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Guidelines for GaAs MMIC PHEMT/MESFET and HBT Reliability Accelerated Life Testing

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Guidelines for GaAs MMIC PHEMT/MESFET and HBT Reliability Accelerated Life Testing

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Introduction

These guidelines apply to GaAs Monolithic Microwave Integrated Circuits (MMICs) and their individual component building blocks, such as GaAs Metal-Semiconductor Field Effect Transistors (MESFETs), Pseudomorphic High Electron Mobility Transistors (PHEMTs), Heterojunction Bipolar Transistors (HBTs), resistors, and capacitors. While the procedure described in this document may be applied to other semiconductor technologies, especially those used in RF and microwave frequency analog applications, it is primarily intended for technologies based on GaAs and related III-V material systems (InP, AlGaAs, InGaAs, InGaP, GaN, etc).

The objective of the tests described here is to estimate the expected wear-out lifetime of the devices at operational temperatures and normal electrical bias conditions; usually the median lifetime (50% failure) is projected for this purpose. The standard method for predicting device lifetime, where this value is too large (many years) to be measured directly, is to run a series of accelerated life tests. Generally, only one parameter, usually the device ambient temperature, is varied. A lifetime distribution is obtained at each stressed temperature. These values are then fit to an acceleration model and extrapolated to the temperature of interest. In other cases, the objective may be simply to determine the lifetime at a given temperature.

The purpose of this document is to define a standard approach for evaluating the expected life of GaAs MMICs so that results from different life tests can be compared, and so that a user of MMICs can predict a lifetime for a specific application. It is assumed in the wording of this document that the MMIC contains at least one FET or HBT, but the use of this document has no such limitations. Furthermore, the wording suggests that the failures occur at the transistor; if this is not the case, then the stresses, tests and failure criteria need to be re-evaluated to ensure that they are appropriate to the failing component.

To perform the life tests, a sample of devices is selected and subjected to a stress in excess of normal use conditions to accelerate the failure or to decrease the lifetime. The devices used can be MMICs. Alternatively, the lifetime of MMICs can be determined by determining the failure rate vs. time of component structures within the MMIC, e.g., FETs, PHEMTs, HBTs, resistors, capacitors and bond wires, given the structure and temperature profile of a MMIC. This latter calculation is not a straightforward one and a specific procedure is not addressed in this document. If it is assumed that the failure mechanisms are independent, the percentage of MMICs surviving to a given time is the product of the percentages of survival of each component.

Conducting accelerated tests of these devices can be very difficult because of the complexity of determining the channel temperature Tc in the PHEMT or junction temperature Tj in the HBT, the high cost of large sample sizes (especially where radio frequency (RF) stressing is performed), the possible device damages by EOS or mishandling during the multiple measurements, and the need to extrapolate to the temperatures of actual device use. In particular, any difference in the techniques for determining the device thermal resistance that results even in a small change of the thermal resistance value may have substantial impact on the corresponding predicted failure rate. For example, every 10°C increase in channel temperature would result in a factor of 1.5 to 3 in device lifetime reduction for activation energy of 1 eV according to Arrhenius model. The task of standardizing a method for determining channel or junction temperature is not addressed by this document; however, whichever technique is used should be documented and described in any resulting life test report.

Guidlines for GaAs PHEMT/MESFET and HBT Reliability Accelerated Life Testing

(From JEDEC Board Ballot JCB-18-35, formulated under the cognizance of JC-14.7 Subcommittee on Gallium Arsenide Reliability and Quality Standards.)

1 Scope

Life tests are run for various purposes. Tests run to detect the level of infant mortality involve short time duration; unless the percentage of devices having infant mortality is extremely high, the sample size specified in this document is not nearly sufficient. Tests to determine device lifetime for a specific application may be conducted by or for a customer; here the stress and test conditions may be specific to the application. Other life tests are run by a manufacturer and are concerned with determining the lifetime of devices under typical or extreme operation.

It is assumed that a given MMIC product is designated either as a power, general purpose, or low-noise (small signal) device, based on the intended use of the product. For low-noise devices and passive components, the RF voltage levels are small enough that it may be possible to simulate the stress accurately by imposing only DC bias.

This document applies both to packaged and unpackaged devices. Where the devices are bare die or in packages not suitable for stressing at high temperature, additional failures may occur due to the packaging, which are not considered part of the product being tested. If this occurs, such failures should be excluded from the population when calculating predicted failure rate.

Since it is unlikely that every structure and failure mechanism in a MMIC is known when these guidelines are written, some judgment must be used in applying the principles of this document to the specific tests. Where an unusual circumstance forces exceptions to these guidelines, the exception shall be stated in the life test report.

2 Related documents

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

JESD226, *RF Biased Life (RFBL) Test*

3 Sample selection and screening

Screens may include electrical measurements to eliminate devices that do not meet specification, thermal resistance or x-ray techniques to eliminate devices that will operate at atypical channel temperatures, and environmental stress to eliminate infant failures For more general application, the test may include an inspection and thermal and reliability screening to eliminate potential infant failures, so that enough devices survive to allow a valid lifetime calculation. The screening conditions and limits shall be included in the life test report.

The devices selected for life testing shall be representative of the lot being evaluated. If an application-specific life test is being run, the screen used shall be no more stringent than the production screen used before shipment of the product. For example, if a stabilization bake burn-in is not a standard process before product shipment, the selected device samples should not be baked before reliability lifetest.

4 Life tests

4.1 Electrical and thermal characterizations

Each of the devices to be life-tested (plus control samples) shall be electrically characterized in their life test packages prior to, periodically during, and at the end of life test. In addition to spot measurements, some functional I-V curves should be measured periodically with full electrical sweep to allow identification of the fundamental failure mode as well as any secondary modes. If the device has failed due to an EOS or ESD event, then simply measuring some spot parameters may not reveal the true cause.

