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Standard Method for Calculating the Electromigration Model Parameters for Current Density and Temperature

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STANDARD METHOD FOR CALCULATING THE ELECTROMIGRATION MODEL PARAMETERS FOR CURRENT DENSITY AND TEMPERATURE

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STANDARD METHOD FOR CALCULATING THE ELECTROMIGRATION MODEL PARAMETERS FOR CURRENT DENSITY AND TEMPERATURE

(From JEDEC Council Ballot JCB-97-17, formulated under the cognizance of JC-14.2 Committee on Wafer-Level Reliability)

1 Scope

1.1 The method provides procedures that use linear regression analyses for calculating sample estimates, and their confidence intervals, of the electromigration model parameters for current density and temperature of thin-film metal interconnects used in microelectronic devices.

1.2 The method assumes that the median time to failure (t_{50}) data from accelerated stress tests of metal interconnect test structures can be satisfactorily modeled by Black's equation [1] (see eq. 3.2). Hence, the model parameter for current density, J, is the value of the exponent, n, to which J is raised and the model parameter for temperature is the activation energy, E_A, of the electromigration process. The linear regression analyses calculate sample estimates of E_A directly, while sample estimates of n are obtained from analyses that involve the calculation of sample estimates of a slope S, where S = -n.

1.3 The method requires existing failure-time (t_f) data or median-time-to-failure (t_{50}) data. When t_{50} data is used, they must be from **at least three** electromigration stress tests conducted at different stress levels when only the current density or only the temperature is varied. They must come from **at least four** stress tests if both current density and temperature are varied to obtain the t_{50} data.

1.4 The method can be used with censored t_f data if JEDEC standard JESD37 [2] (or its equivalent) is used to convert the censored data to t_{50} estimates and the method used with these t_{50} values. In the context of this standard, censored t_f data refers to the case where the stress test is halted before all test parts have failed. Hence, the number of t_f values available for analysis is less than the sample size of the test.

1.5 Examples of three types of calculations by this method are given in Annex A. One is to obtain sample estimates of n and of their confidence interval when t_{50} or t_f data are available from experiments conducted at different current-density stresses. The second is to obtain sample estimates of both n and E_A and of their confidence intervals when t_{50} or t_f data are available from experiments conducted at different current-density and temperature stresses. The third involves calculations with censored data.

1.6 This method does not preclude the use of other methods as long as they have been shown to provide equivalent results. The calculation examples referred to in 1.5 may be used to show equivalence.

2 Introduction Significance and use

2.1 Electromigration is a failure mechanism of electrical interconnects that is of great concern, especially for the reliability assessment of very large scale integrated (VLSI) microelectronics. The drivers of the electromigration process in Black's equation are the current density and the temperature.

2 Introduction Significance and use (cont'd)

2.2 To obtain reliability data from thin-film metal interconnect test structures in a time much shorter than their expected lifetime, samples of similar interconnects are subjected to accelerated stress tests. These tests provide sets of failure times for current density and temperature conditions that are more severe than would normally be encountered in use. To assess the reliability of such parts **under use conditions** requires that the model parameters for both current density (n) and temperature (E_A) be determined and used to extrapolate the results of stress tests to use conditions. Because only sample estimates of the model parameters can be obtained, it is also important to determine the confidence limits for these sample estimates.

2.3 Confidence intervals for the sample estimates of the model parameters of electromigration are necessary to determine the statistical significance of any differences noted in the values determined: from similar interconnect test structures measured at different times, from test structures with different designs, or from interconnects fabricated at different times, at different laboratories, or with different processes.

2.4 This method can be useful in evaluating and optimizing the selection of metal alloys and processes, and in identifying the key input material and process parameters that affect the reliability of interconnects.

3 Summary of method

3.1 To obtain sample estimates and their confidence intervals of the model parameter for the current density, for the temperature, or for both requires a set of median-time-to-failure (t_{50}) data or a set of time-to-fail (t_f) data obtained from several electromigration stress tests with different stress conditions. These data are best obtained by following the procedure of the standard electromigration test method [3] and the standard method for determining the joule heating in a test line [4]. The electromigration test method includes procedures for calculating sample estimates of both t_{50} and σ from the failure times of the test parts. The sample estimates for t_{50} and σ are obtained from the average and the standard deviation, respectively, of the natural logarithm of the individual failure times. That is,

$$\hat{t}_{50} = \exp\,[\ln t_f(j)]_{av}\,;\ \hat{s} = [\ln t_f(j)]_{sdt.\,dev.}, \qquad (3.1)$$

where j runs from 1 to N and N is the sample size. The test method also includes procedures for calculating the confidence intervals for these estimates. In that method [3], as in this method, the impact of sample size on confidence intervals is demonstrated. In performing such electromigration tests and in following this method, it must be understood that the stress temperature of the structures being stressed is the **sum** of the local ambient stress temperature and of the temperature increase of the test line due to power dissipation in the test structure and elsewhere on the wafer or chip (see 4.4).

