambda_{CL} = \frac{\chi^2{}_{\%CL,2f+2} \cdot 10^9}{2 \cdot t \cdot ss \cdot AF}$$

$$\lambda_{60\%CL} = \frac{33.4 \cdot 10^9}{2 \cdot 2000h \cdot 500 \cdot 78.6}$$ **(χ^2 for 15 failures is 33.4 for 60% confidence)**

= 212.46 **~ 212 FITs**

$$\lambda_{90\%CL} = \frac{42.6 \cdot 10^9}{2 \cdot 2000h \cdot 500 \cdot 78.6}$$ **(χ^2 for 15 failures is 42.6 for 90% confidence)**

= 270.99 **~271 FITs**

3.2 Case II: multiple activation energy procedure for constant failure rate distributions

Assumption:

- NO TEST INTERVALS (single read point of 2000 hours)
- KNOWN FAILURE MECHANISMS
- NOMINAL VOLTAGES DURING STRESS TEST

For this method, the data set is the same as in section 5.1, but now it is known that the devices failed due to several different failure mechanisms to which can be assigned the appropriate activation energies.

3.2 Case II: Multiple activation energy procedure for constant failure rate distributions (cont'd)

3.2.1 Summarize the additional data available

- FM#1 from 3 failures at E_A = 0.5 eV
- FM#2 from 5 failures at E_A = 0.7 eV
- FM#3 from 7 failures at E_A = 1.0 eV

Total # of failures = 15

3.2.2 Calculate the acceleration factors

Calculate the acceleration factors for each failure mechanism (known activation energy) at the given stress and use temperatures using the Arrhenius equation (1)

- AF(FM#1) 0.5 eV = 22.6
- AF(FM#2) 0.7 eV = 78.6
- AF(FM#3) 1.0 eV = 510

3.2.3 Calculate the failure rates

Calculate the point estimate of the failure rate for each failure mechanism and add to obtain the point estimate of the total failure rate.

$$\lambda_{POINT} = \frac{f \cdot 10^9}{t \cdot ss \cdot AF}$$

$$\lambda_{FM\#1} = \frac{3 \cdot 10^9}{2000h \cdot 500 \cdot 22.6} \quad \textbf{(0.5 eV)}$$

= 132.74 **~133 FITs**

$$\lambda_{FM\#2} = \frac{5 \cdot 10^9}{2000h \cdot 500 \cdot 78.6} \quad \textbf{(0.7 eV)}$$

= 63.6 **~64 FITs**

$$\lambda_{FM\#3} = \frac{7 \cdot 10^9}{2000h \cdot 500 \cdot 510} \quad \textbf{(1.0 eV)}$$

= 13.7 **~14 FITs**

3.2 Case II: Multiple activation energy procedure for constant failure rate distributions (cont'd)

3.2.3 Calculate the failure rates (cont'd)

$$\lambda_{TOTAL,POINT} = \sum_{1}^{n} \lambda_{FM\#}$$

$$= 132.74 + 63.6 + 13.7$$

$$= 210.4$$ **~210 FITs**

3.2.4 Calculate the upper confidence bound of the total failure rate

$$\lambda_{TOTAL,CL} = \lambda_{TOTAL,POINT} \cdot \left(\frac{\chi^2_{\%CL,2f+2}}{2f} \right)$$

$$\lambda_{TOTAL,60\%CL} = \frac{210 \cdot 33.4}{30}$$

$$= 233.8$$ **~234 FITs**

$$\lambda_{TOTAL,90\%CL} = \frac{210 \cdot 42.6}{30}$$

$$= 298.2$$ **~298 FITs**

3 Methods for calculating failure rates (cont'd)

3.3 Case III: Multiple activation energy procedure for constant failure rate distributions with known test interval

For this method, the data set is the same as in sections 5.1 and 5.2, but the stress was now performed using different test intervals to determine when each of the failures occurred. This type of detail enables a calculation of the average failure rate within a given time interval. The early life, or nonconstant failure rate, segment can be calculated using a Weibull distribution ($m < 1$). Make an assumption about where the constant or steady state failure rate time interval begins. This time interval should be with respect to the use conditions, not the test time, since different failure mechanisms exist in the failures. Note that, if the failure mechanisms were unknown, a steady state time interval for the constant failure rate in terms of the stress time could be used. The time period before the beginning of the time interval is assumed to represent a nonconstant failure rate (e.g., infant mortality-type failures) and can be represented by a Weibull distribution ($m < 1$). For this example, we assume our application displays a breakpoint between early life and inherent life at 10,000 hours use time.