Parameters to be measured will depend on the device function, but shall include every parameter that has a failure criterion, and shall be measured using the same method as during the life test. In some cases, the design of the MMIC will prevent measurement of certain parameters; otherwise, the following measurements should be made periodically:

PHEMT/MESFET

Spot measurements:

1. Saturated drain-source current (Idss), pinch-off voltage (Vp), channel-on resistance (Ron), transconductance (Gm)
2. drain-gate voltage at a reverse leakage current of 1 mA/mm channel width (BVdg)

Functional curves:

1. I-V family curves
2. Transfer curve
3. Forward and reverse diode characteristics
4. RF characteristics (such as gain, output power, noise figure; as appropriate for the technology and/or application)

4.1 Electrical and thermal characterizations (cont'd)

HBT

Spot measurements:

1. Current gain beta (β) and emitter resistance (Re) at nominal bias conditions (Ib, Ic)
2. Ideality factor;

Functional curves:

1. I-V family curves
2. Gummal plot
3. Forward base-collector and base-emitter diode characteristics;
4. RF characteristics (such as gain, output power, noise figure; as appropriate for the technology and/or application)

During accelerated stress, if possible, the in-situ stress voltage and currents for both gate (base) and drain (collector) should be recorded to monitor the degradation drift over time.

Power and general-purpose devices shall have 1dB compression point and, if possible, gate (base) current measured, while low noise devices shall have noise figure data. RF data shall be taken as a function of frequency and include a point in the center plus one point at each end of the band of interest for the device. These measurements will serve as the reference points to compare against subsequent data to determine the level of degradation that has taken place; consequently, no change in the test conditions or tuning shall be made. Measurement may be performed at any base plate temperature at or below 125 °C. Measurements made at elevated temperatures should be correlated to room temperature measurements.

Due to the sharp temperature dependence of degradation rate in GaAs transistors, it is vital to perform accurate assessment of device channel or junction temperature under various electrical biases. Thermal resistance shall be determined using infrared scan or any other test or modeling technique that becomes widely accepted after these guidelines are issued. For HBT, electrical measurements are widely employed using the Dawson [4] or Yeats [5] techniques. For PHEMT/MESFET, there has been no well-established, simple electrical technique to measure the thermal resistance. Alternatively, Cooke's model [6] has been widely used to calculate the channel temperature based on the FET geometry.

Experimental data shall be taken on at least 10% of the devices used for the life test to verify consistency. If the standard deviation of these measurements multiplied by the device power dissipation is no greater than 5 °C, the average value may be used for all devices. If this is not the case, then the relative thermal resistance of each device must be measured and used to determine the actual difference between case and channel temperature.

If a series of life tests is being run at different temperatures, due to a strong temperature dependence of thermal conductivity in GaAs, the device thermal resistance shall be determined at the case temperature of the second highest (+/- 25 °C) steady state life test temperature. If infrared scan is used, appropriate correction shall be made for infrared emissivity.

4.1 Electrical and thermal characterizations (cont'd)

For packaged devices, if infrared scan or liquid crystal is used, an electrical method shall be used to adjust the thermal resistances for the effect of the package lid. To do this, measure the device temperature using the electrical method (or other accepted method) before and after the lid is applied, calculate the increase in temperature, and add this to the value determined on the open package.

The rise above ambient of the hottest location on the test vehicle divided by the power dissipated by the device shall be used as the thermal resistance unless failure analysis shows that the predominant failure location is elsewhere. This value averaged over the devices measured may be used for all devices and temperatures in the life test to convert between case and channel temperatures unless thermal resistance has been determined on 100% of the devices. Thermal resistance at the maximum channel/junction temperature under worst-case use conditions should also be determined on a sample so that results obtained later can be related to a case temperature.

4.2 Step stress tests

If there are no data available on similar devices that can by used to determine the stress temperatures to be used, a step stress test shall be performed. This test should use at least six devices, and have the same bias and RF input power as is planned for the life test. Starting at 150 °C base plate temperature, proceed in steps of 25 °C, with a duration of at least 24 hours at each temperature. The electrical measurements to be used in the life test must be made between every step. Similar step stress tests using constant temperature and increasing the DC bias or RF input power may also be used to verify reasonable bias conditions for long-term constant stress life testing.

4.3 Choice of ambient temperatures and other operating conditions

The highest steady state stress temperature used shall be based on an expected median life of at least 100 hours. If too long an interval is used, the lowest temperature life test may take an unreasonable time or the life test temperatures may be too close together for a reasonable extrapolation. If the step stress test is used, the highest steady state stress base plate temperature shall be at least 20 °C below the step stress base plate temperature which produces 50% failure in 24 hours. In addition, if it is known that the dominant failure mechanism changes as the device temperature is raised above the temperature of application, the life tests shall be performed at temperatures below that transition temperature.

There shall be at least three temperatures of steady state stress. The second shall be at least 15 °C below the highest, and the third shall be at least 15 °C below the second. In addition, if the lowest of the three base plate temperatures is greater than 200 °C, a fourth sample of devices shall be run at a base plate temperature 50 °C above the device maximum operating temperature. If the maximum operating temperature is not specified, this fourth test shall be run at a base plate temperature of 150 °C for a minimum of 2000 hours to verify the validity of the extrapolation to the operation range. At this temperature, few (or no) failures may be observed, so that the analysis method of 4.9 could only state with high certainty that the median life is greater than 2000 hours. (A 2000-hour life at a channel temperature of 200 °C corresponds to 1 year at a device maximum operating temperature of 150 °C if the failure activation energy is 0.5 eV, or 32 years if the failure activation energy is 2 eV.)

4.3 Choice of ambient temperatures and other operating conditions (cont'd)

Stresses other than temperature can also be performed for the purpose of determining acceleration factors. While they can not be expressed as activation energies, the dependence of device life on voltage, current, and other variables relevant to the device can be determined; the devices can be stressed above normal operating conditions to accelerate the test. Analysis of the data is similar to temperature dependence except that the functional dependence on each variable may be different. In AlGaAs and InGaP HBTs, it has been frequently reported that the device Mean Time To Failure (MTTF) also strongly depends on the emitter current density J_e. The equation that models the dependence on T_j and J_e is:

$$MTTF \propto A \frac{1}{J_e{}^n} \exp\left(\frac{E_a}{kT_j}\right)$$

with the current factor n typically ranging from 0.5 to 2. It is likely that the value of n depends on both process and semiconductor material; therefore it should be determined experimentally for each combination of process and material.

When using electrical overstress, the device temperature may change enough to impact device lifetime, and the ambient temperature T_a of each electrical overstress group may have to be different to keep the transistor channel/junction temperatures equal. Alternatively, one can keep constant T_a by varying the current density J and bias voltage (V_{ds} or V_{ce}), keeping a constant power density $P = VJ$.