3 Summary of method (cont'd)

3.2 Assumptions

3.2.1 The method assumes that the set of t_{50} or t_f values can be modeled by Black's equation:

$$t_{50} = \frac{A}{J^n} \times \exp\left(\frac{E_A}{kT}\right), \tag{3.2}$$

where:

J is the current density in the metal test lines (A/cm^2),
n is the model parameter for current density,
E_A is the model parameter for temperature, i.e. activation energy (eV),
T is the temperature of the metal test lines (K),
k is Boltzmann's constant (8.617×10^{-5} eV/K), and
A is a constant.

3.2.2 When dealing with failure-time data, t_f, to determine n or E_A, it is assumed in 5.2, 6.2, and 7.2 that there is no censoring of these data. If there is data censoring in some or all of the tests, the t_f data from all tests must be used to obtain sample estimates of t_{50} in the manner described in section 8. These sample estimates of t_{50} are then used to obtain sample estimates of n, E_A, or both as described in 5.1, 6.1, and 7.1, respectively.

NOTE — Using t_{50} data rather than the failure-time (t_f) data to obtain sample estimates of n, E_A, or both, results in an increase in the length of the confidence interval for these estimates. The reason for the increase is that the level of information from the individual t_f values is reduced in the process of subsuming them in the t_{50} data. But, the larger the number of experiments involved in calculating the sample estimates, the less significant will be this increase. The expected value for the ratio of the confidence interval (I_{50}) from t_{50} data to the interval (I_f) from t_f data can be estimated from:

$$\frac{I_{50}}{I_f} \approx \frac{t(1 - \frac{a}{2}; N - p)}{t(1 - \frac{a}{2}; N_s - p)}$$

where:

N is the number of stress tests (t_{50} values),
N_S is the sum of the numbers of test structures in the N stress tests,
$1-\alpha$ is the confidence coefficient for the confidence interval, and
p = 2 when **either** J or T is varied among the tests to obtain sample estimates of n or E_A, and
p = 3 when **both** J and T are varied to obtain sample estimates for both n and E_A.

See examples described in Annex A, paragraphs A.2.2 and A.4.3.

3 Summary of method (cont'd)

3.3 Sample estimates for n or E_A are obtained from a linear regression analysis for one independent variable (sections 5 and 6). The analysis requires failure-time data from several electromigration stress tests when these tests are conducted at different levels of current-density or temperature stress, respectively. When both current density and temperature are varied, sample estimates are obtained from a multiple linear regression for two independent variables (section 7).

3.3.1 If the current density is varied while the stress temperature of the metal test lines is kept constant in a number of electromigration stress tests, then t_{50} will be proportional to $1/J^n$ and hence

$$\ln t_{50} = -n \ln J + B, \qquad (3.3a)$$

or

$$\ln t_{50} = S \ln J + B, \qquad (3.3b)$$

where B is a constant involving A and E_A. A plot of *ln* t_{50} versus *ln* J will display data points aligned generally along a straight line. This is illustrated in figure 1A. A linear regression analysis of the *ln* t_{50} - *ln* J data pairs will yield a least-squares, sample estimate of the slope, S, of the best-straight-line fit to the data and the confidence interval for this slope. The sample estimate for n, the model parameter for the current density, is obtained from the relation S = -n. The method depends critically on the assumption of linearity (see 4.1, 4.2, and 9.). A very useful tool in assessing the validity of the assumption is a visual inspection of the plotted data (see 9.2).

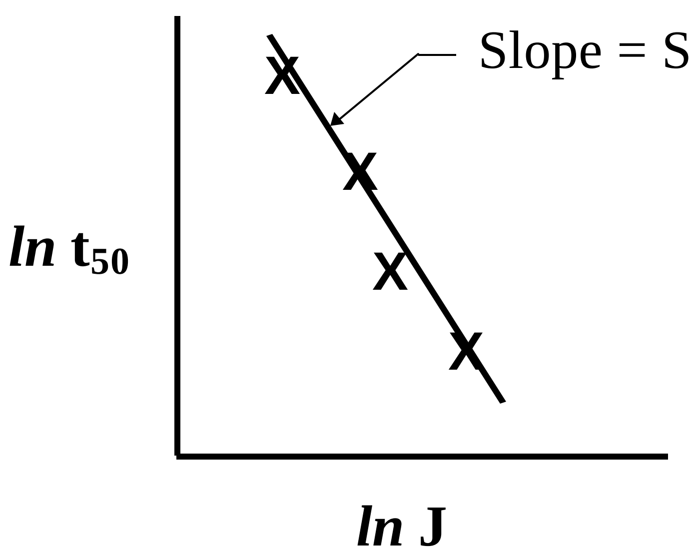

Figure 1A — Plot of *ln* t_{50} versus *ln* J to illustrate the behavior of eq. 3.3b and the best-straight-line fit to the data from which the value of n can be obtained and the linearity of the dependence may be judged.