$0\text{hr} < t_{USE,WEIBULL} < 10{,}000$ h nonconstant failure rate (infant mortality)

$t_{USE,EXPONENTIAL} > 10{,}000$ h constant failure rate (operational life)

It is assumed that this particular life test does not stress the devices to the wearout portion of their lifetime. If the data shows a nonconstant (increasing) failure rate before the end of the stress time, then the failure rate for that segment can be calculated using the method described below for a Weibull distribution ($m > 1$).

Assumption:

- KNOWN TEST INTERVALS
- KNOWN FAILURE MECHANISMS
- NOMINAL VOLTAGES DURING STRESS TEST

3.3.1 Summarize the additional data available

	Stress Time→	48 h	168 h	500 h	1000 h	2000 h
Acceleration Factor	Sample Size→	500	497	495	493	490
	# Failed→	3	2	2	3	5
22.6 FM # 1	0.5 eV	**0**	**0**	1	0	2
78.6 FM # 2	0.7 eV	**1**	0	0	2	2
510 FM # 3	1.0 eV	2	2	1	1	1

3.3 Case III: Multiple activation energy procedure for constant failure rate distributions with known test interval (cont'd)

3.3.2 Separate the data into early life and inherent life periods

The field equivalent hours of 10,000 (depending on the application, different times may also be used) is used to find the equivalent time for each mechanism as follows:

0.5 eV = 10,000/22.6 = 177 hours
0.7 eV = 10,000/78.6 = 50.9 hours
1.0 eV = 10,000/510 = 7.8 hours

This means that the first two read points of 48 and 168 hours for the 0.5 eV belongs in the early life period. The first read point of 48 hours read point for the 0.7 eV group also belongs in the early life period while all the rest of the read points will belong to the inherent life group (the constant or steady state failure rate). The early life data points are highlighted in the table in 3.3.1. This data is rearranged separating the early life portion from the inherent life for ease of illustration.

3.3.3 Calculate the early life failure rate

For the use condition time interval between 0 and 10,000 hours, assume a Weibull distribution with a declining failure rate to reflect the infant mortality portion of the lifetime bathtub curve ($m < 1$). Calculate a failure rate for a given stress time interval inside the nonconstant failure rate interval.

22.6 FM # 1	0.5 eV Time→	48	168			
	Sample Size→	500	497			
	# Failed→	0	0			

78.6 FM # 2	0.7 eV Time→	48				
	Sample Size→	500				
	# Failed→	1				

Since there is only one failure in the early life period, the Weibull distribution can not be applied to this data set. Also, calculating the failure rates based on more then two read points minimize the error in estimate. However, with very few failures and large sample sizes, we may use the exponential model to estimate the early life failure rate.

3.3 Case III: Multiple activation energy procedure for constant failure rate distributions with known test interval (cont'd)

3.3.3 Calculate the early life failure rate (cont'd)

$$\lambda_{FM\#1} = \frac{0.6 \cdot 10^9}{168h \cdot 500 \cdot 22.6}$$ **(0.5 eV) (for zero failure, substitute .6 for 50% confidence)**

= 316.05 ~**316 FITs**

$$\lambda_{FM\#2} = \frac{1 \cdot 10^9}{48h \cdot 500 \cdot 78.6}$$ **(0.7 eV)**

= 530.11 ~**530 FITs**

Total = 316.05 + 530.11 = 846.16 **~ 846 FITs**

3.3.3.1 Use of Weibull distribution

Consider a test where the activation energy for the observed failure mechanism and test conditions result in an acceleration factor of 100. The test started with a sample of 500 pieces and one failure occurred at 48 hours. The remaining sample was continued to 96 hours wherein one additional failure occurred.

The cumulative failure values are thus:

F(48) =[1-(499/500)] = 0.002

F(96) = {1-[(499/500)*(498/499)]}={1-(498/500)}=2/500 = 0.004

3.3.3.2 Apply test parameters to Weibull distribution

The basic Weibull parameters are "m," the shape parameter and "c," the characteristic life. m is defined as follows:

$$m = \ln[-\ln\{1-F(t)\}] \, / \, [\ln(t) - \ln(c)] \qquad \textbf{(2)}$$

$$= \ln[-\ln\{(1-0.00200)\}] \, / \, [\ln(48) - \ln(c)] = -6.21361 / [3.8712 - \ln(c)]$$

$$= \ln[-\ln\{(1-0.0040)\}] \, / \, [\ln(96) - \ln(c)] = -5.51946 / [4.5643 - \ln(c)]$$

3.3.3 Calculate the early life failure rate (cont'd)

3.3.3.3 Solving for ln(c)

ln(c) = 10.076

and c= 23762 hours.

