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Early Life Failure Rate Calculation Procedure for Semiconductor Components

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JEDEC Solid State Technology Association

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EARLY LIFE FAILURE RATE CALCULATION PROCEDURE FOR SEMICONDUCTOR COMPONENTS

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Introduction

Early life failure rate (ELFR) measurement of a product is typically performed during product qualifications or as part of ongoing product reliability monitoring activities. These tests measure reliability performance over the product's first several months in the field. It is therefore important to establish a methodology that will accurately project early life failure rate to actual customer use conditions.

EARLY LIFE FAILURE RATE CALCULATION PROCEDURE FOR SEMICONDUCTOR COMPONENTS

(From JEDEC Board Ballot JCB-07-03, formulated under the cognizance of the JC-14.3 Subcommittee on Silicon Devices Reliability Qualification and monitoring.)

1 Scope

This standard defines methods for calculating the early life failure rate of a product, using accelerated testing, whose failure rate is constant or decreasing over time. For technologies where there is adequate field failure data, alternative methods may be used to establish the early life failure rate.

The purpose of this standard is to define a procedure for performing measurement and calculation of early life failure rates. Projections can be used to compare reliability performance with objectives, provide line feedback, support service cost estimates, and set product test and screen strategies to ensure that the ELFR meets customers' requirements.

2 Reference documents

JESD22-A108, *Temperature, Bias, and Operating Life*

JESD659, *Failure-Mechanism-Driven Reliability Monitoring*

JESD47, *Stress-Test-Driven Qualification of Integrated Circuits*

JEP122, *Failure Mechanisms and Models for Silicon Semiconductor Devices*

JESD91, *Method for Developing Acceleration Models for Electronic Component Failure Mechanisms.*

JESD85, *Methods for Calculating Failure Rate in Units of FIT*

JESD94, *Application Specific Qualification Using Knowledge Based Test Methodology*

JEP143, *Solid State Reliability Assessment Qualification Methodologies*

JEP148, *Reliability Qualification of Semiconductor Devices Based on Physics of Failure Risk and Opportunity Assessment*

3 Terms and definitions

accelerated ELF test time (t_A): The duration of the accelerated ELF test.

acceleration factor (A): For a given failure mechanism, the ratio of the time it takes for a certain fraction of the population to fail, following application of one stress or use condition, to the corresponding time at a more severe stress or use condition.

acceleration factor, temperature (A_T): The acceleration factor due to changes in temperature.

acceleration factor, voltage (A_V): The acceleration factor due to changes in voltage.

apparent activation energy (E_{aa}): An equivalent energy value that can be inserted in the Arrehenius equation to calculate an acceleration factor applicable to changes with temperature of time-to-failure distributions.

NOTE 1 An apparent activation energy is often associated with a specific failure mechanism and time-to-failure distribution for calculating the acceleration factor.

NOTE 2 A composite apparent activation energy is often used to calculate a single acceleration factor, for a given time-to-failure distribution, that is equivalent to the net effect of the various thermal acceleration factors associated with multiple failure mechanisms.

NOTE 3 Various physical thermal activation energies may contribute to the shape of the time-to-failure distribution.

NOTE 4 The term "apparent" is used because E_{aa} is analogous in use to E_a in the Arrhenius equation; E_{aa} is used for a time-to-failure distribution, while E_a applies to a chemical thermal reaction rate.

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

characteristic life (for the Weibull distribution)(η): The time at which F(t) equals ($1-e^{-1}$) (≈63.2%)

countable failure: A failure due to an inherent defect in the semiconductor component during early-life-failure (ELF) stress tests.

NOTE Failures due to electrical overstress (EOS), electrostatic discharge (ESD), mechanical damage, etc., are not counted, but the units are considered to have completed testing through the last successful readout when computing device hours.

cumulative distribution function of the time-to-failure; cumulative mortality function [F(t)]: The probability that a device will have failed by a specified time t_1 or the fraction of units that have failed by that time.

NOTE 1 The value of this function is given by the integral of f(t) from 0 to t_1.

NOTE 2 This function is generally expressed in percent (%) or in parts per million (ppm) for a defined early-life failure period.

NOTE 3 The abbreviation CDF is often used; however, the symbol F(t) is preferred.

3 Terms and definitions (cont'd)

cumulative fraction failing (CFF): The total fraction failing based on the starting sample size over a given time interval.

NOTE This is generally expressed in percent (%) or in ppm.

early life: The customer initial use period.

NOTE This period typically ranges from three months to one year of operation.

early-life-failure (ELF) test: An accelerated test designed to measure the early life failure rate (ELFR), which may be experienced during the customer initial use period.

NOTE The test process is specified in JESD47.

early life period (t_{ELF}): The specified early life period as defined by the user or the supplier.

failure rate (λ): The fraction of a population that fails within a specified interval, divided by that interval.

NOTE The statistical upper limit estimate of the failure rate is usually calculated using the chi-squared function.

failures in time (FIT): The number of failures per 10^9 device-hours.

population failure distributions: The applicable mortality functions.

NOTE Typically used failure distributions for early-life failures include the Weibull and Poisson (exponential); for useful life and wear-out and also the Gaussian (normal) and lognormal distributions are used.

ppm: Parts per million.

ppm/time period: The number of failures per million units in the time period of interest.

qualification family: Products sharing the same semiconductor process technology.

signature analysis: The process of assigning the most likely failure mechanism to a countable failure based on its unique electrical failure characteristics and an established physical analysis database for that mechanism.

use condition time (t_U): The time interval equivalent to the ELF test duration, as determined by the product of the acceleration factor and the actual accelerated test time: $A \times t_A$.

4 General requirements

4.1 Test samples

ELFR testing requires, as specified in JESD47D's Table 1 and Table A, a statistically significant sample size at a minimum 60% confidence to measure the ELFR associated with the component. The sample shall be drawn from a minimum of 3 nonconsecutive production lots, and shall be comprised of representative samples from the same qualification family. Samples from any single lot should not exceed 40% of the total sample required. All samples shall be fabricated and assembled in the same production site and with the same production process. The test vehicle should represent the highest design density available for qualification. Lower sample sizes may be used with justification (e.g., high component costs, limited supply).

ELFR is required to show the process capability of each technology, process, or product family. These data are generic in nature and are generally accumulated through an internal reliability monitor program. For a new device qualification that is the first of its kind in the technology, process, or product family, it may take up to one year post-qualification to accumulate adequate statistical sampling to fulfill this requirement.

4.2 Test conditions

Test samples shall be placed under stress as per applicable JEDEC test methods, e.g., JEDEC Standard JESD22-A108. Stress tests will be conducted at a voltage level, frequency, temperature, humidity, and other parameters as recommended in the JEDEC test methods. Alternative stress conditions that yield equivalent results may be used if empirically justified.

4.3 Test duration

Stress test conditions shall be continuously applied for a time sufficient to represent customer's early life period. The minimum duration will be dictated by the acceleration for the expected or established prevailing defect mix. Common practice stress durations are between 48 and 168 hours. Test durations outside the stipulated range may be used with empirical model justification. Determination of failure times prior to the termination of stress can be useful; either continuous monitoring via in situ testing or interim test readouts that can help bound failure times prior to the end of stress. The time of failure is the earliest readout at which a device fails one or more electrical tests per the datasheet specification.

4.4 Failure analysis

It is recommended that failures will be electrically and physically analyzed to root cause. Signature analysis may be applied.

5 Calculating ELFR

A typical time distribution for semiconductor component failures is depicted by the "bathtub" curve in Figure 5.1. The curve has three distinct regions: a rapidly decreasing "infant mortality" portion; a stable, useful life portion where the failure rate continues to decrease or is essentially constant; and a period of increasing failure rate representing the onset of wear-out. Infant mortality and useful life failures are caused by defects introduced during the manufacturing process. Many of these component defects can be removed by effective reliability screens. Early life fails are defect-induced component failures during board or system assembly processes, or during initial customer use.

Reliability models used for ELFR calculations must be established prior to ELFR testing, and must accurately reflect the technology, process, and fabrication and assembly site being measured, including test and screen practices. They must also be statistically updated with any major change in process, tests, or screens. JESD47 provides guidelines for process change qualification of a component.

Product ELFR data typically includes several different failure mechanisms which may contribute failures differently as a function of voltage, temperature and time. It is important to apply the correct voltage and temperature acceleration factors for each individual failure mechanism when projecting reliability performance to actual use conditions. This can be critical when the failure mix includes mechanisms with relatively low acceleration.

A detailed description of how to establish the underlying failure distribution is outside the scope of this standard. The methods described in this document apply to devices which are both sampled and produced without the use of an accelerated stress pre-conditioning, such as burn-in. Devices which are screened in production using accelerated stress methodologies typically require a more complex analysis, e.g., conditional probability, to account for the truncation of the screened portion of the distribution.