3 Summary of method (cont'd)

3.3.2 If the temperature of the test lines is changed while the current-density stress is kept constant in a number of different stress tests, then t_{50} will be proportional to $\exp(E_A/kT)$ and hence

$$ln\ t_{50} = \frac{E_A}{k} \times \frac{1}{T} + C\ , \qquad (3.4)$$

where C is a constant involving A and n. A plot of *ln* t_{50} versus 1/T will display data points aligned generally along a straight line. This is illustrated in figure 1B. A linear regression analysis of the *ln* t_{50} - 1/T data pairs will yield a least-squares, sample estimate of the slope of the best-straight-line fit to the data and of the confidence interval for this slope. The slope of this line is E_A/k, the activation energy divided by Boltzmann's constant (8.617×10^{-5} eV/K). The method depends critically on the assumption of linearity (see 4.3 and 9). A very useful tool in assessing the validity of the assumption is a visual inspection of the plotted data (see 9.2).

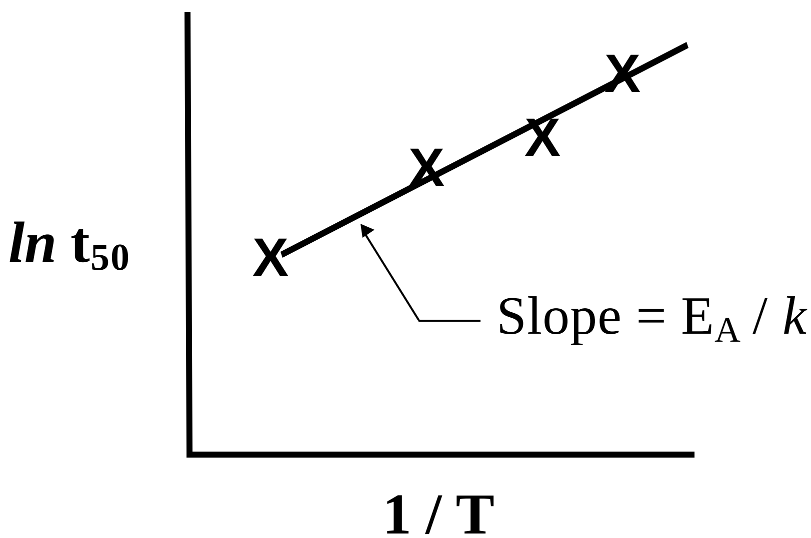

Figure 1B — Plot of *ln* t_{50} versus 1/T to illustrate the behavior of eq. 3.4 and the best-straight-line fit to the data from which the value of E_A can be obtained and the linearity of the dependence may be judged.

3.4 The method offers procedures for calculating sample estimates and their confidence intervals for either S, E_A, or both, depending on the data available. Values for the sample estimates for n and their confidence intervals are obtained by recognizing that S = -n.

3 Summary of method (cont'd)

3.4.1 When only t_{50} values are available and they are given either as a function of current density or of temperature, then the procedure leads, accordingly, to a sample estimate and confidence interval for either S or E_A. See 5.1 and 6.1, respectively. If the sample sizes for the different experiments are available, their effect is included in the procedure.

> NOTE — This procedure is useful when evaluating reported values for n or E_A (with t_{50} data), and any conclusions derived therefrom, when information about the confidence intervals for these values are not provided.

3.4.2 When failure times, t_f, are available from experiments to determine the dependence of t_{50} values on either current density or temperature, then the procedure leads, accordingly, to a sample estimate and confidence interval for either S or E_A. See 5.2 and 6.2, respectively.

3.4.3 When t_{50} or t_f data are available from experiments where both temperature and current density were varied, then the procedure provides a means for calculating sample estimates and confidence intervals for both S and E_A. See 7.1 and 7.2.

3.4.4 When censored t_f data (instead of complete data) are available from all or some experiments, where either the current-density, the temperature, or both stresses are different, then the procedure provides a means for calculating sample estimates and confidence intervals for S, E_A, or both. See section 8.

4 Precautions and interferences

4.1 In calculating the model parameters with t_{50} data, it is assumed that the t_{50} data comes from a population where the sigma is constant over the range of test conditions used to determine $\hat{S}$ and $\hat{E}_A$. The method is still robust when there are variations in sigma over the range of conditions that might be used. But, a statistically different sigma at one or more these stress conditions of the experiment may be an indication of a change in the operation of the electromigration process at these conditions that could affect S, E_A, or both.

4.2 If errors are made in estimating the joule heating of test lines, the linearity assumption of 3.3.1 may not be valid. If the joule heating is systematically underestimated, or ignored entirely, a plot of *ln* t_{50} versus *ln* J will follow a curve whose slope becomes increasingly more negative with increasing current density.

4.3 The activation energy for electromigration through the metal lattice is higher than that along the grain boundaries of the metal film. For metal interconnect lines with metal grains whose median size is comparable with or larger than the line width, significant migration may occur through the lattice within the temperature range used in the stress tests to determine E_A. In this case, the assumption of linearity in 3.3.2 will not be valid. A plot of *ln* t_{50} versus 1/T will indicate any significant indication of nonlinearity. For such metal interconnects, it will be necessary to evaluate if tests can be conducted at different ranges of temperature to separate competing mechanisms.