3.3.3.4 Then solving equation [2] for m

m = 1.001446

3.3.3.5 The Weibull equation for instantaneous failure rate

$h(t) = (m/c) * (t/c)^{m-1}$

For t = 1 hour,

h(t) = 41,535 FITs

With very few failures, and m closer to 1, the Weibull distribution reduces to the exponential form and is a better estimate for failure rates.

$$\lambda = \frac{2 \cdot 10^9}{96h \cdot 500 \cdot 100}$$

= 416.67 **~417 FITs**

3.3.4 Calculate the inherent life failure rate

3.3.4.1 For 0.5 eV mechanism

22.6 FM # 1	0.5 eV Time→	**1085**	**3797**	11,300	22,600	45,200
	Sample Size→	**500**	**497**	495	493	490
	# Failed→	**0**	**0**	1	0	2

Since 11,300 hours is greater then 10,000 hours for the early life period with one failure and that there was no failure at the 3797 read point, we do not know if this failure occurred within the early life period or beyond. Therefore, the failure rate would be averaged beyond the early life period of 3797. If we assume a constant failure rate between 3797 and 11,300 hours, the likelihood of the one failure occurring after the early life breakpoint of 10,000 hours is:

3.3.4 Calculate the inherent life failure rate (cont'd)

3.3.4.1 For 0.5 eV mechanism (cont'd)

$$a = \frac{11{,}300 - 10{,}000}{11{,}300 - 3797} = 0.17$$

and f = 2+.17= 2.17

$$\lambda_{POINT} = \frac{f \cdot 10^9}{ss \cdot t_{USE,INTERVAL}}$$

$$\lambda_{0.5eV} = \frac{3 \cdot 10^9}{500 \cdot (45200 - 11300)}$$

to

$$\lambda_{0.5eV} = \frac{2.17 \cdot 10^9}{500 \cdot (45200 - 10000)}$$

= 123.29 **~123 FITs**

3.3.4.2 For 0.7 eV mechanism

78.6 FM # 2	0.7 eV Time→	**3773**	13,205	39,300	78,600	157,200
	Sample Size→	**500**	497	495	493	490
	# Failed→	**0**	0	0	2	2

In the case with 0.7 eV, there are no failures beyond early life and the first read point in inherent life, thus the failure rate (4 fails) will be averaged between 13,205 and 157,200 hours.

$$\lambda_{0.7eV} = \frac{4 \cdot 10^9}{500 \cdot (157200 - 13205)}$$

= 55.56 **~56 FITs**

3.3.4 Calculate the inherent life failure rate (cont'd)

3.3.4.3 For 1.0 eV mechanism

510 FM # 3	1.0 eV Time→	**24,480**	85,680	255,00	510,000	1,020000
	Sample Size→	**500**	497	495	493	490
	# Failed→	**2**	2	1	1	1

In the case with 1.0 eV, there are 2 failures that could have occurred during early life or inherent life. Since the inherent life period is assumed to have a constant failure rate and we have more than one data point in this region to use, the first two failures (shaded in the table above) can be ignored. Thus the failure rate (5 fails) will be averaged between 24,480 and 1,020,000 hours.

$$\lambda_{1.0eV} = \frac{5 \cdot 10^{9}}{500 \cdot (1020000 - 24480)} \qquad = 10.05 \quad \mathbf{\sim 10\ FITs}$$

The total failure rate in the constant failure rate time interval is the sum of all individual failure rates:

$$\lambda_{TOTAL,POINT} = \sum_{1}^{n} \lambda_{FM\#}$$

$$= 123.29_{\ 0.5ev} + 55.6_{\ 0.7ev} + 10.05_{\ 1.0ev} \qquad = 188.94 \quad \mathbf{\sim 189\ FITs}$$

The upper confidence bounds can be obtained using the same procedure shown in the previous methods. A comparison of the results of the first three cases using the same data set can be found in Annex 3.