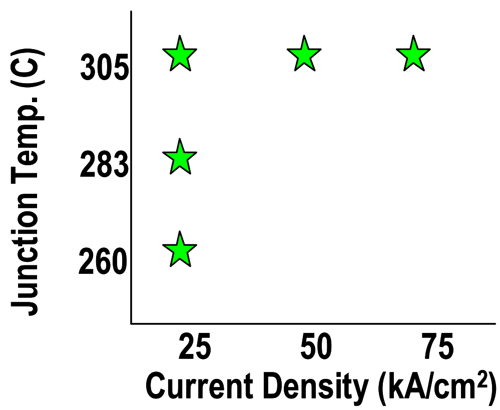


Figure 1 — HBT stressed at three junction temperatures and three current densities

Figure 1 illustrates an example of how to find the parameters for T_j dependence (E_a) and J_e dependence (n). First, three groups of devices are stressed at three differentambient temperatures (T_a) at a constant current density J = 25 kA/cm^2 with the highest T_j = 305°C, from which the E_a is extracted. Next another two groups of devices are stressed at a constant T_a (e.g. 200°C). The current density J is doubled (50 kA/cm^2) and tripled (75 kA/cm^2) while the voltage drops to half and 1/3 to maintain constant T_j = 305 °C, from which the current factor n is extracted.

4.4 Electrical stress

During the step stress and steady state life tests, the devices shall be operated under recommended DC operational electrical stress. If no recommended conditions exist, the bias conditions used shall be stated in the life test report. Unless special circumstances prevail, low-noise and passive devices may be stressed with DC only. General purpose and power devices, and MMICs not containing FETs shall be stressed with continuous wave RF. It is desirable that the RF stress level drive the device at least 1dB into compression at the stress temperature. The value of the RF input power, amount of compression, and RF frequency of the stress shall be stated in the life test report. If the life test is being run by or for a specific user, the operational DC and RF stress for the application shall be used.

During the life tests, the devices shall be monitored periodically to detect the occurrence of catastrophic failure and to adjust the equipment so that the applied stresses (temperature, current, voltage, etc.) are unchanged within tight tolerance except as described in the remainder of this section. Since the ideal life test is performed at constant temperature and with constant electrical stresses, any drift in device performance prevents the ideal from being met. Engineering judgment shall be used to determine the best compromise in keeping the electrical stresses and the channel temperature of the devices constant, and either gate voltage or ambient temperature shall be periodically adjusted as required during the test to implement this compromise. This compromise shall be described in the life test report, in order that the reader understands the life test conditions, and as a precedent for others facing the same problem in subsequent life tests.

To facilitate failure analysis, the device stress circuitry should be designed to quickly remove voltage from the device if it fails catastrophically; this practice will minimize subsequent damage due to a runaway condition such as a shorted FET.

4.5 Sample size

A minimum sample size of 50 devices is recommended. This represents the sum of all temperature groups, which are taken to at least 70% failure. A larger sample size will provide more precise results in that the calculated confidence intervals will be smaller.

Allocation of the devices to the various stress temperatures is optimized by the technique of [3]. Since the lowest stress temperature (assumed greater than the operating temperature of interest) has the greatest impact in the extrapolation to the temperature of interest, and is expected to have the fewest failures, more devices should be stressed at this temperature than at the others.

4.6 Failure criteria

The failure criteria shall be expressed as a parametric change, and shall be stated if different from those listed here. Unless stated otherwise, for FETs, drain and gate voltages used in measurement shall be kept constant, allowing currents under measurement conditions to vary. For HBTs, three different degradation modes are commonly seen in β during reliability stress tests: 1) initial β drift after the first few hours of stress, 2) relatively stable β over certain period of time and 3) a fast β degradation when the devices start to wear out or catastrophically fail. Sudden β degradation is the fundamental failure mode for HBTs, thus it is recommended that a sufficiently large change in β is used as a failure criteria to avoid overlap with other degradation modes. Typical degradation behavior for PHEMT and HBT is shown in Figure 2.

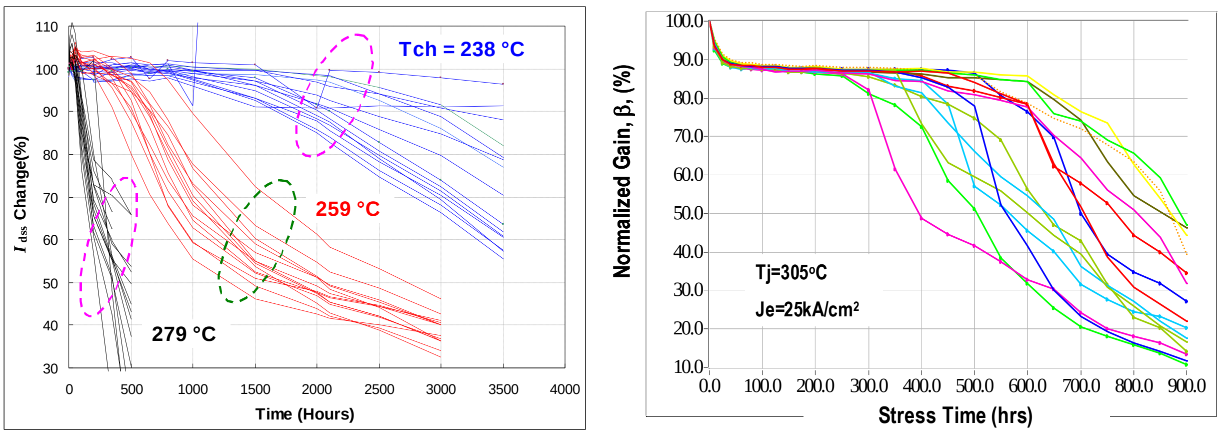


Figure 2 — Degradation under stress for PHEMT in Idss (left) **and HBT in beta** (right)

In defining failures, the measurement temperature shall be consistent with 4.1.

4.6.1 Recommended failure criteria

Current (operating or Idss)	±20%
Gate bias current	as specified by manufacturer
Transconductance	± 20%
Breakdown voltage	50% drop
HBT Current Gain (β)	± 30%
RF small signal gain	± 1dB
Power added efficiency	± 20% of initial value (amplifiers only)
Output power at 1 dB gain compression	-1 dB (power devices only)
Noise figure	± 0.5 dB (low-noise devices only)
Isolation	3 dB change and less than 20 dB final isolation (switches only)
Switching time	+ 100% (switches only)
Insertion loss	+ 1 dB (switches only)
Phase error	± 11° (phase shifters only)
Other	as specified by manufacturer

Operating current is defined as the current drawn when the device is biased as it was at the start of the life test.