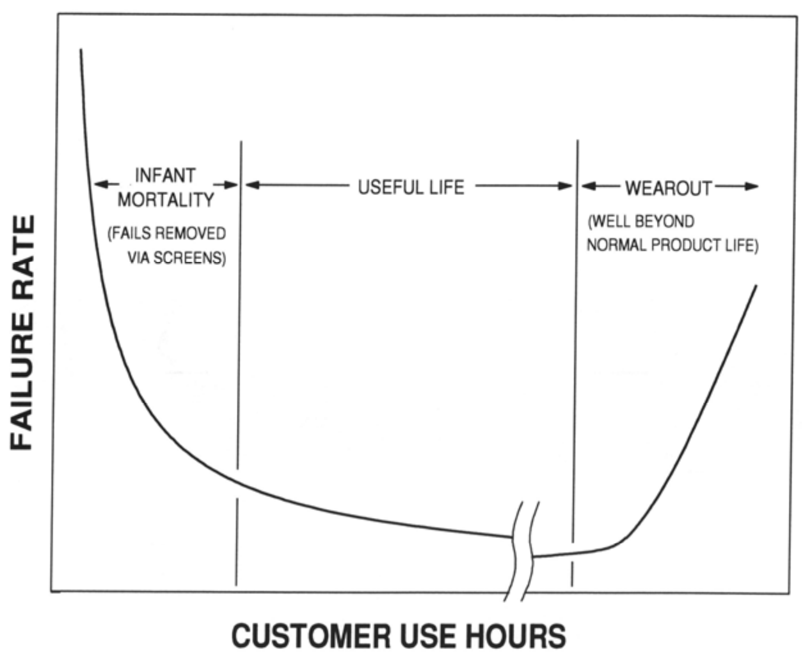

Figure 5.1 — Reliability bathtub curve

5 Calculating ELFR (cont'd)

A method for developing and validating composite temperature and voltage acceleration factors might begin by conducting extended accelerated stress testing of a separate group of samples at a minimum of two different temperatures at the same voltage and a minimum of two different voltages at the same temperature. Testing at a minimum of three temperatures and three voltages is preferred. All failures must be analyzed to root cause and then separated by failure mechanism, noting the unique voltage and temperature behavior of each mechanism. Samples without accelerated stress screening may be used to provide a more comprehensive coverage of product failure mechanisms and allow for better modeling. JESD91 and JEP122 provide method for developing acceleration failure mechanism models for semiconductor devices.

Acceleration models

Temperature Acceleration

Temperature acceleration of semiconductor failure mechanisms is usually described by the Arrhenius equation:

$$A_T = \exp\,[(E_{aa}/k) \times (1/T_U - 1/T_A)] \qquad [1]$$

where

A_T = Temperature acceleration factor
E_{aa} = Apparent activation energy in electron volts (eV)
k = Boltzmann's constant (8.617×10^{-5} electron volts/^{o}Kelvin)
T_U = Junction temperature at normal use conditions in degrees Kelvin
T_A = Junction temperature at accelerated conditions in degrees Kelvin

Voltage Acceleration

Unless an experimentally validated voltage acceleration model has been derived, the following model is recommended:

$$A_V = \exp\,[(K/X) \times (V_A - V_U)] = \exp\,[\gamma_V \times (V_A - V_U)] \qquad [2]$$

where

A_V = voltage acceleration factor
K = Experimentally determined electric field constant (expressed in thickness per volt)
X = Thickness of stressed dielectric
γ_V = (K/X) (units are V^{-1})
V_A = Stress voltage in accelerated ELF test
V_U = Use voltage

The total acceleration factor commonly is equivalent to the product of voltage acceleration and temperature acceleration factors,

$$A = A_T \times A_V \qquad [3]$$

where

A = acceleration factor for the ELF test.

The equivalent actual use condition period is calculated as:

$$t_U = A \times t_A \qquad [4]$$

where

t_U = use condition time in hours
t_A = accelerated ELF test time in hours

5 Calculating ELFR (cont'd)

Units failing for one mechanism shall be censored at the time of failure for purposes of calculating the failure rate due to other mechanisms. Where multiple mechanisms apply, the overall reliability is the product of the reliability with respect to each mechanism as below. When there are few mechanisms and the failure rate for each is small, the exact value can be reasonably approximated by a simple sum of the failure rates for each mechanism.

$$ELFR = 1 - \prod(1 - ELFR_i) \text{ for mechanisms 1 to i}$$

In addition, for a product having multiple failure mechanisms, each mechanism will contribute to the estimated failure rate at use conditions based upon the respective acceleration factors. Additionally, each mechanism may have a unique pair of Weibull distribution parameters. Consequently, where possible, each defect type should be treated independently. Calculation of failure rates for multiple failure mechanisms is described in 5.1.3 and 5.2.3. An alternate way of calculating the ELF rate using a chi-square value for the total number of failures instead of the individual failure mechanism is represented in 5.3.

In order to determine whether multiple failure mechanisms exist, analysis of the entirety of the failures must be performed. A more general treatment, however, may be necessary when an exact treatment taking into account each failure mechanism may not be possible.

Where no failures are observed the previously determined activation energy for that technology shall be used to calculate the failure rate.

The activation energies and voltage acceleration models for failure mechanisms should be experimentally determined for the product technology being qualified. If such information is not available, refer to JEP122 for the appropriate values.

In order to estimate the ELFR from accelerated test data, one must have knowledge of the acceleration factors involved in converting the test data to operating conditions and know how the failure rate behaves with time.

ELFR is defined as the average failure rate of a product over a **specified early life period, t_{ELF}**. As such, the dimensions of ELFR are fraction failing/time period. Once the time period is specified, the ELFR is often stated in ppm, with specified early life period to which it is applicable.

Calculation methodology for two situations is presented. 1) Exponential distribution (constant failure rate); 2) Decreasing failure rate (modeled by the Weibull distribution with the shape parameter, m, less than one).

5 Calculating ELFR (cont'd)

5.1 Exponential distribution (constant failure rate)

5.1.1 Exponential distribution-single ELF test

If a constant failure rate over the early lifetime period can be justified, the failure rate at customer operating conditions can be projected using the exponential distribution.

The upper c%-confidence bound of the failure rate, λ, using the χ^2 distribution, is given by

$$\lambda = \chi^2_{c,d} / (2 \times A \times N \times t_A) \qquad [5]$$

where

- A = acceleration factor for the ELF test ($A_T \times A_V$)
- N = sample size
- t_A = accelerated ELF test time in hours
- χ^2 = chi squared statistic
- subscript c = desired confidence level (often 60%)
- subscript d = degrees of freedom = $2 \times f + 2$
- f = number of failures in the ELF test

λ is the failure rate in the exponential distribution, and is a fraction per device hour (as opposed to percentage). The upper c%-confidence bound of the failure rate in FIT is

$$\text{ELFR (in FIT)} = 10^9 \times \lambda = 10^9 \times \chi^2_{c,d} /(2 \times A \times N \times t_A) \qquad [6]$$

Since the failure rate is assumed to be a constant, it is acceptable to express ELFR in terms of FIT. It is often desired to express the ELFR in ppm. However, ppm is a measure of the cumulative fraction failing per device, whereas FIT is a measure of fraction failing per **device-hour**. Thus, when ELFR is expressed in ppm, the early life period must also be specified.

If the failure rate is constant and the early life period in hours is t_{ELF}, the ELFR in FIT is converted to the ELFR in ppm/t_{ELF} as follows:

$$1 \text{ FIT} = 10^{-9} \text{ failures per device hour} \qquad [7]$$

$$1 \text{ ppm per } t_{ELF} = 10^{-6} \text{ failures per device in } t_{ELF} \text{ hr}$$

$$= 10^{-6} \times (1/ t_{ELF}) \text{ failures per device hr} \qquad [8]$$

Therefore,

$$1\text{FIT}/(1 \text{ ppm per } t_{ELF}) = 10^{-9} \text{ failures per dev. hour} /(1/ t_{ELF}) \times 10^{-6} \text{ failures per dev. hr}$$

$$1\text{FIT}/(1 \text{ ppm per } t_{ELF}) = 10^{-3} \times t_{ELF} \qquad [9]$$

$$1 \text{ FIT} = 10^{-3} \times t_{ELF} \text{ ppm per early life period} \qquad [10]$$

Therefore,

$$\text{ELFR (in FIT)} = [1/(t_{ELF} \times 10^{-3}) \times \text{ppm}] \qquad [11]$$

5.1 Exponential distribution (constant failure rate) (cont'd)

5.1.1 Exponential distribution-single ELF test (cont'd)

Or, to convert from FIT to ppm per early time period,

$$\text{ELFR (in ppm per } t_{ELF}) = [t_{ELF} \times 10^{-3} \times \text{ELFR in FIT}] \quad [12]$$

where

t_{ELF} = the specified early life period

The ELFR in ppm applies only to the specified early life period and is, in fact, 10^6 times the CDF at the end of the specified early life period.

When a product is not powered continuously, it may be desirable to calculate the early life failure rate using the power-on time during the early life period instead of the entire early life period (t_{ELF}). Suppose the fraction of time the product is powered is P (P is a number between zero and one). Then the ELFR in ppm is given by

$$\text{ELFR} = P \times t_{ELF} \times 10^{-3} \times \text{ELFR in FIT} \quad [13]$$

5.1.1.1 Calculation example: Exponential distribution–one failure mechanism, single ELF test

An example of an ELFR calculation for a single ELF test and assuming a constant failure rate is shown in **Annex A**.

5.1.1.2 Calculation example: Exponential distribution–two failure mechanisms, single ELF test

Often ELF tests exhibit more than one failure mechanism with different temperature acceleration and voltage acceleration factors. An example of such an ELFR calculation is shown is **Annex B**.