4 Precautions and interferences (cont'd)

4.4 The method provides procedures to calculate the sample estimates of S and E_A and their confidence intervals where it is assumed that all test parts in a given accelerated stress test were subjected to the same current-density and temperature stresses. But, this is only an idealization of actual conditions. For example, even if the current through each test line is the same and is held constant throughout the test, some small variations in the width and thickness of the test lines will invariably exist and result in variations in the current-density stresses among the test structures stressed in a given test. The stress temperature of a test line is the sum of 1) the ambient temperature provided by an oven or a hot chuck (for wafer-level tests), 2) the temperature increase due to power dissipation in the test structure caused by the stress current, and 3) the temperature increase in the test line due to power dissipation elsewhere on the wafer or chip. Therefore, differences and changes with time are also expected for the stress temperatures of the lines under test. There will be some variation in the resistance of the structures under test and each will exhibit a different change in resistance with test time. Variations and changes in the magnitude of the other components to the stress temperature may also be expected. When these variations are relatively small, see 4.5. When they are larger, see 4.6.

4.5 Small random variations in the current-density and temperature stresses to which the test lines are subjected in a given stress test can be tolerated without significantly degrading the quality of the estimates of the confidence intervals. This can be done by using the means of the measured test line temperatures and of the estimated current densities in the procedures of the method.

NOTE — It has been assumed that the population of $Y_{i\,j} = ln\ t_f(J_i\ ,T_i\ ,j)$ values for the i-th test, are normally distributed with a mean of $ln\ t_{50}$ and a variance of σ^2, where $t_f(J_i\ ,T_i\ ,j)$ is the failure time of the j-th line to fail in the i-th test and where the stress conditions are J_i and T_i. The effect of variations in the stress conditions can be modelled [5] by adding to $Y_{i\,j}$ an independent random variable, v_j, that is normally distributed with a mean of zero and a variance of v^2. The new population will still have a mean of $ln\ t_{50}$, but it will have an increased variance of $\sigma^2 + v^2$. The relative effect of the variations on the new sigma of the population, $\sigma_{new} = (\sigma^2 + v^2)^{1/2}$, only becomes significant when v becomes comparable to σ. When the v_j values are small, the variations in $Y_{i\,j}$ propagate as fractional variations of the original time to fail, $t_f(J_i\ ,T_i\ ,j)$. Percent variations of as much as 20% in the $t_f(J_i\ ,T_i, j)$ values (v = 0.20) will lead to an increase in σ_{new} of not more than 20.2%, if σ = 0.30 or larger. Variations in J and T of 5% and 5°C, respectively, can each produce variations of approximately 15% in $t_f(J_i\ ,T_i\ ,j)$. The variations in $t_f(J_i\ ,T_i\ ,j)$ as a result of the two processes in combination, will increase a sigma of 0.3 to not quite 0.37.

4.6 When analyzing the results of accelerated stress tests where there had been known and relatively large variations in the current-density and temperature stresses of the test lines, use procedure 7.2.1B.

5 Procedure for calculating the sample estimate of S and its confidence interval

5.1 When $t_{50}(J_i)$ values are available from N stress tests.

5.1.1 Define the following [6] for use in 5.1 (see 4.4):

$X_{1i} = \ln J_i$,
$Y_i = \ln t_{50}(J_i)$,
$N_s = \Sigma_i s_i$,
$X_{1av} = \Sigma_i s_i X_{1i} / N_s$,
$Y_{av} = \Sigma_i s_i Y_i / N_s$,
$SSX1 = \Sigma_i s_i (X_{1i} - X_{1av})^2$,
$SX_1Y = \Sigma_i s_i (X_{1i} - X_{1av}) (Y_i - Y_{av})$,
$SSY = \Sigma_i s_i (Y_i - Y_{av})^2$,
$\hat{B} = Y_{av} - \hat{S} X_{1av}$,
$\hat{Y}_i = \hat{B} + \hat{S} X_{1i}$, and
$SSE = \Sigma_i s_i (Y_i - \hat{Y}_i)^2$,

where i is summed from 1 to N, N is the number of stress tests, and s_i is the sample size of the i-th experiment. If the sample sizes are either all equal or are unknown, $s_i = 1$. Implicit are the assumptions that all test structures in a given test are subjected to the same current-density stress and that the stress temperature is the same for all test parts in each of the N stress tests. See 4.4 when there may be deviations from these assumptions.

5.1.2 Calculate sample estimates of S (-n) and its variance. Set s_i equal to the known sample sizes. If there is no information about the sample sizes or the sample sizes for the stress tests are all equal, use $s_i = 1$.