Unstressed control devices shall be used to verify calibration of the measurement equipment. Measurements should be made at the same temperature throughout the life test.

4.7 Data taking

Section 4.6 (or an alternate definition) states the criteria for failure. Measurement of all these parameters shall be taken at intervals suggested by the step stress results. Devices may be, but do not have to be, removed from the life test fixture for parametric testing. Data used for fitting to a failure distribution shall start after 10% of the samples have failed. Measurements shall be taken frequently enough to provide at least five time intervals that contain new failures after 10% and before 90% of the total population has failed. The purpose is to interpolate the time where half the sample has failed.

If the life test is to be performed with a minimal number of interruptions for parametric tests, note that in a normal distribution of lifetime the interval between tests (in a log normal distribution, the log of the time interval between tests) should be decreased as the devices approach the expected median life. If more data points are taken, the risk of not achieving five points as described above and the random error in fitting a curve in 4.9 are both decreased.

The median life of a sample should always be estimated using step stress or comparison to similar devices to provide the best judgment that the base plate temperature chosen is reasonable. Once the estimated median life is determined, a set of measurement intervals can be chosen; it can be revised if the devices are failing more or less rapidly than expected. A possible set of measuring intervals as a multiple of expected median life is: .277, .43, .59, .78, 1, 1.28, 1.69, 2.3, 3.6. These numbers correspond to the increments of 10% failure for a log normal distribution with sigma =1; if the life test followed this distribution perfectly, there would be nine measurement times fitting the requirement of this section, and the final measurement would have 90% cumulative failure.

The time at which parametric failure occurrs for a given device can be obtained by interpolation of parametric data. If so desired, this time may be used for the analysis discussed in 4.9. (This is not done in Annex B.) This approach creates a slight bias to the data, as described by the concept of median ranks. One formula [1] for removing this bias is to define cumulative failure fraction as:

$$(i-0.3) / (N + 0.4)$$

where: i = number of failures, and
N = starting population

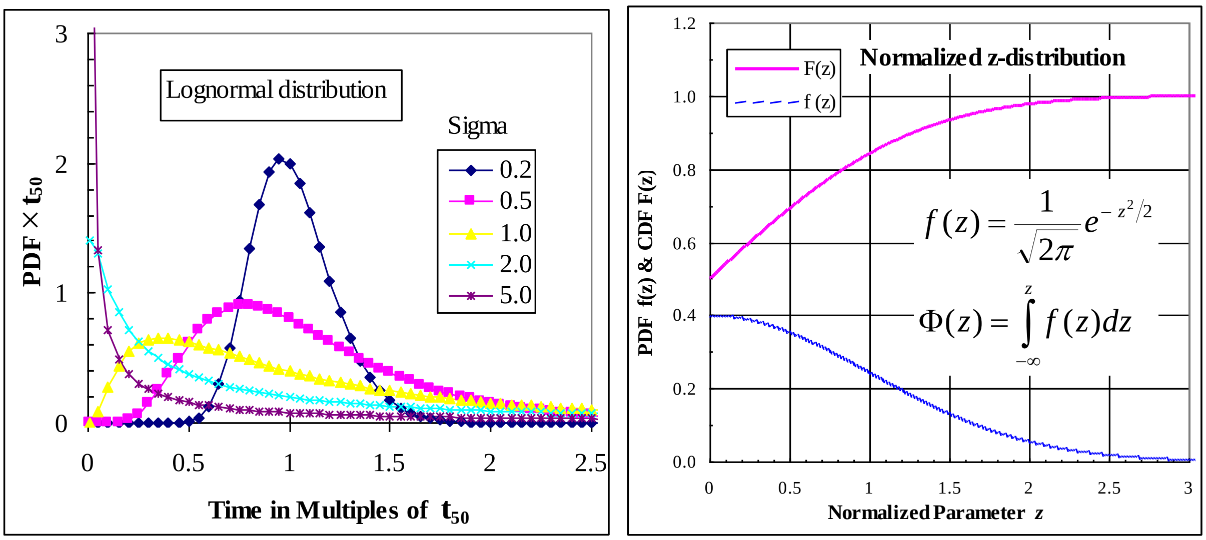
4.8 Failure analysis

Examination using a microscope shall be performed on every device failure to determine whether there is visible evidence of the failure site. Full failure analysis shall be performed on representative samples to determine the failure mechanism. Failure mechanisms which are incidental to the test, e.g., test fixtures, and broken bond wires on devices to be sold unpackaged, shall be reported, but may be ignored in subsequent calculations if it is determined that the failure was not caused by the device. A sample of parametric failures (but not all of them, to avoid their destruction by a catastrophic failure mode) may be placed back on life test to allow determinations of lifetime using a looser failure criterion, and to see whether the parametric failure leads to catastrophic failure.

4.9 Data analysis

Analysis shall be performed and reported separately for each failure mode. The five or more points descried in 4.7 will be used to create a curve of cumulative failure percentage vs. elapsed time. The data shall be analyzed to determine a statistical distribution that fits the data. To do this, it is recommended that the data be plotted on on a graph with axes that make the curve a straight line; for example, a lognormal plot. From the line, the parameters of the curve, e.g., median life and sigma for lognormal, may be determined. If the curve is not straight, one possibility is that the wrong distribution was chosen. The lognormal distribution equation is given by

$$\text{PDF} = f(t) = \frac{1}{\sigma t \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln t - \ln t_{50}}{\sigma}\right)^2}$$



$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2}$$

$$\Phi(z) = \int_{-\infty}^{z} f(z)dz$$

Figure 3 — Lognormal distribution and normalized z-distribution

An alternative is to transform the data. For example, to fit data to a lognormal distribution, use the standard normal variant (z), taken from a normal distribution table, corresponding to the value of phi that equals the cumulative failure fraction. For the time axis, use the logarithm of the time. The typical Lognormal- and normalized z-distributions are plotted in Figure 3.

The range of these parameters with 60% confidence shall be stated for each channel temperature. Statistical methods are described in Annex A.

It is not necessary to know when during the interval between parametric tests the devices failed so long as there are enough intervals (data points) to produce a smooth curve with little error in interpolation. The number of devices that have failed is plotted as a function of elapsed stress time.