3.4 Case IV: Different test conditions (truncated data)

This method is used when dealing with censored (OR Type II) data, which is data that is obtained after a truncation of a test either after a given number of failures or after a certain period of time. Other types of censoring include interval (data recorded only during certain intervals) and suspended (functioning parts removed during life test) censoring. The latter requires the use of the Kaplan-Meier method of data treatment by collecting the relative (vs. absolute) failures. This will be illustrated in the following example.

Here, there are three more sets of data with different rates and occurrences of failures, and stressed at different temperatures so as to produce different accelerations. Thus, different termination times are produced when calculated for use times. For simplicity, we assume in the example below the same activation energy (0.7 eV) for all the failures.

3 Methods for calculating failure rates (cont'd)

3.4 Case IV: Different test conditions (truncated data) (cont'd)

Assumptions:

- KNOWN TEST INTERVALS
- UNKNOWN FAILURE MECHANISMS
- NOMINAL VOLTAGES DURING STRESS TEST
- MULTIPLE STRESS TEMPERATURES

3.4.1 Summarize the additional data available

There are four sampling of 500 devices each. The default activation energy for all failures is assumed to be 0.7 eV. Failures after each read-point for each stress temperature are shown below. An "x" indicates that a read-point was not taken for that sampling.

sampling	T_{STRESS}	48 h	168 h	500 h	1000 h	2000 h
1	100 ^{O}C	2	1	2	2	x
2	125 ^{O}C	3	2	2	3	5
3	125 ^{O}C	2	2	3	x	x
4	150 ^{O}C	4	3	2	3	2

3.4.2 Convert stress times to equivalent use times

Using the Arrhenius equation (0.7 eV for activation energy), convert the stress times to equivalent use times (use temperature of 55 °C) as summarized in the table below. The numbers in parentheses ( ) below are the ordering of the use hours from shortest to longest.

T_{STRESS}	AF	48 h	168 h	500 h	1000 h	2000 h
100 ^{o}C	20.0	960 (1)	3360 (2)	10000 (4)	20000 (7)	40000 (9)
125 ^{o}C	78.6	3773 (3)	13205 (6)	39300 (8)	78600 (11)	157,200 (13)
150 ^{o}C	263	12624 (5)	44184 (10)	131,500 (12)	263,000 (14)	526,000 (15)

3.4 Case IV: Different test conditions (truncated data) (cont'd)

3.4.3 Order the failure occurrences by equivalent use time

If we make the optimistic assumption that the failures occurred at the end of the test interval, we obtain the following failure distribution extrapolated to useful life conditions. The "-" indicates no reading taken at that equivalent use time.

a	sampling(s)=> use hours:	1	2	3	4	f = total fails@a	ΣF=cum fails	ΣF%= % Fail	n=pop.
1	960	2	-	-	-	2	2	0.10	2000
2	3360	1	-	-	-	1	3	0.15	1998
3	3773	-	3	2	-	5	8	0.40	1997
4	10000	2	-	-	-	2	10	0.50	1992
5	12624	-	-	-	4	4	14	0.70	1990
6	13205	-	2	2	-	4	18	0.91	1986
7	20000	2	-	-	-	2	20	1.01	1982
8	39300	x	2	3	-	5	18 (20+5-7)	1.21	1487 (1982-500+7-2)
9	40000	x	-	x	-	0	11 (18+0-7)	1.11	989 (1487-500+7-5)
10	44184	x	-	x	3	3	14	1.42	989
11	78600	x	3	x	-	3	17	1.57	986
12	131,500	x	-	x	2	2	19	1.93	983
13	157,200	x	5	x	-	5	24	2.45	981
14	263,000	x	x	x	3	3	12 (24+3-15)	2.44	491 (981-500+15-5)
15	526,000	x	x	x	2	2	14	2.87	488

An "x" indicates that there were no more components from a specific sample in the test.

NOTE For sampling # 1, the last read point was 20,000; for sampling # 2, the last read point was 157,200; for sampling # 3, the last read point was 39,300 and for sampling # 4, the last read point was 526,000 (indicated by shading in the appropriate field).
Refer to Annex 1 for sample calculation of cum failures.