5.1.2 Exponential distribution–one failure mechanism, multiple ELF tests

The ELFR is normally estimated using results from multiple ELF tests, which may be run at different temperatures, voltages, and for different durations. In the case of a constant failure rate, only one failure mechanism, and **n** ELF tests, the upper c%-confidence bound of the ELFR is calculated using the equation:

$$\text{ELFR (in FIT)} = 10^9 \times \chi^2_{c,d} / [(2 \times A_1 \times N_1 \times t_1)+(2 \times A_2 \times N_2 \times t_2)+(\ldots)+(2 \times A_n \times N_n \times t_n)] \quad [14]$$

where

A_1, N_1, and t_1 are the parameters for ELF test 1
A_2, N_2, and t_2 are the parameters for ELF test 2
A_n, N_n, and t_n are the parameters for ELF test n
χ^2 = chi squared statistic
subscript c = desired confidence level (often 60%)
subscript d = degrees of freedom = $2 \times f + 2$
f = the combined number of failures in all tests

The ELFR (in ppm) is calculated from the ELFR (in FIT) using equation [12].

5.1 Exponential distribution (constant failure rate) (cont'd)

5.1.2 Exponential distribution–one failure mechanism, multiple ELF tests (cont'd)

5.1.2.1 Calculation example: Exponential distribution–one failure mechanism, multiple ELF tests

An example of an ELFR calculation using one failure mechanism in multiple ELF tests is shown in **Annex C**.

5.1.3 Exponential distribution–multiple failure mechanisms, multiple ELF tests

It is also common to observe multiple failure mechanisms from an ELF test conducted using multiple sample lots. When there are few mechanisms and the failure rate for each is small, the exact value can be reasonably approximated by a simple sum of the failure rates for each mechanism. In the case of a constant failure rate the upper c%-confidence bound of the ELFR is calculated using the equation

$$\text{Total ELFR (in FIT)} = \Sigma\ [\text{ELFR (mechanism i)}],\ i = 1 \text{ to } p \qquad [15]$$

where

$$\text{ELFR (mechanism i)} = 10^9 \times \chi^2_{c,d} / [2 \times A_i \times \Sigma(N_Z \times t_{AZ})],\ z = 1 \text{ to } n \qquad [16]$$

where

- A_i = acceleration factor for failure mechanism i
- t_{AZ} = the accelerated ELF test time for test z
- N_Z = sample sizes for ELF test z
- χ^2 = chi squared statistic
- subscript c = desired confidence level (usually 60% or 90%)
- subscript d = degrees of freedom = 2 × f + 2
- f = the number of failures of mechanism **i** in all **n** tests
- p = the number of distinct failure mechanisms
- n = the number of ELF tests

Where multiple mechanisms are known, suspected, or possible, an acceptable alternative to quantify the combined failure rate (as cited further in 5.3) is to apply an empirically-justified composite acceleration factor to a group of failures.

5.1.3.1 Calculation example: Exponential distribution–two failure mechanisms, multiple ELF tests

An example of an ELFR calculation in the case of multiple failure mechanisms and multiple ELF tests is shown in **Annex D**.

5.2 Decreasing failure rate

Early life failures generally have a decreasing failure rate, which ~~is~~ can be modeled by the Weibull distribution with a shape parameter, m, less than 1. Using this method, the ELFR for the case of a constant failure rate can be obtained by substituting m = 1. Other distributions can also model early life failures with decreasing failure rate and may be even more appropriate for certain failure mechanisms.

When an ELF test is performed, the equivalent time at use conditions, $t_{U,}$ is given by equation [4].

5.2 Decreasing failure rate (cont'd)

The specified early life period, t_{ELF}, as defined at the end of Section 5, is not necessarily the same as t_U.

The cumulative fraction failing (CFF) at ELFR conditions represents a point on the mathematical distribution for comparison with expected results, as shown in Figure 5.2. The CFF at equivalent use conditions can be calculated using voltage and temperature acceleration factors derived for the technology, then compared to a reliability objective at the equivalent use point on the mathematical distribution.

Figure 5.2 shows one method of determining the decreasing failure rate of the cumulative distribution function of the product historically. In this figure, a point represents the ELFR result at 48 hours of accelerated testing. The failures are concentrated at shorter times and the failure rate drops off rapidly with time conforming to the Weibull distribution with shape parameter, m or β = 0.4. This effect is presented as the infant mortality portion of the Reliability Bathtub Curve (Figure 5.1) where the failure rate starts out high but decreases rapidly.

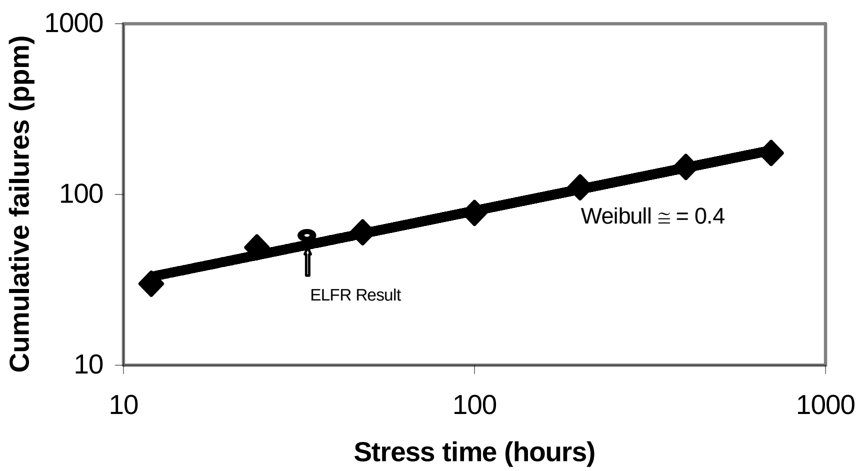

Figure 5.2 — Cumulative failures versus stress time

5.2.1 Decreasing failure rate, single ELF test

The Weibull cumulative distribution function (CDF) is

$$F(t) = 1 - \exp[-(t/\eta)^m] \quad [17]$$

where

- F(t) = the Weibull cumulative distribution function (CDF).
- [F(t) is the fraction failing from time = 0 to time = t]
- t = the time of interest
- η = the characteristic life
- (η is the time when 63.2% of parts have failed)
- m = Weibull shape parameter (also called β), which is either measured or estimated based on

5.2 Decreasing failure rate (cont'd)

5.2.1 Decreasing failure rate, single ELF test (cont'd)

When m = 1, the Weibull distribution reduces to the exponential distribution:

$F(t) = 1-\exp(-t/\eta)$. So the failure rate, λ, of the exponential distribution is $1/\eta$.

The value of F(t) is the CDF in the ELF test (i.e. cumulative ppm without a time frame) over the use period equivalent to the ELF test (i.e. t_U). Thus, $F(t_U)$ is known.

Since all quantities in equation [17] except η are now known, the equation is solved for η:

$$\eta = t_U/(\{-\ln[1-F(t_U)]\}^{1/m}) \qquad [18]$$

The units of η are the same as the units of t_U (typically hours or years)

Now that η is known, it is substituted into equation [17]. The desired time period is the early life time period, t_{ELF}. The result is $F(t_{ELF})$, which is the cumulative distribution function at the time t_{ELF}. This is the CDF from time zero to t_{ELF}, which is the desired ELFR.

$$F(t_{ELF}) = 1 - \exp[-(t_{ELF}/\eta)^m] \qquad [19]$$

Multiply by 10^6 to obtain ppm.

This ELFR cannot be expressed in FIT unless m = 1. So ppm must be used. The ppm value applies to the time period t_{ELF}.

The equations above are seldom used directly. The equation for the Weibull CDF gives the point estimate of the failure rate. This can lead to questionable results, especially in extreme cases. For example, if there are zero failures in the ELF test, then $F(t_U) = 0$, and η is undefined. One would conclude that the ELFR is zero.

Most often, the failure rate is desired at some upper confidence level (often 60%). Thus, the χ^2 distribution is used. Then the CDF, or F(t), for the ELF test in ppm is given by

$$\text{CDF at c\% confidence} = \chi^2_{c,d}/(2 \times N) \qquad [20]$$

where

- N = sample size
- χ^2 = chi squared statistic
- subscript c = desired confidence level (often 60%)
- subscript d = degrees of freedom = $2 \times f + 2$
- f = number of failures in the ELF test

This value is fraction failing at c% confidence in the ELF test. To obtain ppm, multiply by 10^6.

NOTE Equation [20] gives the CDF only at the ELF test time t_A. With the acceleration factor calculation, this is equivalent to t_U at use conditions ($t_U = A \times t_A$).) Therefore, equation [20] gives the failure rate only at time t_U. The ELFR at t_{ELF} must be calculated, as described below.

5.2 Decreasing failure rate (cont'd)

5.2.1 Decreasing failure rate, single ELF test (cont'd)

Since the value in equation [20] is the CDF at t_U, the Weibull distribution becomes

$$F(t_U \text{ at c\% confidence}) = 1 - \exp[-(t_U/\eta)^m] = \chi^2_{c,d}/(2 \times N) \qquad [21]$$

or expressed in ppm,

$$F(t_U) \text{ in ppm} = 10^6 (1 - \exp[-(t_U/\eta)^m]) = 10^6 \times \chi^2_{c,d}/(2 \times N) \qquad [22]$$

Next, equation [21] is solved for η (the CDF must be expressed as a fraction to solve for η).

$$\eta = t_U/(\{-\ln[1 - \chi^2_{c,d}/(2 \times N)]\}^{1/m}) \qquad [23]$$

In order to obtain $F(t_{ELF})$ the resulting value for η is substituted into equation [19]with $t = t_{ELF}$.

$$F(t_{ELF}) = 1 - \exp[-(t_{ELF}/\eta)^m]$$

This quantity is the ELFR expressed as a fraction. It represents the c%-confidence upper fraction of parts failing in the time period between 0 and t_{ELF}. Multiply by 10^6 to get the upper c%-confidence bound of the ELFR in ppm.

$$F(t_{ELF}) \text{ in ppm} = 10^6 \times \{1- \exp[-(t_{ELF}/\eta)^m]\} \qquad [24]$$

where
- $F(t_{ELF})$ = Failure rate in ppm of a device during early life failure time period
- t_{ELF} = the early life failure period
- η = the characteristic life

η is obtained from the ELF test results, as shown in equation [23]:

$$\eta = t_U/(\{-\ln[1 - \chi^2_{c,d}/(2 \times N)]\}^{1/m}) \qquad [25]$$

where
- t_U = use condition time in hours
- t_A = accelerated ELF test time
- A = acceleration factor of the ELF test
- N = sample size
- χ^2 = chi squared statistic
- subscript c = desired confidence level (often 60%)
- subscript d = degrees of freedom = $2 \times f + 2$
- f = number of failures in the ELF test

5.2.1.1 Calculation example: Decreasing failure rate–one failure mechanism, single ELF test

Assuming that the failure rate is decreasing and follows a Weibull distribution with m < 1, an example is shown in **Annex E**. It uses the same data as used in Annex A, and the two results are compared.