5.1.2.1 Calculate the sample estimate of S by using:

$$\hat{S} = \frac{SX_1Y}{SSX_1} . \tag{5.1}$$

5.1.2.2 Calculate $s^2(\hat{S})$, the sample estimate of the variance of $\hat{S}$, by using:

$$s^2(\hat{S}) = \frac{SSE}{(N-2)SSX_1} . \tag{5.2}$$

5 Procedure for calculating the sample estimate of S and its confidence interval (cont'd)

5.1.3 Calculate the two-sided confidence interval, $I_{S50}(1-\alpha)$, for $\hat{S}$ with confidence coefficient $1-\alpha$ by using:

$$I_{S50}(1-\alpha) = \hat{S} \pm d_{S50} = \hat{S} \pm t(1-\frac{\alpha}{2}; N-2) \bullet \sqrt{s^2(\hat{S})}, \qquad (5.3)$$

where N is the number of stress tests (t_{50} values) and $t(1-\alpha/2;N-2)$ is the $1-\alpha/2$ percentile of the t distribution for N - 2 degrees of freedom. The degrees of freedom is a parameter of the distribution and is related to the amount of information in the data for estimating variability.

NOTE — The number of experiments, N, must be at least three. This is because the degrees of freedom for the $1-\alpha/2$ percentile of the t distribution in eq. 5.3 is N - 2. An N of four is preferable because of the significant penalty on the size of the confidence interval from having only one degree of freedom instead of two in $t(1-\alpha/2;N-2)$. That penalty also increases as the confidence coefficient $(1-\alpha)$ is increased. At a confidence coefficient of 0.65, for example, the penalty is over 40%; the penalty increases to over 200% at the higher confidence coefficient of 0.90. Also, having at least four experimental t_{50} points may permit a better evaluation of the validity of the linearized form of Black's equation (eq. 3.3b) and of the presence of measurement interferences mentioned in 4.1 and 4.2.

5.2 When $t_f(J_i, j)$ values are available for N stress tests.

5.2.1 Define the following for use in 5.2 (see 4.4):

$X_{1i} = \ln J_i$,

$Y_{ij} = \ln t_f(J_i, j)$,

$N_S = \Sigma_i s_i$,

$X_{1av} = \Sigma_i s_i X_{1i} / N_S$,

$Y^*_{av} = \Sigma_i \Sigma_j Y_{ij} / N_S$,

$SSX_1 = \Sigma_i s_i (X_{1i} - X_{1av})^2$,

$SX_1Y^* = \Sigma_i \Sigma_j (X_{1i} - X_{1av})(Y_{ij} - Y_{av})$,

$SSY^* = \Sigma_i \Sigma_j (Y_{ij} - Y_{av})^2$,

$\hat{B} = Y^*_{av} - \hat{S} X_{1av}$,

$\hat{Y}_i = \hat{B} + \hat{S} X_{1i}$, and

$SSE^* = \Sigma_i \Sigma_j (Y_{ij} - \hat{Y}_i)^2$,

where i is summed from 1 to N, N is the number of experiments, j is summed from 1 to s_i, and s_i is the number of test parts in the i-th experiments. Implicit are the assumptions that all test structures in a given test are subjected to the same current-density stress and the stress temperature is the same for all test parts in each of the N stress tests. See 4.4 when there may be deviations from these assumptions.

5.2 When $t_f(J_i, j)$ values are available for N stress tests (cont'd)

5.2.2 Calculate the sample estimate of S by using:

$$\hat{S} = \frac{SX_1Y^*}{SSX_1} . \qquad (5.5)$$

5.2.3 Calculate $s^2(\hat{S})$, the sample estimate of the variance of $\hat{S}$, by using:

$$s^2(\hat{S}) = \frac{SSE^*}{(N_S - 2)\,SSX_1} . \qquad (5.6)$$

5.2.4 Calculate the two-sided confidence interval, $I_{Sf}(1-\alpha)$, for $\hat{S}$ with confidence coefficient $1-\alpha$, using:

$$I_{Sf}(1-a) = \hat{S} \pm d_{Sf} = \hat{S} \pm t(1-\frac{a}{2};\ N_S - 2) \bullet \sqrt{s^2(\hat{S})}, \qquad (5.7)$$

where N_S is the total number of test parts in the N stress tests and $t(1-\alpha/2;N_S-2)$ is the $1-\alpha/2$ percentile of the t distribution for $N_S - 2$ degrees of freedom. The degrees of freedom is a parameter of the distribution and is related to the amount of information in the data for estimating variability.

> NOTE — If the user is not interested in testing the validity of the linearized form of Black's equation (eq. 3.3b) nor is concerned about the possible measurement interferences mentioned in 4.1 and 4.2, then the number of experiments, N, may be as small as two. This is because the degrees of freedom is $N_S - 2$ and not N - 2, as it is when using t_{50} data in eq. 5.3 (see note in 5.1.3).