Lifetimes at other than 50% cumulative failure, e.g., 1% failure, may be determined from the cumulative failure curve. Unless a very large sample size is used, there will be few device failures contributing to the 1% cumulative value, so that the confidence interval will be much larger than for the median life. An alternative approach is to assume a given failure distribution, use the parameters for the distribution (e.g., t50 (median life) and sigma (shape factor) for lognormal), and calculate the time to 1% failure based on this distribution. This approach is acceptable so long as it is stated and the cumulative failure curves are provided.

4.9 Data analysis (cont'd)

Mean time to failure (MTTF) may be determined by assuming a failure distribution, which fits the data well, and using the proper formula for MTTF. For a lognormal distribution,

$$\text{MTTF} = t_{50} e^{\sigma^2/2} = A e^{E_a/k_B T}$$

For a Weibull distribution with shape parameter m and characteristic life parameter c,

MTTF = c * gamma[1 + (1/m)],

where gamma[ ] is the gamma function. It is important to distinguish among median life, MTTF and MTBF. The life test report shall state that since failure rate is generally not a constant, the reader of the report needs to use this calculated MTTF with care and not to use it for mean time between failures (MTBF).

When life test and failure analysis data indicate that more than one failure mechanism is present in the sample, the calculation of failure rate shall be conducted separately for each mechanism. Sometimes, part of the sample will fail by one mode, e.g., broken bond wires, then subsequent failures will fail by a different mode, e.g. shorted FET. In this case, the sample may best be treated as two separate populations. These failure rates can be added to determine the total failure rate, as described in the next paragraph.

If the data analyst observes that the cumulative failure plot is not linear (e.g. an S-shaped curve on a lognormal plot), the test may contain two populations, one with an infant failure mode and one without it. The life test will likely cause all devices having the infant failure mode to fail. Once failure analysis is performed, and if there are enough data points, the analyst will be able to determine the identity of each subpopulation and calculate the median life of each. In this case, the 10% to 90% cumulative failure percentage described in 4.7 applies to each population separately.

4.10 Activation energy and extrapolated lifetime

The logarithm of the median life (neglecting confidence interval) shall be plotted vs. the reciprocal of the channel temperature to obtain the activation energy (Ea) and extrapolated median life at infinite temperature (t0) according to the Arrhenius relation

$$t_{50} = t_0 e^{E_a/k_B T}$$

These values, their 60% confidence interval and the device thermal resistance shall be used to calculate the median life and its 60% confidence interval at the maximum operating channel (junction) temperature of the product under test. Statistical techniques are described in Annex A.

The activation energy may also be calculated using failure percentages other than 50%, but generally there will be a larger statistical uncertainty. This calculated activation energy should not vary with the choice of percent failure. If certain parameters, e.g., sigma for a lognormal distribution, determined in 4.8, vary with temperature, there are two possible explanations: a real variation due to different failure mechanisms, and variation due to statistics of dealing with small sample sizes. In the first case, the analysis is complicated considerably, and life tests may have to be run at additional temperatures. A statistical check can be performed to test whether the sigmas may be considered the same [2]. In the second case, a weighted average (weighted by the reciprocal of the square of the confidence interval) should be used as a constant value.

5 Reportable data

The following data are required to adequately define the results of a life test.

5.1 Devices

- Manufacturer's device number, electronic function, and whether it is low-noise, general purpose or power;
- Package description, and whether packaging failures are included as failures;
- Screening methods and criteria;
- Average thermal resistance at the life test temperatures and method of determination.

5.2 Stresses

- Case temperatures;
- Number of devices for each temperature;
- Electrical stress: bias conditions, RF input or output power and comparison to 1 dB compression point;
- Definition of failure.

5.3 Analysis

- Principal failure mode and mechanism;
- Plot indicating median life for each temperature, including 60% confidence limits.
- Assumed lifetime distribution, if any;
- Arrhenius plot indicating extrapolation to reference temperature, including 60% confidence limits.

6 References

[1] Tobias and Trindade, Applied Reliability, Van Nostrand Reinhold, New York, 1986

[2] Nelson, Applied Life Analysis, Wiley, New York, 1982

[3] Nelson, Accelerated Testing: Statistical Models, Test Plans and Data Analysis, Wiley, New York, 1990, pp. 320-327.

[4] D.E. Dawson, A.K. Gupta, and M.L. Salib, "CW measurements of HBT thermal resistance," *IEEE Trans. Electronic Devices, Vol.* 39, pp. 2235-2239, Oct. 1992.

[5] B. Yeats, "Inclusion of Topside Metal Heat Spreading in the Determination of HBT Temperatures by Electrical and Geometrical Methods," *IEEE GaAs Symposium Proceeding*, 1999, P59

[6] H. F. Cooke, "Precise technique finds FET thermal resistance", Microwave & RF Magazine, vol. 25, no. 8, pp. 85-87, Aug 1986.

General reference: Basic References in Quality Control: Statistical Techniques, ASQC Press, 1985.

Annex A Statistical methods

(In Annex A the notation T50 is used for median time to failure rather than t50 to distinguish from the t-statistic.)

A.1 Uncertainty of a number of failures

When a small number of failures (or a small number still good) have occurred, the statistical uncertainty is large. This makes the data at the ends of the cumulative failure curve less certain than the data at the center. This effect is magnified by the probability scale normally found on graph paper used for cumulative failure curves; including such points and giving them equal weight as the points near 50% gives them too much importance. This is the motivation in 4.7 for restricting the range of percentage failure to the 10-90% interval in fitting a line to the cumulative failure curve.

Given a population and a percentage failure, the percentage failure in a small sample of the population may be quite different. Inferring data on the population from the sample, there is an uncertainty in the population failure percentage. A Clopper-Pearson plot ([1], [2]) can be used to determine this range for the confidence level specified on the plot; a consequence shown by the plot is that the percentage confidence interval of the time for a given failure percentage is smallest at 50% failure.

A.2 Fitting a line to points on a cumulative failure plot

An intuitive method to weight the points is described here. Since the standard deviation of the average of a group is proportional to the reciprocal of the square root of the number of individuals in the group, it follows reasonably that the relative weighting of a point should be the reciprocal of the square of the confidence interval. This confidence interval is the interval on the graph paper between the 60% (or other percentage) limits for each point on the cumulative failure plot. Hence the weighting is influenced by the number failing (or the number not failing) directly through the numerical value of the interval and indirectly through the nonlinear scale on the failure fraction axis. For both reasons, points in the region of 50% failure get weighted more heavily than points at the extremes.