F = total number of failures tested to that specific use hour point.
ΣF = cumulative number of failures seen up to that specific use hour point.
ΣF% = ΣF/n = cumulative % failures up to that specific use hour point.
N = the number of functional components at the start of an interval (population).

$$n_a = n_{a-1} - \left[n_s - \sum f_s\right] - f_{a-1} \qquad \textbf{(3)}$$

Where: a = row number and s = sampling column

3.4 Case IV: Different test conditions (truncated data) (cont'd)

3.4.4 Perform conventional analysis

3.4.4.1 Calculate early life failure rate

Assuming**,** as in 5.3, that the early life failure rate time interval is in the range between 0 and 10,000 hours of use condition, there are 10 cumulative failures from the four sampling:

$$\lambda_{ELFR} = \frac{\sum_{tINTERVAL} f \cdot 10^9}{ss \cdot t_{INTERVAL}}$$

$$= \frac{10 \cdot 10^9}{2000 \cdot 10000}$$

= 500 FITs

The upper confidence bounds can be obtained using the same procedure shown in the previous methods.

3.4.4.2 Calculate intrinsic failure rate

The average failure rate above 10,000 hours (or intrinsic failure rate) under use conditions has 43 cumulative failures and 10 of these occurred at 10,000 hours or before:

$$\lambda_{INTRINSIC} = \frac{\sum_{tINTERVAL} f \cdot 10^9}{\sum_{SAMPLING=1}^{a} ss_a \cdot \left(t_{STRESS,a} - t_{ELFR}\right)}$$

$$= \frac{33 \cdot 10^9}{497 \cdot (157200 - 10000) + 498 \cdot (39300 - 10000) + 500 \cdot (526000 - 10000) + 495 \cdot (20000 - 10000)}$$

= 92.92 **~93 FITs**

3.4.4 Perform conventional analysis (cont'd)

3.4.4.3 Recalculate cumulative distribution function

Using the Nelson or Stolze methods and preparing the data using the Kaplan-Meier method (decreasing sample size during the test, see appendix-II for example) we recalculate the cum % failing (CDF) with the adjusted sample size as indicated in the table below:

				H	survival p	R	F%	# F =	# Failed
	use hours:	f=total	ss	f/ss	p =1-f/ss	1-∏(p)	CDF100*(1-R)	CDF *ss	Integer
1	960	2	2000	0.00100	0.999000	0.999000	0.10	2.0	2
2	3360	1	1998	0.00050	0.999499	0.998500	0.15	3.0	3
3	3773	5	1997	0.00250	0.997496	0.996000	0.40	8.0	8
4	10000	2	1992	0.00100	0.998996	0.995000	0.50	10.0	10
5	12624	4	1990	0.00201	0.997990	0.993000	0.70	13.9	14
6	13205	4	1986	0.00201	0.997986	0.991000	0.90	17.9	18
7	20000	2	1982	0.00101	0.998991	0.990000	1.00	19.8	20
8	39300	5	1487	0.00336	0.996638	0.986671	1.33	19.8	20
9	40000	0	989	0.00000	1.000000	0.986671	1.33	13.2	13
10	44184	3	989	0.00303	0.996967	0.983678	1.63	16.1	16
11	78600	3	986	0.00304	0.996957	0.980685	1.93	19.0	19
12	131,500	2	983	0.00203	0.997965	0.978690	2.13	20.9	21
13	157,200	5	981	0.00510	0.994903	0.973702	2.63	25.8	26
14	263,000	3	491	0.00611	0.993890	0.967752	3.22	15.8	16
15	526,000	2	488	0.00410	0.995902	0.963786	3.62	17.7	18

3.4.4.4 Conduct regression analysis

The cum F% vs. t_{USE} values can then be fitted onto a log-log or log-normal plot using linear regression. The resultant regression analysis will give the slope and intercept parameters. Care should be taken in applying these methods as very large values of T_{50} may result from a poor fit to the data. The data table is further simplified by eliminating the 40,000 read-point as there were no failures. A useful tool is to find the saturation point of failure in time (linear plot of %f vs time, in this case f_{sat}~4%) and then normalizing the cum failures to this value. This type of analysis identifies the defective sub-population from the main distribution.