6 Procedure for calculating the sample estimate of E_A and of its confidence interval

6.1 When $t_{50}(T_i)$ values are available from N stress tests.

6.1.1 Define the following for use in 6.1 (see 4.4):

$X_{2i} = 1/T_i$,

$Y_i = ln\ t_{50}(T_i)$,

$N_s = \Sigma_i\ s_i$,

$X_{2av} = \Sigma_i\ s_i\ X_{2i} / N_s$,

$Y_{av} = \Sigma_i\ s_i\ Y_i / N_s$,

$SSX_2 = \Sigma_i\ s_i\ (X_{2i} - X_{2av})^2$,

$SX_2Y = \Sigma_i\ s_i\ (X_{2i} - X_{2av})\ (Y_i - Y_{av})$,

$SSY = \Sigma_i\ s_i(Y_i - Y_{av})^2$,

$\hat{C} = Y_{av} - (\hat{E}_A/k)\ X_{2av} = Y_{av} - 11605\ \hat{E}_A\ X_{2av}$,

$\hat{Y}_i = \hat{C} + (\hat{E}_A/k)\ X_{2i} = \hat{C} + 11605\ \hat{E}_A\ X_{2i}$, and

$SSE = \Sigma_i\ s_i(Y_i - \hat{Y}_i)^2$,

6.1 When $t_{50}(T_i)$ values are available from N stress tests (cont'd)

6.1.1 Define the following for use in 6.1 (see 4.4) (cont'd)

where i is summed from 1 to N, N is the number of stress tests, and s_i is the sample size of the i-th experiment. If the sample sizes are either all equal or are unknown, $s_i = 1$. Implicit are the assumptions that all structures in a given test are subjected to the same temperature stress and that the current density is the same for all test parts in each of the N stress tests. See 4.4 when there may be deviations from these assumptions.

6.1.2 Calculate the sample estimates for E_A and its variance. Set s_i equal to the known sample sizes. If there is no information about the sample sizes or the sample sizes are all equal, use $s_i = 1$.

6.1.2.1 Calculate the sample estimate of E_A (in units of eV) by using:

$$\hat{E}_A = \frac{1}{11605} \bullet \frac{SX_2Y}{SSX_2}. \tag{6.1}$$

6.1.2.2 Calculate $s^2(\hat{E}_A/k)$, the sample estimate of the variance of $\hat{E}_A/k$, by using:

$$s^2(\hat{E}_A/k) = \frac{SSE}{(N-2)SSX_2}. \tag{6.2}$$

6.1.3 Calculate the two-sided confidence interval, $I_{E50}(1-\alpha)$, for $\hat{E}_A$ with confidence coefficient $1-\alpha$ by using:

$$I_{E50}(1-\alpha) = \hat{E}_A \pm d_{E50} = \hat{E}_A \pm \frac{t(1-\frac{\alpha}{2};\, N-2) \bullet \sqrt{s^2(\hat{E}_A/k)}}{11605}, \tag{6.3}$$

where N is the number of stress tests (t_{50} values) and $t(1-\alpha/2;N-2)$ is the $1-\alpha/2$ percentile of the t distribution for N - 2 degrees of freedom.

> NOTE — The number of experiments, N, must be at least three. This is because the degrees of freedom for the $1-\alpha/2$ percentile of the t distribution in eq. 6.3 is N - 2. An N of four is preferable because of the significant penalty on the size of the confidence interval from having only one degree of freedom instead of two in $t(1-\alpha/2;N-2)$. That penalty also increases as the confidence coefficient $(1-\alpha)$ is increased. At a confidence coefficient of 0.65, for example, the penalty is over 40%; the penalty increases to over 200% at the higher confidence coefficient of 0.90. Also, having at least four experimental t_{50} points may permit a better evaluation of the validity of the linearized form of Black's equation (eq. 3.4) and of the presence of measurement interferences mentioned in 4.1 and 4.3.

6.2 When $t_f(T_i, j)$ values are available from N stress tests.

6.2.1 Define the following for use in 6.2 (see 4.4):

$X_{2i} = 1/T_i$,

$Y_{ij} = \mathit{ln}\ t_f(T_i, j)$,

$N_S = \Sigma_i\ s_i$,

$Y_{2av} = \Sigma_i\ s_i\ X_{2i} / N_S$,

$Y^*_{av} = \Sigma_i\ \Sigma_j\ Y_{ij} / N_S$,

$SSX_2 = \Sigma_i\ s_i\ (X_{2i} - X_{2av})^2$,

$SX_2Y^* = \Sigma_i\ \Sigma_j\ (X_{2i} - X_{2av})\ (Y_{ij} - Y^*_{av})$,

$SSY^* = \Sigma_i\ \Sigma_j\ (Y_{ij} - Y_{av})^2$,

$\hat{C} = Y_{av} - (\hat{E}_A/k)\ X_{2av} = Y^*_{av} - 11605\ \hat{E}_A\ X_{2av}$,

$\hat{Y}_i = \hat{C} + (\hat{E}_A/k)\ X_{2i} = \hat{C} + 11605\ \hat{E}_A\ X_{2i}$, and

$SSE^* = \Sigma_i\ \Sigma_j\ (Y_{ij} - \hat{Y}_i)^2$,

where: i is summed from 1 to N, N is the number of stress tests, j is summed from 1 to s_i, and s_i is the sample size of the i-th test. It is assumed that all test structures in a given test are subjected to the same temperature stress and that the current density is the same for all test parts in each of the N stress tests. See 4.4 when there may be deviations from these assumptions.