There are many computer programs containing linear regression, which will fit a line to a group of data points. Whether or not the method described in the previous paragraph is used, the error in fitting a line to the data will be minimized by having several data points between 10% and 90% cumulative failure.

A.3 Confidence interval for median life

The equations for calculating confidence intervals of relevant reliability parameters (e.g. MTTF) using the method of maximum likelihood are complicated [2], so this technique is typically only applied using statistical analysis software.

If using the least squares approach, the lower bound of the confidence interval for MTTF for a device following lognormal distribution is given as

$$\ln[T50(B)\min] = \ln[T50] - t(N-1, B)*S.E.,$$

where:

ln is the natural logarithm,
N is the number of temperatures (usually 3),
T50 is the median lifetime as determined by fitting a curve to the Arrhenius plot,
t(N-1,B) is the t-statistic for N-1 degrees of freedom and a confidence level B, and

$$S.E.(MTTF_0) = \sigma\sqrt{\frac{1}{N} + \frac{(x_0 - \bar{x})^2}{\sum_{i=1}^{N}(x_i - \bar{x})^2}}$$

$x_0 = 1/kT_0$ where T_0 is the temperature of interest (e.g. 125 ºC),
$x_i = 1/kT_i$ where T_i is the i^{th} temperature,
$\bar{x}$ (read x-bar) is the average of all the individual values of $1/kT_i$ over all temperatures, and
σ is the estimated lognormal shape factor.

The minimum limit of the confidence interval of median life for a device following lognormal distribution is given as

ln[T50(B)min] = ln[T50] – sigma *t(N-1, B)/sqrt(N),

where variables are defined as shown above.

For sample sizes typical of life tests, the t-statistic can be approximated by the inverse standard normal cumulative distribution function with little loss of accuracy [2].

Annex B Example of a life test

In this annex, a life test is performed to serve as an example of the method of determining the lifetime distribution parameters from accelerated test data. The lognormal distribution is used in the example, so the parameters of interest are t50 (median life) and sigma (lognormal shape factor). Similar calculations can be performed using other distributions e.g., Weibull, and should be performed if the cumulative failure curve does not appear as a straight line on lognormal paper.

B.1 Statement of the problem

In this example it is desired to predict the lifetime (t50) of an electronic device at the maximum use ambient (Ta) of 115 °C. Previous versions of this device have had sigma of 0.7, and activation energy (Ea) of the failure mechanism has been 1.7 eV. The anticipated lifetime is 10^7 hours at 115 °C ambient. The device does not function above 275 °C channel temperature. The approach is to develop an accelerated test scheme, then to analyze the data to determine t50 at the test temperature, sigma and Ea, and finally t50 at the temperature of interest.

B.2 Accelerated test scheme

Thermal resistance (4.1) is measured or modeled; the channel temperature is 25 °C above ambient in the temperature range of the life tests for the DC bias conditions applied.

Choice of test operating conditions (4.2, 4.3): Since the device being tested is similar to an existing device and there is an estimate of the lifetime, step stress is not necessary. With a 275 °C temperature limit and 25 °C rise, the upper stress ambient is limited to 250 °C. The minimum delta between the stress ambients is 15 °C, so temperatures of 220 °C, 235 °C, and 250 °C could be used.

Choice of these temperatures will result in the minimum test time. However, there are reasons to consider alternatives. First, as temperature spacing decreases, the need for temperature extrapolation increases, since all test temperatures are high (here, the lowest temperature is 105 °C above the ambient of interest). Second, errors in regression slope increase as stress temperature spacing decreases. Both these problems are reduced by using wider spacing between stress temperatures. Using temperatures with wider spacing is practical where the activation energy is small, but for an expected 1.7 eV activation energy, the test time at the lowest temperature may become excessive.

Operating at a temperature very close to spontaneous failure involves considerable risk. Accordingly, for this series of life tests, the ambient temperatures were reduced by 20 °C, and were chosen as 200 °C, 215 °C, and 230 °C. Since the lowest temperature used is not greater than 200 °C, a fourth temperature (4.3) is not needed.

Sample sizes (4.5): For this example a total of 70 devices (plus standards) is available

B.2 Accelerated test scheme (cont'd)

Data taking (4.7): Timing for measurements is calculated from the procedure in section 4.7, using the information from the problem statement and the similar device. First, we estimate t50 at each test condition using the estimates of Ea and t50 at the temperature of interest (i.e., Ea = 1.7 eV, and t50 = 10^7 hours at 115 °C), and the Arrhenius relation:

$$L2 = L1 * \exp[Ea/k * (1/T2 - 1/T1)] \qquad (1)$$

where:

T*i* is the channel temperature in K
L*i* (*i* = 1 or 2) is t50 for temperature T*i*, and
k is Boltzmann's constant (8.62E-5 eV/deg).

Substituting these estimates, the predicted t50 at 200 °C ambient is

$$L(200) = 107 * \exp[1.7/8.62E\text{-}5 * (1/(273 + 200 + 25) - (1/(273 + 115 + 25))] = 2886 \text{ hours}$$

Similarly, the predicted t50 at 215 °C ambient is 907 hours and 230 °C is 304 hours.

Second, we calculate the test intervals in terms of t50 calculated above. Since we have an estimate of sigma of 0.7, we adjust each interval in section 4.7 by raising it to the 0.7 power. For example, the first interval is

$$t50 * (0.277\text{^ } 0.7) = t50 * 0.41.$$

So our intervals are 0.41, 0.55, 0.69, 0.84, 1, 1.19, 1.44, 1.81, and 2.45, each multiplied by t50. The test intervals as shown in Table 1 are these values adjusted slightly for convenience. Table 1 serves as a data sheet.

Table 1 — Data Sheet

200 °C		**215 °C**		**230 °C**	
Time	**#fail**	**Time**	**#fail**	**Time**	**#fail**
1094		344		115	
1521		478		160	
1948		612		205	
2338		735		246	
2886		907		304	
3469		1090		365	
4185		1315		441	
5169		1624		544	
6797		2136		716	

Third, we decide how many devices to use at each temperature. It is hoped that enough test intervals having additional failures occur on the lowest temperature test to allow the test to be discontinued before 90% failure. With this in mind, 30 devices are run at 200 °C, 20 at 215 °C, and 20 at 230 °C. An alternative would be to use the technique described in 4.5.