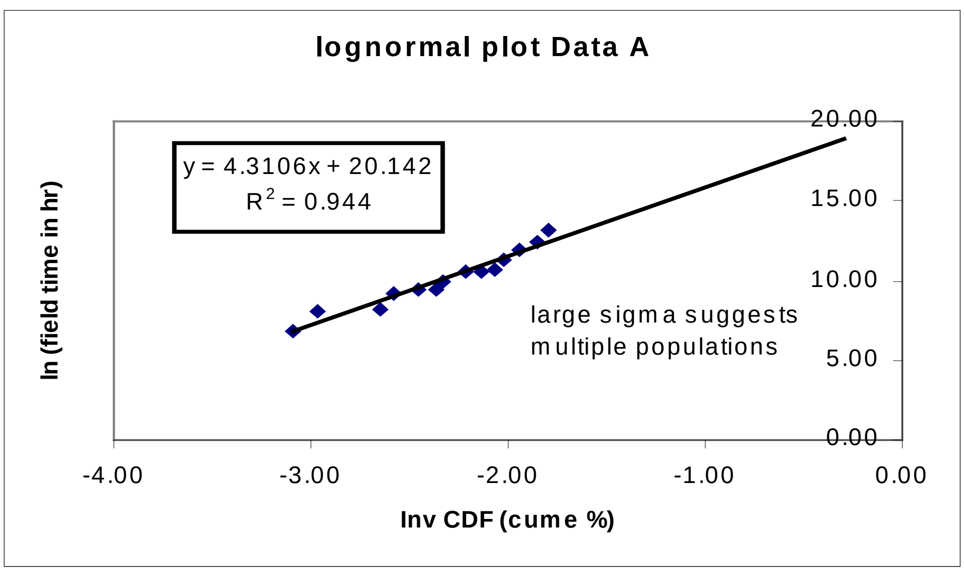
3.4.4 Perform conventional analysis (cont'd)

3.4.4.4 Conduct regression analysis (cont'd)

Data		Defective Sub-Population		Standard Analysis	
Use hours (t)	Ln (t) [ordinate]	Cum%f x 100 / f_{sat}	Z(def subpop) [abscissa]	Cum % fail	Z(cum%fail) [abscissa]
960	6.87	3%	-2.0	0.10%	-3.09
3360	8.12	4%	-1.8	0.15%	-2.97
3773	8.24	10%	-1.3	0.40%	-2.65
10000	9.21	13%	-1.2	0.50%	-2.58
12624	9.44	18%	-0.9	0.70%	-2.46
13205	9.49	23%	-0.8	0.90%	-2.37
20000	9.90	25%	-0.7	1.00%	-2.33
39300	10.58	33%	-0.4	1.33%	-2.22
44184	10.60	41%	-0.2	1.63%	-2.14
78600	10.70	48%	0.0	1.93%	-2.07
131500	11.27	53%	0.1	2.13%	-2.03
157200	11.97	66%	0.4	2.63%	-1.94
263000	12.48	81%	0.9	3.22%	-1.85
526000	13.17	91%	1.3	3.62%	-1.80

3.4.4.5 Effect on plot using standard inverse CDF

The following plots illustrate the significance of graphical analysis and the defective sub-population. If we perform a standard analysis by plotting ln t vs. cum f inv CDF:

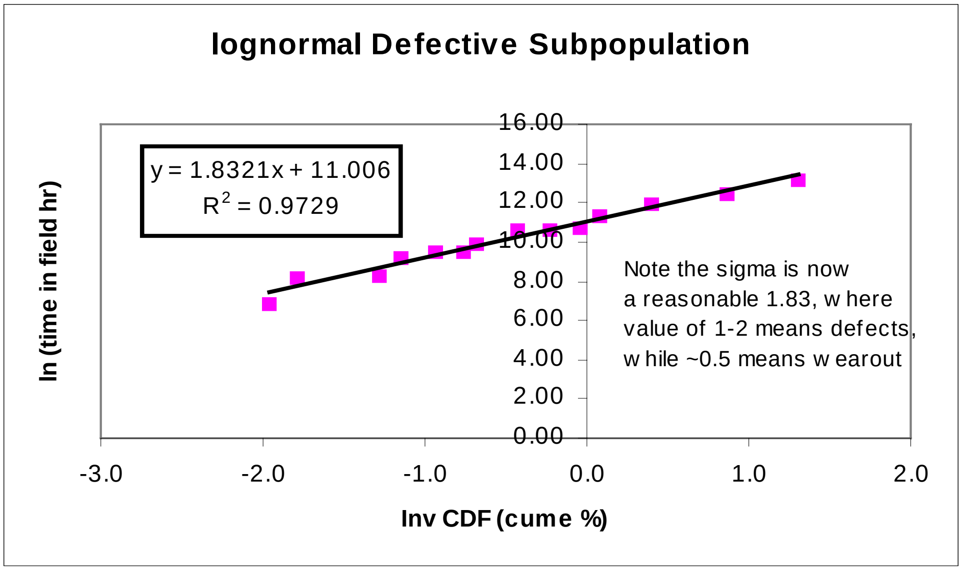


In the log-normal plot of cum defective versus log time, we obtain a straight line with reasonable fit as indicated by the R^2 of 0.944 from the regression analysis. However, the large sigma of 4.31 indicates that there are multiple mechanisms present. The same data, when normalized to a saturated cum failure rate of 4% (saturation point from linear plot of CDF vs time) will also yield a straight line and a more reasonable values of sigma and T_{50}.