5.2 Decreasing failure rate (cont'd)

5.2.1 Decreasing failure rate, single ELF test (cont'd)

5.2.1.2 Calculation example: Decreasing failure rate–two failure mechanisms, single ELF test

Assuming that the failure rate is decreasing and follows a Weibull distribution with $m < 1$, an example is shown in **Annex F**. It uses the same data as is used in Annex B, and the two results are compared.

5.2.2 Decreasing failure rate–one failure mechanism, multiple ELF tests

As shown in equation [4], when an ELF test is performed, the equivalent time at use conditions, t_U, is the product of the acceleration factor, A, and the actual ELF test time, t_A. Using the Weibull distribution with decreasing rate for analyzing data from multiple ELF tests requires a more involved calculation. It is necessary to find the weighted average in order to obtain the ELFR for multiple tests. As an engineering method to translate a c%-confidence upper failure rate at t_U to a c%-confidence upper failure rate at t_{ELF} in the early life period with decreased failure rate, assuming a Weibull distribution and assuming the Weibull shape parameter, the calculation is done by determining a weighted average t_U (called t_{UWA}) for the aggregate of the ELF tests by taking the average, weighted by the sample size, of the t_U's of the individual tests. t_{UWA} becomes the parameter in the Weibull equations replacing t_U.

Suppose there are **n** ELF tests each producing a different t_U. The sample size of the i'th test is Ni. The t_U for the i'th test is t_{Ui}. The total sample size of all n tests is **S**.

The weighted average t_U is

$$t_{UWA} = \{\Sigma(N_i \times t_{Ui})\}/S \qquad \text{for } i = 1 \text{ to } n \qquad [26]$$

Then

$$F(t_{UWA}) = \chi^2_{c,d}/(2 \times S) = (1 - \exp[-(t_{UWA}/\eta_{WA})^m]) \qquad [27]$$

where

- m = Weibull shape parameter (either assumed or measured)
- S = total sample size of all the ELF tests
- χ^2 = chi squared statistic
- subscript c = desired confidence level (often 60%)
- subscript d = degrees of freedom = $2 \times f + 2$
- f = the combined number of failures in all tests
- η_{WA} is the weighted average value of η

All quantities in equation [27] are known except η_{WA}. Solving for η_{WA},

$$\eta_{WA} = t_{UWA}/(\{-\ln[1 - \chi^2_{c,d}/(2 \times S)]\}^{1/m}) \qquad [28]$$

Finally,

$$F(t_{ELF}) = 1 - \exp[-(t_{ELF}/\eta_{WA})^m] \qquad [29]$$

$$F(t_{ELF}), \text{ in ppm} = 10^6 \times \{1 - \exp[-(t_{ELF}/ \eta_{WA})^m]\} \qquad [30]$$

This is the same equation that is used for a single ELF test, equation [24]. The difference is that η_{WA}, which is based on the weighted average t_{UWA} of the tests, is the parameter used in place of η.

5.2 Decreasing failure rate (cont'd)

5.2.2 Decreasing failure rate–one failure mechanism, multiple ELF tests (cont'd)

5.2.2.1 Calculation example: Decreasing failure rate–one failure mechanism, multiple ELF tests

An example of an ELFR calculation for multiple ELF tests, assuming that the failure rate is decreasing and follows a Weibull distribution with $m < 1$, is shown in **Annex G**. This example uses the same data as is used in Annex C, and the two results are compared.

5.2.3 Decreasing failure rate–multiple failure mechanisms, multiple ELF tests

When there are few mechanisms and the failure rate for each is small, the exact value can be reasonably approximated by a simple sum of the failure rates for each mechanism. In the case of a decreasing failure rate, multiple failure mechanisms, and multiple ELF tests, the ELFR is calculated using the following method:

$$\text{Total ELFR (in ppm)} = \Sigma\ [\text{ELFR (mechanism i)}],\ i = 1 \text{ to } p \qquad [31]$$

where

$$\text{ELFR (in ppm) (mechanism i)} = 10^6 \times F_i\,(t_{ELF}) = 10^6 \times \{1 - \exp[-(t_{ELF}/\eta_i)^m]\} \qquad [32]$$

where

$F_i\,(t_{ELF})$ = ELFR due to failure mechanism i, during t_{ELF} duration
t_{ELF} = early life period
η_i = the characteristic life of the i'th failure mechanism
m = Weibull shape parameter
p = number of distinct failure mechanisms

Details on calculating $F_i(t_{ELF})$ can be found in 5.2.1 and the calculation process is illustrated in example 5.2.3.1.

Where multiple mechanisms are known, suspected, or possible, an acceptable alternative to quantify the combined failure rate (as cited further in 5.3) is to apply an empirically-justified composite acceleration factor to a group of failures.

5.2.3.1 Calculation example: Weibull distribution–two failure mechanisms, multiple ELF tests

An example of an ELFR calculation for multiple ELF tests and two failure mechanisms, assuming that the failure rate is decreasing and follows a Weibull distribution with $m < 1$, is shown in **Annex H**. This example uses the same data as is used in Annex D, and the two results are compared.

5.3 Alternate ELFR calculation for multiple failure mechanisms

It is recognized that using the simple sum of the failure rates when multiple failure mechanisms are observed can result in a calculated failure rate that is considerably higher than the failure rate actually observed. The reason lies in the fact that the χ^2 statistic is used to specify the failure rate at a certain confidence level. When each failure mechanism is considered separately, the χ^2 is applied to the failures for each mechanism and then these χ^2's are added together. The effect is to add the error estimates for each failure mechanism. Consequently the calculation using equation [15] or [31] causes the reported failure rate to be higher than is observed based on the total number of failures in the test. For this reason, an engineering method is presented here as an alternative for reporting the ELFR for multiple failure mechanisms, the supplier may report the ELFR in two ways: 1) using the calculation method illustrated in this document for multiple failure mechanisms as described in 5.1.3 and 5.2.3; and 2) using a weighted chi-square factor, as described below. First, the value of chi- square is calculated using the sum of all failures in the test (thus aggregating the failures). This aggregate chi-square is denoted by χ^2_{AGG}. Then a weighted, or effective, chi-square is calculated. This weighted chi-square, χ^2_F, compensates for adding the χ^2's for each failure mechanism.

The weighted chi-square factor is defined as follows,

$$\chi^2_F = \chi^2_{AGG} / \Sigma \left(\chi^2_i\right) \qquad [33]$$

where

χ^2_{AGG} = chi-square value based on the total number of failures in the test, regardless of failure mechanism

χ^2_i = chi-square value based on the number of failures for the i'th failure mechanism

The ELFR based on aggregating the failures in the test is given by

$$ELFR_{AGG} = \Sigma(ELFR_i) \times \chi^2_F \qquad [34]$$

where

$ELFR_{AGG}$ = early life failure rate based on total number of failures in the test

$ELFR_i$ = early life failure rate due to the i'th failure mechanism (as given by equation [16] or [32])

χ^2_F = weighted chi-square factor

This method avoids the adding the χ^2 for each failure mechanism and is thus more representative of the observed failure rate, especially when there are multiple ELF tests and/or some failure mechanisms exhibit no failures in the tests.

When multiple failure mechanisms are observed, reporting the ELFR using equation [15] or [31] is mandatory, and reporting the ELFR using equation [34] is optional.

Example: 373 FIT @ 60% UCL treating each failure mechanism separately
286 FIT @ 60% UCL aggregating the failure mechanisms

as shown in Annex B.

Alternatively, an empirically justified composite acceleration factor may be applied to handle situations where multiple mechanisms exist or are possible.