B.3 Lifetime prediction

Data Analysis (4.9): The life tests are run providing the data shown in Table 2. The transformed values ln(time) and the inverse normal (z) of the cumulative failure fraction (F) are also shown.

First determine t50 and sigma for each temperature. This can be done by plotting the data on a time vs F graph using a special graph paper e.g., lognormal. (Using a plot is a convenient method to verify that there are no data collection errors and that the failures fit the assumed distribution.) Then draw a best fit line or perform a regression. If a regression is used, it is important to use the mathematical transformation of the variables or to use the distances measured from the graph, and not the time and F. (Note that various statistical software packages offering the ability to simplify this analysis are commercially available.) Figure 4 shows the plotted data.

Table 2a — Life Test Data and Lognormal Transformation (200 °C sample size: 30)

Time (hours)	ln(time)	# of failures	Cumulative failures	Cumulative % failures	z
1094	6.998	3	3	10.0	-1.282
1521	7.327	2	5	16.7	-0.967
1948	7.575	4	9	30.0	-0.525
2338	7.757	2	11	36.7	-0.430
2886	7.968	5	16	53.3	0.168
3469	8.152	2	18	60.0	0,253
4185	8.339	3	21	70.0	0.525
5169	8.550				
6797	8.824				

Table 2b — Life Test Data and Lognormal Transformation (215 °C sample size: 20)

Time (hours)	ln(time)	# of failures	Cumulative failures	Cumulative % failures	z
344	5.841	2	2	10.0	-1.282
478	6.170	1	3	15.0	-1.037
612	6.417	3	6	30.0	-0.525
735	6.600	2	8	40.0	-0.253
907	6.810	3	11	55.0	0.127
1090	6.994	1	12	60.0	0.253
1315	7.182	1	13	75.0	0.385
1624	7.393	3	16	80.0	0.842
2136	7.667	1	17	85.0	1.037

B.3 Lifetime prediction (cont'd)

Table 2c — Life Test Data and Lognormal Transformation (230 °C sample size: 20 Time (hours))

Time (hours)	ln(time)	# of failures	Cumulative failures	Cumulative % failures	z
115	4.745	2	2	10.0	-1.282
160	5.075	2	4	20.0	-0.847
205	5.323	2	6	30.0	-0.525
246	5.505	0	6	30.0	-0.525
304	5.717	3	9	45.0	-0.127
365	5.900	3	12	60.0	0.253
441	6.089	3	15	75.0	0.674
544	6.299	2	17	85.0	1.037
716	6.574	1	18	90.0	1.282

Alternatively, the mathematical transformation can be used to provide a linear relation for least squares fitting. Since

$$z = [\ln(t) - \ln(t50)]/\text{sigma} \qquad (2)$$

$$\ln(t) = \text{sigma} * z + \ln(t50) \qquad (3)$$

where:

sigma is the slope,
z is the independent variable, and
ln(t50) is the y-intercept.

In this example, linear regression is performed using least squares. Best fit lines are drawn on Figure 4.

The value of t50 can be read from the graph by judging the best linear fit and reading its value at F=50%. It can also be calculated from the equation as the time for z = 0. Sigma is determined from the slope of the line. On some graph paper designed for life tests, the paper has a scale to convert from slope to sigma. If the transformation was used to find t50, then sigma is the slope in Equation (3). The value of t50, its 60% confidence interval, and sigma for each test temperature are shown in Table 3.

NOTE The lower and middle temperature life tests in this section were terminated before 90% failure in order to reduce total test time. At the time the test was terminated, the analyst could tell that there were enough measurement points.

Ea and t50 at the temperature of interest (4.10): Sigma should be the same at each temperature; if it varies with temperature (other than random variation due to small sample sizes), this may be an indication of different failure mechanisms at different temperatures. Using lognormal paper, sigma is proportional to the slope of the cumulative failure line. If the line was determined using linear regression, then a computer statistical package can be used to determine the 60% confidence interval of the slope, hence of sigma.

If the subsequent math steps were performed using data where sigma varied with temperature, the calculated value of Ea would depend on the value of F chosen, which is not a likely physical situation. For this example, a chi-square test was performed and it was found that sigma is constant across temperature [2] and the values of sigma obtained above are averaged.

B.3 Lifetime prediction (cont'd)

The activation energy (Ea) can be determined graphically (Figure 5), using a graph paper containing a reciprocal temperature scale and a log scale for the time, and fitting ln(t50) vs (Ea/k)/Tc using least squares. It is very important to use the absolute channel temperature (in K) when performing this analysis, rather than the ambient temperature. Recall that in this example the channel temperature is approximately 25 °C higher than the ambient temperature. The equation of the line on the graph is

$$\ln(t50) = \ln(t0) + (Ea/k)*(1/Tc)$$

Where t0 is the fictitious median life at infinite temperature.

For this example, the regression yields

$$\ln(t50) = -31.888 + 19849/Tc$$

$$t0 = 1.42E\text{-}14 \text{ hours,}$$
$$Ea/k = 19849, \text{ and}$$
$$Ea = 1.71 \text{ eV}$$

Finally, the value of t50 is determined at the maximum operating temperature (115°C ambient; 140°C channel temperature) by applying the results of the linear regression to the Arrhenius equation:

$$\begin{aligned} t50 &= t0 * \exp(Ea/k * 1/Tc) \\ &= 1.42E\text{-}14 * \exp(19849 * 1/413) \\ &= 1.05E7 \text{ hours} \end{aligned}$$

Table 3 — Summary of the life test data

T ambient (°C)	t50 (hours)	t50 60% confidence limits		Sigma
		Upper	Lower	
200	2866	2924	2818	0.72
215	919	1018	898	0.74
230	298	306	289	0.67

B.3 Lifetime prediction (cont'd)