3.4.4 Perform conventional analysis (cont'd)

3.4.4.6 Plot of defective subpopulation on inverse CDF

If we use only the defective subpopulation in plotting ln t vs. def sub pop inv CDF:



In this graph, the R^2 value (0.973) indicates a better fit then before (0.944) with more reasonable values of sigma (1.83) and T_{50} [Exp(11.006)]. The T_{50} values are $6x10^4$ (for defective sub-population) compares to $5.6x10^8$ (normal plot). Also note that a sigma of 1 to 2 usually indicates defective sub-population while a sigma of less then 1 indicates a wear-out phenomenon.

4 References

1. JEP122, *Failure Mechanisms and Models for Silicon Devices*

2. JESD63, *Standard Method for Calculating the Electromigration Model Parameters for Current Density and Temperature*

3. James R. King, (1981), *Probability Charts for Decision Making*, 2nd Printing, TEAM, Tamworth, New Hampshire

4. Paul A. Tobias and Dave Trindade, (1986), *Applied Reliability*, Van Nostrand Reinhold, New York

Annex A

x/y	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Line				sampling=>				Cum Failed			Cum	% Cum	
		use hours:	1	2	3	4	f=total					Failed	Failed	n=pop
7	1	960	2	-	-	-	2	2				2	0.10%	2000
8	2	3360	1	-	-	-	1	3				3	0.15%	1998
9	3	3773	-	3	2	-	5	8				8	0.40%	1997
10	4	10000	2	-	-	-	2	10				10	0.50%	1992
11	5	12624	-	-	-	4	4	14				14	0.70%	1990
12	6	13205	-	2	2	-	4	18				18	0.91%	1986
13	7	20000	2	-	-	-	2	20	sub # 1			20	1.01%	1982
14	8	39300	493	2	3	-	5		18			18	1.21%	1487
15	9	40000	7f	-	493	-	0		11	sub # 2		11	1.11%	989
16	10	44184		-	7f	3	3			14		14	1.42%	989

NOTE 1 Line 14-8 in above table reduced the cum failures to 18 (cell J14). The figure below illustrates the formula used to calculate the cum failure. There were 20 cum failure at prior read point to which 5 new failures are added (E14+F14). Since group 1 has ended the stress test, the cum failures for this group (D7+D8+D10+D13) are removed from the cum count (=20-7+5=18).

x/y	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Line				sampling=>				Cum Failed			Cum	% Cum	
		use hours:	1	2	3	4	f=total					Failed	Failed	n=pop
7	1	960	2	-	-	-	2	2				2	0.10%	2000
8	2	3360	1	-	-	-	1	3				3	0.15%	1998
9	3	3773	-	3	2	-	5	8				8	0.40%	1997
10	4	10000	2	-	-	-	2	10				10	0.50%	1992
11	5	12624	-	-	-	4	4	14				14	0.70%	1990
12	6	13205	-	2	2	-	4	18				18	0.91%	1986
13	7	20000	2	-	-	-	2	20	sub # 1			20	1.01%	1982
14	8	39300	493	2	3	-	5		=+I13-D13-D10-D8-D7+E14+F14				1.21%	1487
15	9	40000	7f	-	493	-	0		11	sub # 2		11	1.11%	989
16	10	44184		-	7f	3	3			14		14	1.42%	989

Similarly, the figure below illustrates the total sample size (cell O14) reduced by sample size from group-1 (493) and by the failure encountered in immediate prior read point (2).