6.2.2 Calculate the sample estimate of E_A (in units of eV) by using:

$$\hat{E}_A = \frac{1}{11605}\ \frac{SX_2Y^*}{SSX_2} . \tag{6.5}$$

6.2.3 Calculate $s^2(\hat{E}_A/k)$, the sample estimate of the variance of $\hat{E}_A/k$, by using:

$$s^2(\hat{E}_A/k) = \frac{SSE^*}{(N_S-2)SSX_2} . \tag{6.6}$$

6.2.4 Calculate the two-sided confidence interval, $I_{Ef}(1-\alpha)$, for $\hat{E}_A$ with confidence coefficient 1-α, using:

$$I_{Ef}(1-a) = \hat{E}_A \pm d_{Ef} = \hat{E}_A \pm \frac{t(1-\frac{a}{2};\ N_S-2) \bullet \sqrt{s^2(\hat{E}_A/k}}{11605} , \tag{6.7}$$

where N_S is the total number of test parts used in the N stress tests and $t(1-\alpha/2;N_S-2)$ is the 1-α/2 percentile of the t distribution for N_S - 2 degrees of freedom.

> NOTE — If the user is not interested in testing the validity of the linearized form of Black's equation (eq. 3.4) nor is concerned about the possible measurement interferences mentioned in 4.1 and 4.3, then the number of experiments, N, may be as small as two. This is because the degrees of freedom is N_S and not N - 2, as it is when using t_{50} data (see note in 6.1.3).

7 Procedure for calculating sample estimates of S and E_A, and their confidence intervals

7.1 When $t_{50}(J_i, T_i)$ values are available for N stress tests.

7.1.1 Define the following [6] for use in 7.1 (see 4.4),

$N_S = \Sigma_i \; s_i$,
$X_{1i} = ln\, J_i$; $X_{1av} = \Sigma_i \; s_i X_{1i} / N_S$,
$X_{2i} = 1/T_i$; $X_{2av} = \Sigma_i \; s_i X_{2i} / N_S$, and
$Y_i = ln\, t_{50}(J_i,T_i)$; $Y_{av} = \Sigma_i \; s_i \; Y_i / N_S$.

$SSX_1 = \Sigma_i \; s_i (X_{1i} - X_{1av})^2$,
$SSX_2 = \Sigma_i \; s_i (X_{2i} - X_{2av})^2$,
$SSY = \Sigma_i \; s_i (Y_i - Y_{av})^2$,
$SX_1X_2 = \Sigma_i \; s_i (X_{1i} - X_{1av})(X_{2i} - X_{2av})$,
$SX_1Y = \Sigma_i \; s_i (X_{1i} - X_{1av})(Y_i - Y_{av})$,
$SX_2Y = \Sigma_i \; s_i (X_{2i} - X_{2av})(Y_i - Y_{av})$,
$D = SSX_1 \bullet SSX_2 - (SX_1X_2)^2$,
$\hat{Y}_i = Y_{av} + \hat{S} \bullet (X_{1i} - X_{1av}) + 11605 \bullet \hat{E}_A \bullet (X_{2i} - X_{2av})$, and
$SSE = \Sigma_i \, s_i (Y_i - \hat{Y}_i)^2$.,

where i is summed from 1 to N, N is the number of stress tests, and s_i is the sample size of the i-th experiment. If the sample sizes are either all equal or are unknown, $s_i = 1$. It is assumed that all test structures in a given test are subjected to the same current-density and temperature stresses. See 4.4 when there may be deviations from this assumption.

7.1.2 Calculate the sample estimates of S and E_A. Set s_i equal to the known sample sizes. If there is no information about the sample sizes or the sample sizes are all equal, use $s_i = 1$.

7.1.2.1 Calculate the sample estimate of S from:

$$\hat{S} = \frac{SSX_2 \bullet SX_1Y - SX_1X_2 \bullet SX_2Y}{D} . \qquad (7.1)$$

7.1.2.2 Calculate sample estimate of E_A (in units of eV) from :

$$\hat{E}_A = \frac{1}{11605} \bullet \frac{SSX_1 \bullet SX_2Y - SX_1X_2 \bullet SX_1Y}{D} . \qquad (7.2)$$

7.1 When $t_{50}(J_i, T_i)$ values are available for N stress tests (cont'd)

7.1.3 When there is interest in the confidence interval for $\hat{S}$ only, calculate the **individual**, two-sided confidence interval, $I_{SE50}(1-\alpha)$, for S with confidence coefficient 1-α from:

$$I_{SE50}(1-\alpha) = \hat{S} \pm d_{SE50} = \hat{S} \pm t(1-\frac{\alpha}{2};N-3) \bullet \sqrt{\frac{SSE}{N-3}} \bullet \sqrt{\frac{SSX_2}{D}}\ , \qquad (7.3)$$

where N is the number of stress tests (t_{50} values) and t(1-α/2;N-3) is the 1-α/2 percentile of the t distribution for N - 3 degrees of freedom.