Annex A – Example using the exponential distribution with 1 failure mechanism and a single ELF test

Following are calculations of ELFR from an ELF test with the data given below:

Test conditions:	**Use conditions:**
Voltage, $V_A = 1.6V$	Voltage, $V_U = 1.2V$
$T_A = 130^oC$	$T_U = 70^oC$
Test duration, $t_A = 48$ hours	Early life period, $\mathbf{t_{ELF}} = 5,840$ hrs, or 8 months (8760 hours × 8/12)
Sample size, N = 3,000	
Number of failures, f = 2	
$E_{aa} = 0.65$ eV	
$\gamma_V = 5.5V^{-1}$	

60% confidence (Chi Square values are shown in **Annex J**)

Apply equation [1], $A_T = \exp[(0.65/k) \times (1/343 - 1/403)] = 26.4$

Apply equation [2], $A_V = \exp[5.5 \times (1.6\text{-}1.2)] = 9.03$

Apply equation [3], $A = A_T \times A_V = 238.5$

Use Table J.1 in Annex J to get χ^2 value for 2 failures. The degrees of freedom = 6, and $\chi^2 = 6.21$

Apply equation [6], $\text{ELFR (in FIT)} = 10^9 \times \chi^2_{c,d} /(2 \times A \times N \times t_A)$

$$\text{ELFR (in FIT)} = 10^9 \times \chi^2_{c,d} /(2 \times 238.5 \times 3000 \times 48\text{hr})$$

$$\text{ELFR (in FIT)} = 10^9 \times 6.21/(2 \times 238.5 \times 3000 \times 48\text{hr}) = 90 \text{ FIT}$$

To express the ELFR in ppm during the early life period, t_{ELF} , use equation [12],

ELFR (in ppm, 8 months) = $5,840 \times 10^{-3} \times 90$ FIT = 528 ppm during the first 8 months of usage.

Suppose the early life period is specified to be 6 or 12 months respectively, while the FIT rate remains the same (since the failure **rate** is a constant) the ppm level does not. The ppm is:

ELFR (in ppm, 6 months) = $4,380 \times 10^{-3} \times 90$ FIT = 396 ppm during the first 6 months of usage
ELFR (in ppm, 12 months) = $8,760 \times 10^{-3} \times 90$ FIT = 792 ppm during the first 12 months of usage.

Annex B - Example using the exponential distribution with 2 failure mechanisms and a single ELF test

Following are calculations of ELFR from an ELF test with the data given below:

ELFR test conditions:
Voltage, $V_A = 3.9V$
Temperature, $T_A = 125^oC$
Test duration, $t_A = 48$ hours
Sample size, N = 3,000
Number of failures, f = 2 (1 gate oxide, 1 metal particle)
$E_{aa} = 0.7$ eV, $\gamma_V = 3.0\ V^{-1}$ for gate oxide failure
$E_{aa} = 0.5$ eV, $\gamma_V = 1.0\ V^{-1}$ for metal particle failure
60% confidence (Chi Square values are shown in Annex J)

Use conditions:
Voltage, $V_U = 3.3V$
Temperature, $T_U = 55^oC$
Early life period, $\mathbf{t_{ELF}}$ = 6 months or 4,380 hours (8,760 hrs × 6/12)

Gate oxide acceleration factor calculation:

Apply equation [1], $A_T = \exp[(0.7/k) \times (1/328 - 1/398)] = 77.9$
Apply equation [2], $A_V = \exp[3 \times (3.9 - 3.3)] = 6.1$
Apply equation [3], $A = A_T \times A_V = 472$

Metal particle acceleration factor calculation:

Apply equation [1], $A_T = \exp[(0.5/k) \times (1/328 - 1/398)] = 22.5$
Apply equation [2], $A_V = \exp[1 \times (3.9 - 3.3)] = 1.8$
Apply equation [3], $A = A_T \times A_V = 41$

Use Table J.1 in Annex J to get χ^2 value for 1 failure. The degrees of freedom = 4, and $\chi^2 = 4.04$

Gate oxide ELFR (in FIT) $= 10^9 \times \chi^2_{c,d} / (2 \times A \times N \times t_A)$
$= 10^9 \times 4.04/(2 \times 472 \times 3{,}000 \times 48)$
= 30 FIT

Use Table J.1 in Annex J to get χ^2 value for 1 failure. The degrees of freedom = 4, and $\chi^2 = 4.04$

Metal Particle ELFR (in FIT) $= 10^9 \times 4.04/(2 \times 41 \times 3{,}000 \times 48)$
= 343 FIT

Since the failure level is small,

ELFR (in FIT) = 30 FIT + 343 FIT = 373 FIT

To express the ELFR in ppm during the early life period, t_{ELF} , use equation [12]

ELFR (in ppm, 4,380 hrs) $= 4{,}380 \times 10^{-3} \times 373$ FIT = 1,632 ppm during the first 6 months of usage.

Suppose the early life period is specified to be 12 months (8,760 hrs), while the FIT rate remains the same (since the failure **rate** is a constant) the ppm level does not. The ppm is:

ELFR (in ppm, 8,760 hrs) $= 8{,}760 \times 10^{-3} \times 373$ FIT = 3,264 ppm during the first 12 months of usage.

Annex B - Example using the exponential distribution with 2 failure mechanisms and a single ELF test (cont'd)

An alternate calculation of the $ELFR_{AGG}$ as presented in 5.3 is shown below.

Use Table J.1 in Annex J to get χ^2 value for 2 aggregate failures, $\chi^2_{AGG} = \chi^2_{60\%, 6} = 6.21$

Using equation [33]

$$\chi^2_F = \chi^2_{AGG} / \Sigma (\chi^2_i) = 6.21 / (4.04 + 4.04) = 0.769$$

Using equation [34]

$$ELFR_{AGG} = \Sigma(ELFR_i) \times \chi^2_F = 373 \times 0.769 = 286 \text{ FIT}$$

With this alternate calculation, the ELFRs are summarized as follows:

ELFR (in FIT) = 373 FIT @ 60% UCL treating each failure mechanism separately
$ELFR_{AGG}$ (in FIT) = 286 FIT @ 60% UCL aggregating the failure mechanisms
ELFR (in ppm, 4,380 hrs) = 1,632 ppm during the first 6 months of usage.
$ELFR_{AGG}$ (in ppm, 4,380 hrs) = $4{,}380 \times 10^{-3} \times 286$ FIT = 1,255 ppm during the first 6 months of usage.
ELFR (in ppm, 8,760 hrs) = 3,264 ppm during the first 12 months of usage.
$ELFR_{AGG}$ (in ppm, 8,760 hrs) = $8{,}760 \times 10^{-3} \times 286$ FIT = 2,509 ppm during the first 12 months of usage.

Annex C – Example using the exponential distribution with 1 failure mechanism in 3 ELF tests

Calculation of ELFR from an ELF test involved three lot samples with the data given below.

	ELF Test lot #1	**ELF Test lot#2**	**ELF Test lot#3**
Use temperature, T_U	55 deg. C, 328 deg. K	55 deg. C, 328 deg. K	55 deg. C, 328 deg. K
Stress temperature, T_A	125 deg. C, 398 deg. K	125 deg. C, 398 deg. K	125 deg. C, 398 deg. K
Use voltage, V_U	1.2 V	1.2 V	1.2 V
Stress voltage, V_A	1.6 V	1.6 V	1.6 V
E_{aa}	0.7 eV	0.7 eV	0.7 eV
Electric field, γ_V	5 V^{-1}	5 V^{-1}	5 V^{-1}
ELF test time, t_A	48 hrs	24 hrs	48 hrs
Sample size, N	1,000	1,500	1,200
Number of failures, f	2	1	0

Confidence level = 60 percent (Chi Square values are shown in Annex J)
Early life period, $\mathbf{t_{ELF}}$ = 6 months or 4,380 hours, and 12 months or 8,760 hours.

Apply equations [1], [2], and [3] to calculate the acceleration factor, A, for each of the tests:

$A_{T1} = \exp[(0.7/k) \times (1/328 – 1/398)] = 77.9$; $A_{V1} = \exp[5 \times (1.6 – 1.2)] = 7.4$; $A_1 = 77.9 \times 7.4 = 576$

$A_{T2} = \exp[(0.7/k) \times (1/328 –1/398)] = 77.9$; $A_{V2} = \exp[5 \times (1.6 – 1.2)] = 7.4$; $A_2 = 77.9 \times 7.4 = 576$

$A_{T3} = \exp[(0.7/k) \times (1/328 –1/398)] = 77.9$; $A_{V3} = \exp[5 \times (1.6 – 1.2)] = 1.7.4$; $A_3 = 77.9 \times 1.7.4 = 576$

Use Table J.1 in Annex J to get χ^2 value of 3 failures, degrees of freedom = 8: χ^2 value = 8.35

Apply equation [14] to calculate the ELFR (in FIT):

ELFR (in FIT) = $10^9 \times 8.35/[(2\times576\times1{,}000\times48)+(2 \times 576 \times 1{,}500 \times 24)+(2\times 576 \times 1{,}200 \times 48)]$= 51 FIT

To express the ELFR in ppm during the early life period, t_{ELF} , use equation [12]

ELFR (in ppm, 4,380 hrs) = $4{,}380 \times 10^{-3} \times 51$ FIT = 224 ppm during the first 6 months of usage.

For the early life period of 12 months, the ppm is:

ELFR (in ppm, 8,760 hrs) = $8{,}760 \times 10^{-3} \times 51$ FIT = 448 ppm during the first 12 months of usage.

Annex D – Example using the exponential distribution with 2 failure mechanisms in 3 ELF tests

Calculation of ELFR from an ELF test involved three lot samples with the data given below.