10	4	10000	2	-	-	-	2	10				10	0.50%	1992
11	5	12624	-	-	-	4	4	14				14	0.70%	1990
12	6	13205	-	2	2	-	4	18				18	0.91%	1986
13	7	20000	2	-	-	-	2	20	sub # 1			20	1.01%	1982
14	8	39300	493	2	3	-	5		18			18		=+O13-H13-D14
15	9	40000	7f	-	493	-	0		11	sub # 2		11	1.11%	989
16	10	44184		-	7f	3	3			14		14	1.42%	989
17	11	78600		3		-	3			17		17	1.72%	986

Annex B

Kaplan-Meier Approximation (estimator) (4, pp124-126)

A procedure to calculate survival probability estimates at various times. It allows calculations of reliability statistics with multi-censored data. Basically, the probability of a component surviving during an interval of time is estimated from the observed fallout of units starting the interval. The estimates at each time interval are multiplied together to provide a survival or probability estimate from time zero. The cumulative distribution function can be estimated at each failure time by subtracting the survival values from 1.0. Following example illustrates this method:

1 Small Sample size

Time	Sample Size	Failure	Removed for analysis	Survival probability	Survival Estimates	Survival Estimates
200	8	1	1	7/8	7/8	0.875
300	6	1		5/6	(7/8)*(5/6)	0.729
400	5	1	1	4/5	(7/8)*(5/6)*(4/5)	0.583
500	3	1		2/3	(7/8)*(5/6)*(4/5)*(2/3)	0.389
600	2	1		1/2	(7/8)*(5/6)*(4/5)*(2/3)*(1/2)	0.194

Time	Survival Estimates	CDF 1-Survival	Cum Failures CDF
200	0.875	0.125	1.25%
300	0.729	0.271	2.71%
400	0.583	0.417	4.17%
500	0.389	0.611	6.11%
600	0.194	0.806	8.06%

2 Example using data from mechanism # 3 and for 1.0 eV

Time	*# Failed*	*# Removed*	*Sample Size*	*Survivor*	*Cum p Of survival*	*CDF*
24480	2	1	500	0.996000	0.996000	0.400000
85680	2	0	497	0.995976	0.991992	0.800805
25500	1	1	495	0.997980	0.989988	1.001207
510000	1	2	493	0.997972	0.987980	1.202016
1020000	1	4	490	0.997959	0.985964	1.403645

Minimum Information	Known mechanism	Known mechanisms and time interval
F =15 Ss=500 Ts = 125 °C Tu = 55 °C Ea = 0.7 ev (Assumed) t=2000 hours	f = 3,5, 7 Ea = 0.5, 0.7, 1.0 t=2000 hours	(see table below)
AF = 78.6	AF = 22.6, 78.6, 510	

	Stress Time→	48	168	500	1000	2000
Acceleration	Sample Size→	500	497	495	493	490
Factor →	# Failed	3	2	2	3	5
22.6 FM # 1	0.5 ev	**0**	**0**	1	0	2
78.6 FM # 2	0.7 ev	**1**	**0**	0	2	2
510 FM # 3	1.0 ev	2	2	1	1	1

Minimum Information

$$= \frac{15 \cdot 10^9}{2000hr \cdot 500 \cdot 78.6}$$

= 191 FITs

= 191 FITs

Known mechanism

$$\lambda_{FM\#1} = \frac{3 \cdot 10^9}{2000hr \cdot 500 \cdot 22.6}$$ **(0.5 ev)**

= 133 FITs

$$\lambda_{FM\#2} = \frac{5 \cdot 10^9}{2000hr \cdot 500 \cdot 78.6}$$ **(0.7 ev)**

= 63.6 FITs

$$\lambda_{FM\#3} = \frac{7 \cdot 10^9}{2000hr \cdot 500 \cdot 510}$$ **(1.0 ev)**

= 13.7 FITs

$$\lambda_{TOTAL,POINT} = \sum_{1}^{n} \lambda_{FM\#}$$

= 133 + 63.6 + 13.7

= 210 FITs

Known mechanisms and time interval

$$\lambda_{0.5eV} = \frac{2.17 \cdot 10^9}{500 \cdot (45{,}200 - 10{,}000)}$$

= 123 FITs

$$\lambda_{0.7eV} = \frac{4 \cdot 10^9}{500 \cdot (157{,}200 - 13205)}$$

= 55.6 FITs

$$\lambda_{1.0eV} = \frac{5 \cdot 10^9}{500 \cdot (1{,}020{,}000 - 24{,}480)}$$

= 10.05 FITs

$$\lambda_{TOTAL,POINT} = \sum_{1}^{n} \lambda_{FM\#}$$

$= 123_{\,0.5ev} + 55.6_{\,0.7ev} + 10.05_{\,1.0ev}$

= 188.65 FITs

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