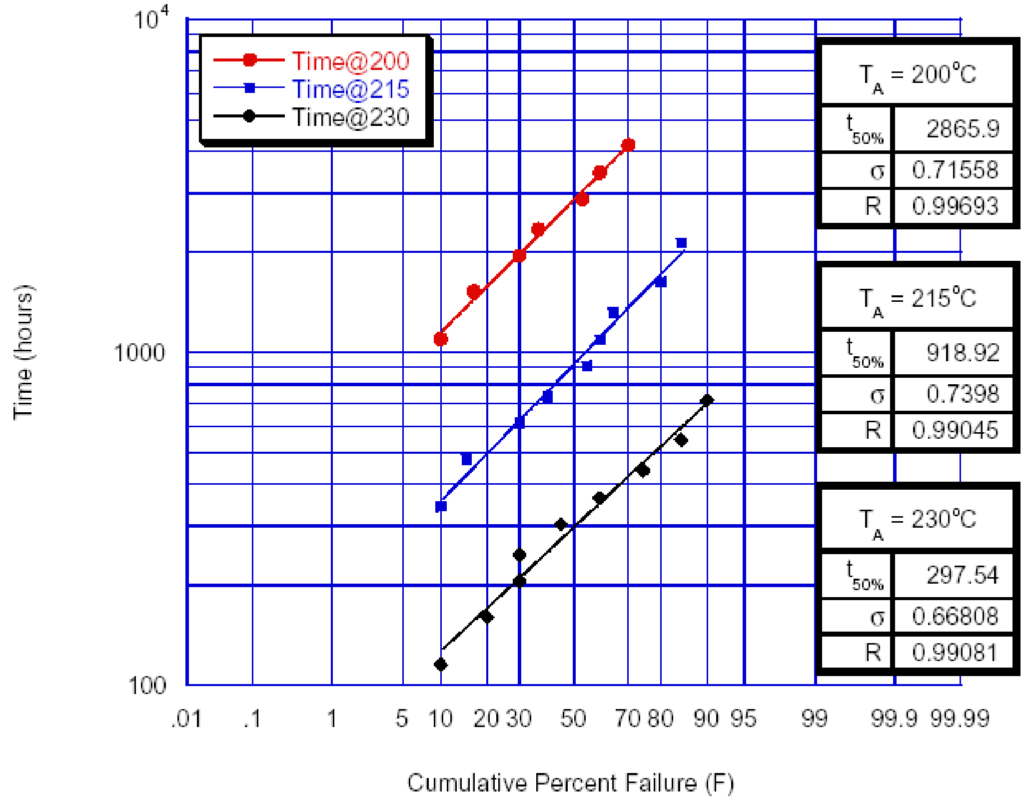


Figure 4 — Log-normal distribution plot of life test data

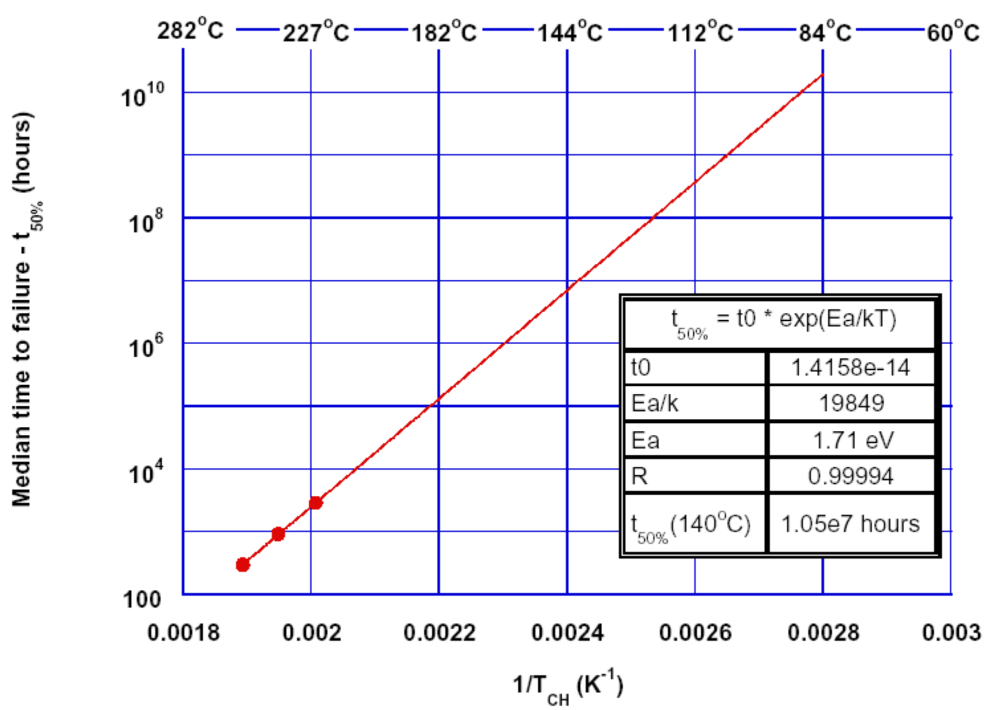


Figure 5 — Arrhenius plot of life test data

Annex C (informative Differences between revisions

This annex briefly describes most of the changes made to entries that appear in this document, JEP118A, compared to its predecessor, JEP118 (January 1993).

JEP118A has been updated to explicitly include psuedomorphic High Electron Mobility Transistor (pHEMT) and Heterojunction Bipolar Transistor (HBT) technologies in its scope. Additional changes have been made to clarify the content of the original document.

Clause	**Description of change**
Title	Inclusion of pHEMT and HBT technologies in the document title
Introduction	Specific reference to pHEMT and HBT technologies; also, explicit reference to many compound semiconductor materials used in these device technologies
2	New section, listing JEDEC documents related to JEP118
4.1	Added a list of recommended electrical measurements to be performed as part of the life tests described in this document, with separate recommendations for FET and bipolar devices
4.1	Added references to techniques for measuring or modeling transistor temperature
4.3	Included statement that HBT reliability depends on both junction temperature and emitter current density; provided a conceptual test plan to assess the impact of both temperature and current density on device reliability
4.6	Added a paragraph describing the degradation modes commonly seen for HBT devices
4.6	Added two graphs: one showing typical pHEMT drain current degradation, and one showing typical HBT beta degradation resulting from temperature accelerated life tests
4.6	Added breakdown voltage and HBT current gain (beta) as recommended failure criteria
4.9	Added descriptive information for the Lognormal distribution
6	Added references for three papers describing thermal characterization techniques relevant to bipolar and field effect transistors (HBTs and MESFETs/pHEMTs)
A3	Provided additional information for the calculation of confidence intervals
B3	Added a computer-generated plot (Figure 4) showing lognormal distribution curves for the life test dara provided in tables 2a, 2b, and 2c
B3	Added a computer-generated plot (Figure 5) showing an Arrhenius plot generated from the distribution data presented in Figure 4

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