	ELF Test lot #1	ELF Test lot#2	ELF Test lot#3
Use temperature, T_U	55 deg. C, 328 deg. K	55 deg. C, 328 deg. K	55 deg. C, 328 deg. K
Stress temperature, T_A	125 deg. C, 398 deg. K	125 deg. C, 398 deg. K	125 deg. C, 398 deg. K
Use voltage, V_U	1.2 V	1.2 V	1.2 V
Stress voltage, V_A	1.6 V	1.6 V	1.6 V
E_{aa}	Note 1	Note 1	Note 1
Electric field, γ_V	Note 2	Note 2	Note 2
ELF test time, t_A	48 hrs	48 hrs	48 hrs
Sample size, N	1,000	1,500	1,200
Number of failures, f	2 (1 failure mech."A", 1 "B")	1 (1 failure mech. "A")	0
NOTE 1 E_{aa}: Failure mechanism "A" = 0.7 eV, failure mechanism "B" = 0.65 eV NOTE 2 Electric field, γ_V : Failure mechanism "A" = 5 V^{-1}, failure mechanism "B" = 6 V^{-1}			

Confidence level = 60 percent (Chi Square values are shown in Annex J)

Early life period, $\mathbf{t_{ELF}}$ = 6 months or 4,380 hours, and 12 months or 8,760 hours.

Apply equations [1], [2], and [3] to calculate the acceleration factor, A, for each of the failure mechanisms:

<u>A for failure mechanism "A":</u>
$A_{T1} = \exp[(0.7/k) \times (1/328 - 1/398)] = 77.9$; $A_{V1} = \exp[5 \times (1.6 - 1.2)] = 7.4$; $A_1 = 77.9 \times 7.4 = 576$

<u>A for failure mechanism "B":</u>
$A_{T2} = \exp[(0.65/k) \times (1/328 - 1/398)] = 57.1$; $A_{V2} = \exp[6 \times (1.6 - 1.2)] = 11.0$; $A_2 = 57.1 \times 11.0 = 629$

Apply equation [16] to calculate the ELFR for each of the failure mechanisms:

<u>ELFR of failure mechanism "A":</u>
Use Table J.1 in Annex J to get χ^2 value of 2 failures, degrees of freedom = 6: χ^2 value = 6.21, N_1 = 1,000, N_2 = 1,500, N_3 = 1,200, t_1 = 48, t_2 = 48, t_3= 48.

$$\text{ELFR (mechanism "A")} = 10^9 \times \chi^2_{c,d} / [2 \times A_1 \times \Sigma(N_z \times t_z)],\ z = 1 \text{ to } 3$$
$$= 10^9 \times 6.21 / [2 \times 576 \times (1{,}000 \times 48 + 1{,}500 \times 48 + 1{,}200 \times 48)]$$
$$= 10^9 \times 6.21 / [2 \times 576 \times 177{,}600] = 30 \text{ FIT}$$

<u>ELFR of failure mechanism "B":</u>
Use Table J.1 in Annex J to get χ^2 value of 1 failure, degrees of freedom = 4: χ^2 value = 4.04, N_1 = 1,000, N_2 = 1,500, N_3 = 1,200, t_1 = 48, t_2 = 48, t_3= 48.

$$\text{ELFR (mechanism "B")} = 10^9 \times \chi^2_{c,d} / [2 \times A_2 \times \Sigma(N_z \times t_z)],\ z = 1 \text{ to } 3$$
$$= 10^9 \times 4.04 / [2 \times 629 \times (1{,}000 \times 48 + 1{,}500 \times 48 + 1{,}200 \times 48)]$$
$$= 10^9 \times 4.04 / [2 \times 629 \times 177{,}600] = 18 \text{ FIT}$$

Annex D – Example using the exponential distribution with 2 failure mechanisms in 3 ELF tests (cont'd)

Since the failure level is small,

Apply equation [15],

Total ELFR (in FIT) = ELFR (mechanism "A") + ELFR (mechanism "B") = 30 + 18 = 48 FIT

To express the ELFR in ppm during the early life period, t_{ELF} , use equation [12]
ELFR (in ppm, 4,380 hrs) = 4,380 $\times 10^{-3} \times$ 48 FIT = 212 ppm during the first 6 months of usage.

For the early life period of 12 months, the ppm is:
ELFR (in ppm, 8,760 hrs) = 8,760 $\times 10^{-3} \times$ 48 FIT = 424 ppm during the first 12 months of usage.

An alternate calculation of the $ELFR_{AGG}$ as presented in 5.3 is shown below.

Use Table J.1 in Annex J to get χ^2 value for 3 aggregate failures, $\chi^2_{AGG} = \chi^2_{60\%, 8} = 8.35$

Using equation [33]

$$\chi^2_F = \chi^2_{AGG} / \Sigma\,(\chi^2_i) = 8.35 / (6.21 + 4.04) = 0.815$$

Using equation [34]

$$ELFR_{AGG} = \Sigma(ELFR_i) \times \chi^2_F = 48 \times 0.815 = 39 \text{ FIT}$$

With this alternate calculation, the ELFRs are summarized as follows:

ELFR (in FIT) = 48 FIT @ 60% UCL treating each failure mechanism separately
$ELFR_{AGG}$ (in FIT) = 39 FIT @ 60% UCL aggregating the failure mechanisms
ELFR (in ppm, 4,380 hrs) = 212 ppm during the first 6 months of usage.
$ELFR_{AGG}$ (in ppm, 4,380 hrs) = 4,380 $\times 10^{-3} \times$ 39 FIT = 173 ppm during the first 6 months of usage.
ELFR (in ppm, 8,760 hrs) = 424 ppm during the first 12 months of usage.
$ELFR_{AGG}$ (in ppm, 8,760 hrs) = 8,760 $\times 10^{-3} \times$ 39 FIT = 345 ppm during the first 12 months of usage.

Annex E – Example using a Weibull distribution with decreasing rate with 1 failure mechanism and a single ELF test

The example given in Annex A in which ELFR is calculated using exponential distribution is repeated here assuming a Weibull distribution with decreasing rate.

ELF test conditions:	**Use conditions:**
Voltage, V_A = 1.6V	Voltage, V_U = 1.2V
$T_A = 130^oC$	$T_U = 70^oC$
Test duration, t_A = 48 hours	Early life period, $\mathbf{t_{ELF}}$ = 5,840 hrs, or 8 months (8760 hours × 8/12)

Sample size, N = 3,000, Number of failures, f = 2, E_{aa} = 0.65 eV, $\gamma_V = 5.5V^{-1}$

Assume m = 0.4 and 60% confidence (Chi Square values are shown in Annex J)

Apply equation [1], $A_T = \exp[(0.65/k) \times (1/343 – 1/403)] = 26.4$
Apply equation [2], $A_V = \exp[5.5(1.6 – 1.2)] = 9.03$
Apply equation [3], $A = A_T \times A_V = 238.5$
Apply equation [4], $t_U = 238.5 \times 48$ hr = 11,446 hr

Use Table J.1 in Annex J to get χ^2 value for 2 failures. The degrees of freedom = 6, and $\chi^2 = 6.21$

Apply equation [21], $F(t_U \text{ at c\% confidence}) = \chi^2_{c,d}/(2 \times N)$
$= \chi^2_{c,d}/(2 \times 3{,}000) = 6.21 / (6{,}000)$
$= 0.001035$

Equation [22] gives ELFR or $F(t_U$ at 60% confidence, in ppm) = 1,035 ppm

Apply equation [23], $\eta = t_U \times \{\ln[1/(1 – F(t_U))]\}^{-1/m} = 11{,}446 \text{ hr} \times \{\ln[1/(1-0.001035)]\}^{-1/0.4}$
$\eta = 11{,}446\text{hr} \times \{1.001036\}^{-2.5} = 3.317 \times 10^{11}$ hours

Now apply equation [24] to find $ELFR(t_{ELF})$ in ppm,

ELFR in ppm = $F(t_{ELF}) = 10^6 \times \{1 – \exp[-(t_{ELF}/\eta)^m]\}$
$= F(5{,}840 \text{ hr}) = 10^6 \times \{1-\exp[-(5{,}840/(3.317 \times 10^{11}))^{0.4}] = 791$ ppm

NOTE This value using Weibull distribution, m = 0.4, is higher than the value obtained using the exponential distribution, m = 1, for the same data set. If a constant failure rate is assumed, a value of m = 1 used for the calculations, the $ELFR(t_{ELF})$ in ppm will yield the same value (528 ppm) as in example in Annex A. The reason that m = 0.4 gives a higher ELFR is that t_U is greater than t_{ELF}. If t_U had been smaller than t_{ELF}, the ELFR derived using the exponential distribution would have been higher than the ELFR using the Weibull distribution.

Annex F – Example using the Weibull distribution with 2 failure mechanisms and a single ELF test

The example given in Annex B in which ELFR is calculated using exponential distribution is repeated here assuming a Weibull distribution with decreasing rate.

ELFR test conditions: Voltage, $V_A = 3.9V$, Temperature, $T_A = 125^oC$
Use conditions: Voltage, $V_U = 3.3V$, Temperature, $T_U = 55^oC$
Test duration, t_A = 48 hours, Early life period, $\mathbf{t_{ELF}}$ = 6 months or 4,380 hours (8,760 hrs × 6/12)
Sample size, N = 3,000, Number of failures, f = 2 (1 gate oxide, 1 metal particle)
$E_{aa} = 0.7$ eV, $\gamma_V = 3.0\ V^{-1}$ for gate oxide failure, $E_{aa} = 0.5$ eV, $\gamma_V = 1.0\ V^{-1}$ for metal particle failure
Assume m = 0.4 and 60% confidence (Chi Square values are shown in Annex J).

Gate oxide acceleration factor calculation:
Apply equation [1], $A_T = \exp[(0.7/k) \times (1/328 – 1/398)] = 77.9$
Apply equation [2], $A_V = \exp[3 \times (3.9 – 3.3)] = 6.1$
Apply equation [3], $A = A_T \times A_V = 472$
Apply equation [4], $t_U = 472 \times 48$ hr $= 22,633$ hr

Use Table J.1 in Annex J to get χ^2 value for 1 failure. The degrees of freedom = 4, and $\chi^2 = 4.04$

Apply equation [21], $F(t_U \text{ at c\% confidence}) = \chi^2_{c,d}/(2 \times N)$
$= \chi^2_{c,d} /(2 \times 3,000) = 4.04/(6,000) = 0.000673333$

Equation [22] gives ELFR or F(t_U at 60% confidence, in ppm) = 673 ppm

Apply equation [23], $\eta = t_U \times \{\ln[1/(1 – F(t_U))]\}^{-1/m} = 22,633 \text{ hr} \times \{\ln[1/(1-0.000673333)]\}^{-1/0.4}$
$\eta = 22,633 \text{ hr} \times [0.00067356]^{-2.5} = 1.922 \times 10^{12}$ hours

Now apply equation [24] to find ELFR(t_{ELF}) in ppm,

ELFR in ppm $= F(t_{ELF}) = 10^6 \times \{1 – \exp[-(t_{ELF}/\eta)^m]\}$
$= F(4,380 \text{ hr}) = 10^6 \times \{1 – \exp[-(4,380/ 1.922 \times 10^{12})^{0.4}] =$ **349 ppm**

Metal particle acceleration factor calculation:
Apply equation [1], $A_T = \exp[(0.5/k) \times (1/328 – 1/398)] = 22.5$
Apply equation [2], $A_V = \exp[1 \times (3.9 – 3.3)] = 1.8$
Apply equation [3], $A = A_T \times A_V = 41$
Apply equation [4], $t_U = 41 \times 48$ hr $= 1,964$ hr

Use Table J.1 in Annex J to get χ^2 value for 1 failure. The degrees of freedom = 4, and $\chi^2 = 4.04$
Apply equation [21], $F(t_U \text{ at c\% confidence}) = \chi^2_{c,d}/(2 \times N)$
$= \chi^2_{c,d} /(2 \times 3,000) = 4.04 /(6,000)$
$= 0.000673333$

Equation [22] gives ELFR or F(t_U at 60% confidence, in ppm) = 673 ppm
Apply equation [23], $\eta = t_U \times \{\ln[1/(1 – F(t_U))]\}^{-1/m} = 1,964 \text{ hr} \times \{\ln[1/(1-0.000673333)]\}^{-1/0.4}$
$\eta = 1,964 \text{ hr} \times [0.00067356]^{-2.5} = 1.668 \times 10^{11}$ hours

Annex F – Example using the Weibull distribution with 2 failure mechanisms and a single ELF test (cont'd)

Now apply equation [24] to find ELFR(t_{ELF}) in ppm,

ELFR in ppm = $F(t_{ELF}) = 10^6 \times \{1 - \exp[-(t_{ELF}/\eta)^m]\}$
$= F(4{,}380\ \text{hr}) = 10^6 \times \{1\text{-}\exp[-(4{,}380/1.668 \times 10^{11})^{0.4}] =$ **927 ppm**

Since the failure level is small,

Total ELFR (in ppm, at 4,380 hours, for both failure mechanisms) = 349 + 927 = **1,276 ppm**

NOTE This value using Weibull distribution, m = 0.4, is lower than the value obtained using the exponential distribution, m = 1, for the same data set. If a constant failure rate is assumed, a value of m = 1 used for the calculations, the ELFR(t_{ELF}) in ppm will yield the same value (1,632 ppm) as the example in Annex B.

An alternate calculation of the ELF R_{AGG} as presented in 5.3 is shown below.

Use Table J.1 in Annex J to get χ^2 value for 2 aggregate failures, $\chi^2_{AGG} = \chi^2_{60\%, 6} = 6.21$

Using equation [33]

$$\chi^2_F = \chi^2_{AGG} / \Sigma(\chi^2_i) = 6.21 / (4.04 + 4.04) = 0.769$$

Using equation [34]

$$ELFR_{AGG} = \Sigma(ELFR_i) \times \chi^2_F = 1{,}276\ \text{ppm} \times 0.769 = 980\ \text{ppm}$$

With this alternate calculation, the ELFRs are summarized as follows:

ELFR (in ppm, 4,380 hrs) = 1,276 ppm @ 60% UCL during the first 6 months of usage.
$ELFR_{AGG}$ (in ppm, 4,380 hrs) = 980 ppm @ 60% UCL during the first 6 months of usage.

Annex G – Example using a Weibull distribution with decreasing rate with 1 failure mechanism and 3 ELF tests

The example given in Annex C in which ELFR was calculated using exponential distribution from several ELF tests is repeated here assuming a Weibull with decreasing rate distribution.

Calculation of ELFR from three ELF tests with the data given below.

	ELF Test lot#1	**ELF Test lot#2**	**ELF Test lot#3**
Use temperature, T_U	55 deg.C, 328 deg. K	55 deg.C, 328 deg. K	55 deg.C, 328 deg. K
Stress temperature, T_A	125 deg.C, 398 deg. K	125 deg. C, 398 deg. K	125 deg.C, 398 deg. K
Use voltage, V_U	1.2 V	1.2 V	1.2 V
Stress voltage, V_A	1.6 V	1.6 V	1.6 V
E_{aa}	0.7 eV	0.7 eV	0.7 eV
Electric field, γ_V	5 V^{-1}	5 V^{-1}	5 V^{-1}
ELF test time, t_A	48 hrs	24 hrs	48 hrs
Sample size, N	1,000	1,500	1,200
Number of failures, f	2	1	0

Assume m = 0.4 and 60% confidence (Chi Square values are shown in Annex J),
Early life period, $\mathbf{t_{ELF}}$ = 6 months or 4,380 hours, and 12 months or 8,760 hours.

Apply equations [1], [2], and [3] to calculate the acceleration factor, A, for each of the tests:
A_{T1} = exp[(0.7/k) × (1/328 – 1/398)] = 77.9; A_{V1} = exp[5 × (1.6 – 1.2)] = 7.4; A_1 = 77.9 × 7.4 = 575

Apply equation [4] to calculate the t_U's for the three ELF tests:
t_{U1} = 575 × 48 hours = 27,644 hours
t_{U2} = 575 × 24 hours = 13,822hours
t_{U3} = 575 × 48 hours = 27,644hours
S = N1 + N2 + N3 = 1,500 + 1,200 + 1,000 = 3,700

Apply equation [26] to calculate t_{UWA},
t_{UWA} = {Σ(Ni × t_{Ui})}/S = (1,000 × 27,644 + 1,500 × 13,822+ 1,200 × 27,644) /(3,700)
t_{UWA} = 22,040 hours

Use Table J.1 in Annex J to get χ^2 value for 3 failures. The degrees of freedom = 8, and χ^2 = 8.35

Apply equation [28] to get the weighted average value of the characteristic time, η_{WA},
η_{WA} = 22,040 /({-ln[1 – 8.35/(2 × 3,700)]}$^{1/m}$) = 5.146 × 10^{11} hours

Apply equation [29] to get the ELFR for early life failure period, t_{ELF} = 4,380 hrs and 8,760 hours
F(4,380 hrs) = 1 – exp [-(4,380 / 5.146 × 10^{11})$^{0.4}$] = 0.000591391
F(8,760 hrs) = 1 – exp [-(8,760 / 5.146 × 10^{11})$^{0.4}$] = 0.000780271

In ppm, the ELFR at 6 months and at 12 months from equation [31] are:

ELFR for 6 months = 591 ppm
ELFR for 12 months = 780 ppm

NOTE These values using Weibull distribution, m = 0.4, are higher than the values obtained using the exponential distribution, m = 1, for the same data set. If a value of m = 1 is used for the above calculations, the ELFR (t_{ELF}) in ppm will yield the same values (224 ppm and 448 ppm respectively) as the example in Annex C.

Annex H – Example using a Weibull distribution with decreasing rate with 2 failure mechanisms and 3 ELF tests

The example given in Annex D in which ELFR was calculated using exponential distribution from several ELF tests is repeated here assuming a Weibull distribution with decreasing rate.

Calculation of ELFR from three ELF tests with the data given below.

	ELF Test lot #1	**ELF Test lot#2**	**ELF Test lot#3**
Use temperature, T_U	55 deg. C, 328 deg. K	55 deg. C, 328 deg. K	55 deg. C, 328 deg. K
Stress temperature, T_A	125 deg. C, 398 deg. K	125 deg. C, 398 deg. K	125 deg. C, 398 deg. K
Use voltage, V_U	1.2 V	1.2 V	1.2 V
Stress voltage, V_A	1.6 V	1.6 V	1.6 V
E_{aa}	Note 1	Note 1	Note 1
Electric field, γ_V	Note 2	Note 2	Note 2
ELF test time, t_A	48 hrs	48 hrs	48 hrs
Sample size, N	1,000	1,500	1,200
Number of failures, f	2 (1failure mech.“A”,1“B”)	1 (1 failure mech. “A”)	0
NOTE 1 E_{aa}: Failure mechanism “A” = 0.7 eV, failure mechanism “B” = 0.65 eV			
NOTE 2 Electric field, γ_V : Failure mechanism “A” = 5 V^{-1}, failure mechanism “B” = 6 V^{-1}			

Confidence level = 60 percent (Chi Square values are shown in Annex J)
Early life period, t_{ELF} = 6 months or 4,380 hours, and 12 months or 8,760 hours.

Apply equations [1], [2], and [3] to calculate the acceleration factor, A, for each of the tests with failures:

A_{T1} = exp[(0.7/k) × (1/328–1/398)] = 77.9; A_{V1} = exp[5 × (1.6–1.2)] = 7.4; A_1 = 77.9 × 7.4 = 575
A_{T2} = exp[(0.65/k) × (1/328–1/398)] = 57.1; A_{V2} = exp[6 × (1.6–1.2)] = 11.0; A_2 = 57.1 × 11.0 = 629

Apply equation [4] to calculate the t_U’s for the two ELF tests with failures:

<u>Failure “A,</u> t_{U1} = 575 × 48 hours = 27,644 hours
<u>Failure “B”</u>, t_{U2} = 629 × 48 hours = 30,213 hours

Total sample size, S = N1 + N2 + N3 = 1,500 + 1,200 + 1,000 = 3,700

Use Table J.1 in Annex J to get χ^2 value for 1 and 2 failures. The degrees of freedom = 4, 6, and χ^2 = 4.04, 6.21 for 1 and 2 failures respectively.

<u>Failure “A”</u>:
Apply equation [21], F(t_U at c% confidence) = $\chi^2_{c,d}$/(2 × N)
= $\chi^2_{c,d}$ /(2 × 3,700) = 6.21 /(7,400) = 0.000839189

Equation [22] gives ELFR or F(t_U at 60% confidence, in ppm) = 839 ppm

Apply equation [23], $\eta = t_U / \{-\ln[(1 - F(t_U))]\}^{1/m}$ = 27,644 / $\{-\ln[(1-0.000839189)]\}^{1/0.4}$
η = 27,644 hr × $[0.000839542]^{-2.5}$ = 1.354 × 10^{12} hours

Annex H – Example using a Weibull distribution with decreasing rate with 2 failure mechanisms and 3 ELF tests (cont'd)

Now apply equation [24] to find ELFR(t_{ELF}) in ppm,

ELFR in ppm = $F(t_{ELF}) = 10^6 \times \{1 - \exp[-(t_{ELF}/\eta)^m]\}$
$= F(4{,}380\text{ hr}) = 10^6 \times \{1\text{-}\exp[-(4{,}380/ 1.354 \times 10^{12})^{0.4}] =$ **402 ppm**

Failure "B":
Apply equation [21], $F(t_U \text{ at c\% confidence}) = \chi^2_{c,d}/(2 \times N)$
$= \chi^2_{c,d} /(2 \times 3{,}700) = 4.04 /(7{,}400) = 0.000545946$

Equation [22] gives ELFR or $F(t_U$ at 60% confidence, in ppm) = 546 ppm

Apply equation [23], $\eta = t_U / \{-\ln[(1 - F(t_U))]\}^{1/m} = 30{,}213 \text{ hr} / \{-\ln[(1\text{-}0.000545946)]\}^{1/0.4}$
$\eta = 30{,}213 \text{ hr} \times [0.000546095]^{-2.5} = 4{,}335 \times 10^{12}$ hours

Now apply equation [24] to find ELFR(t_{ELF}) in ppm,

ELFR in ppm = $F(t_{ELF}) = 10^6 \times \{1 - \exp[-(t_{ELF}/\eta)^m]\}$
$= F(4{,}380\text{ hr}) = 10^6 \times \{1\text{-}\exp[-(4{,}380/ 4{,}335 \times 10^{12})^{0.4}] =$ **252 ppm**

Since the failure level is small,

Total ELFR for 6 months (4,380 hours) in ppm = **402 + 252 = 654 ppm**

The same calculation can also be done for 1 year (8,760 hours):

Failure "A:
ELFR in ppm = $F(t_{ELF}) = 10^6 \times \{1 - \exp[-(t_{ELF}/\eta)^m]\}$
$= F(8{,}760\text{ hr}) = 10^6 \times \{1\text{-}\exp[-(8{,}760 / 1.354 \times 10^{12})^{0.4}] =$ **530 ppm**

Failure "B":
ELFR in ppm = $F(t_{ELF}) = 10^6 \times \{1 - \exp[-(t_{ELF}/\eta)^m]\}$
$= F(8{,}760\text{ hr}) = 10^6 \times \{1 - \exp[-(8{,}760 / 4{,}335 \times 10^{12})^{0.4}] =$ **333 ppm**

Since the failure level is small,

Total ELFR for 1 year (8,760 hours) in ppm = **530 + 333 = 863 ppm**

In summary, the ELFR at 6 months and at 12 months from equation [17] are:

ELFR for 6 months = 654 ppm
ELFR for 12 months = 863 ppm

NOTE These values using Weibull distribution, m = 0.4, are higher than the values obtained using the exponential distribution, m = 1, for the same data set. If a value of m = 1 is used for the above calculations, the ELFR (t_{ELF}) in ppm will yield the same values (212 ppm and 424 ppm respectively) as the example in Annex D.

Annex H – Example using a Weibull distribution with decreasing rate with 2 failure mechanisms and 3 ELF tests (cont'd)

An alternate calculation of the $ELFR_{AGG}$ as presented in 5.3 is shown below.

Use Table J.1 in Annex J to get χ^2 value for 3 aggregate failures, $\chi^2_{AGG} = \chi^2_{60\%, 8} = 8.35$

Using equation [33]

$$\chi^2_F = \chi^2_{AGG} / \Sigma (\chi^2_i) = 8.35 / (6.21 + 4.04) = 0.815$$

Using equation [34]

Aggregate ELFR (in ppm, 6 months) = $ELFR_{AGG} = \Sigma(ELFR_i) \times \chi^2_F = 654 \times 0.815 = 532$ ppm

Aggregate ELFR (in ppm, 12 months) = $ELFR_{AGG} = \Sigma(ELFR_i) \times \chi^2_F = 863 \times 0.815 = 703$ ppm

With this alternate calculation, the ELFRs are summarized as follows:

ELFR (in ppm, 4,380 hrs) = 654 ppm @ 60% UCL during the first 6 months of usage.
$ELFR_{AGG}$ (in ppm, 4,380 hrs) = 532 ppm @ 60% UCL during the first 6 months of usage.
ELFR (in ppm, 8,760 hrs) = 863 ppm @ 60% UCL during the first 12 months of usage.
$ELFR_{AGG}$ (in ppm, 8,760 hrs) = 703 ppm @ 60% UCL during the first 12 months of usage.

Annex J – Chi Square values

Table J.1 — Chi-Square distribution, χ^2 values at various confidence levels

Failures	Degrees of Freedom	99%	95%	90%	80%	70%	60%	50%
0	2	9.21	5.99	4.61	3.22	2.41	1.83	1.39
1	4	13.28	9.49	7.78	5.99	4.88	4.04	3.36
2	6	16.81	12.59	10.64	8.56	7.23	6.21	5.35
3	8	20.09	15.51	13.36	11.03	9.52	8.35	7.34
4	10	23.21	18.31	15.99	13.44	11.78	10.47	9.34
5	12	26.22	21.03	18.55	15.81	14.01	12.58	11.34
6	14	29.14	23.68	21.06	18.15	16.22	14.69	13.34
7	16	32.00	26.30	23.54	20.47	18.42	16.78	15.34
8	18	34.81	28.87	25.99	22.76	20.60	18.87	17.34
9	20	37.57	31.41	28.41	25.04	22.77	20.95	19.34
10	22	40.29	33.92	30.81	27.30	24.94	23.03	21.34

Annex K (informative) Differences between JESD74A and JESD74

This table briefly describes most of the changes made to entries that appear in this standard, JESD74A, compared to its predecessor, JESD74 (April 2000). If the change to a concept involves any words added or deleted (excluding deletion of accidentally repeated words), it is included. Some punctuation changes are not included.

Page	**Description of change**
Cover	Title of document changed from “Early Life Failure Rate Calculation Procedure for Electronic Components” to “Early Life Failure Rate Calculation Procedure for Semiconductor Components.”
i	Table of contents added.
ii	Paragraph changed from “the most critical use period” to “the product’s first several months in the field.”
1	The purpose and scope sections are combined into a single “scope” section.
1	Reference documents section modified to include updated JEDEC documents.
2	Terms and definition updated to include additional terms used in the document.
4	In 4.1; modified to define a relative sampling plan.
4	In 4.3; revised to define test duration as the duration that users believe fit their test plan, depending on the acceleration factor.
5	Clause 5; revised to emphasize removal of component defects by effective reliability screens, instead of just “burn-in,” since it may include temperature cycling, stress voltages, etc.
6-end	Notations of acceleration factors and others are changed to reflect the latest terms and definitions in JEDEC documents.
6..	Introduced a new term , t_U, the equivalent actual use condition period. It is equal to the accelerated test duration times the acceleration factor. This term is used for Weibull distribution with decreasing rate of failure calculation.
6	Introduced a new term, t_{EFL}, the specified early life period. This allows users to calculate the early failure rate in FIT rates, and also to translate the FIT rates into ppm (parts per million), a metric normally used by industries for early failure rates.
8	Introduced constant failure rate and decreasing failure calculations with single ELF test, multiple ELF tests, single failure mode, and multiple failure modes while JESD74 only shows users one example with single ELF test with two failure modes. Examples shown in JESD74A are listed in the Annexes.
16	Introduced an engineering method as an alternative for reporting the ELFR for multiple failure mechanisms.
17-27	Annex A to Annex H show examples of different early life failure tests, single or multiple, and single or multiple failure mechanisms and how to calculate the early life failure rates. They also show users how to convert the FIT rates into ppm if this a selected outcome.
29	Chi Square Table values changed to reflect the Chi Square values instead of the UCL/2 values as shown in JESD74. The table was also moved to Annex J.

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