> NOTE — The number of experiments, N, must be at least four. This is because the degrees of freedom for the 1-α/2 percentile of the t distribution in eq. 7.3 is N - 3. An N of five is much better because of the significant penalty on the size of the confidence interval from having only one degree of freedom instead of two. That penalty also increases as the confidence coefficient (1-α) is increased. At a confidence coefficient of 0.65, for example, the penalty is over 40%; the penalty increases to over 200% at the higher confidence coefficient of 0.90.

7.1.4 When there is interest in the confidence interval for E_A only, calculate the **individual**, two-sided confidence interval, $I_{ES50}(1-\alpha)$, for E_A with confidence coefficient 1-α from:

$$I_{ES50}(1-\alpha) = \hat{E}_A \pm d_{ES50} = \hat{E}_A \pm \frac{t(1-\frac{\alpha}{2};N-3) \bullet \sqrt{\frac{SSE}{N-3}} \bullet \sqrt{\frac{SSX_1}{D}}}{11605}\ , \qquad (7.4)$$

where N is the number of stress tests (t_{50} values) and t(1-α/2;N-3) is the 1-α/2 percentile of the t distribution for N - 3 degrees of freedom. See Note in 7.1.3.

7.1.5 When there is interest in the confidence intervals for both $\hat{S}$ and $\hat{E}_A$, calculate their simultaneous, two-sided confidence intervals [7], $I_{SE50s}(1-\alpha)$ and $I_{ES50s}(1-\alpha)$, according to the method of Bonferroni [7], by using α^* in equations 7.3 and 7.4, respectively, where $\alpha^* = \alpha/2$. Hence, use the 1-α/4 percentile of the t distribution, i.e. t(1-α/4;n-3), in these equations. See Note in 7.1.3.

7.2 When $t_f(J_i, T_i, j)$ or $t_f(J_{ij}, T_{ij})$ values are available from N stress tests.

7.2.1A Define the following [6] for use in 7.2 when it can be assumed that all test structures in a given test are subjected to the same current-density and temperature stresses, or that the variations in a given test are relatively small so that mean values can be used. See 4.4 and 7.2.1B.

$N_S = \Sigma_i s_i$

$X_{1i} = \mathit{ln}\ J_i$, $X_{1av} = \Sigma_i s_i X_{1i} / N_S$;

$X_{2i} = 1/T_i$, $X_{2av} = \Sigma_i s_i X_{2i} / N_S$; and

$Y_{i,j} = \mathit{ln}\ t_f(J_i, T_i, j)$; $Y^*_{av} = \Sigma_i \Sigma_j Y_{ij} / N_S$.

$SSX_1 = \Sigma_i s_i (X_{1i} - X_{1av})^2$,

$SSX_2 = \Sigma_i s_i (X_{2i} - X_{2av})^2$,

$SSY^* = \Sigma_i \Sigma_j (Y_{ij} - Y_{av})^2$,

$SX_1X_2 = \Sigma_i s_i (X_{1i} - X_{1av})(X_{2i} - X_{2av})$,

$SX_1Y^* = \Sigma_i \Sigma_j (X_{1i} - X_{1av})(Y_{ij} - Y_{av})$,

$SX_2Y^* = \Sigma_i \Sigma_j (X_{2i} - X_{2av})(Y_{ij} - Y_{av})$,

$D = SSX_1 \bullet SSX_2 - (SX_1X_2)^2$,

$\hat{Y}_i = Y^*_{av} + \hat{S} \bullet (X_{1i} - X_{1av}) + 11605 \bullet \hat{E}_A \bullet (X_{2i} - X_{2av})$, and

$SSE^* = \Sigma_i \Sigma_j (Y_{ij} - \hat{Y}_i)^2$,

where i is summed from 1 to N, N is the number of stress tests, j is summed from 1 to s_i , s_i is the sample size of the i-th test, and $t_f(J_i, T_i, j)$ is the failure time of the j-th sample in the i-the stress test.

7.2 When $t_f(J_i, T_i, j)$ or $t_f(J_{ij}, T_{ij})$ values are available from N stress tests (cont'd)

7.2.1B Define the following [6] for use in 7.2 when there are significantly large and known variations in the temperature and current-density stresses among the test parts in a given stress test to warrant factoring these variations explicitly into the calculations, rather than using mean values for these stress conditions in a given stress test (see 4.4).

$N_S = \Sigma_i \, s_i$

$X_{1ij} = \ln J_{ij}$, $X_{1av} = \Sigma_i \Sigma_j \, X_{1ij} / N_S$;

$X_{2ij} = 1/T_{ij}$, $X_{2av} = \Sigma_i \Sigma_j \, X_{2ij} / N_S$; and

$Y_{ij} = \ln t_f(J_{ij}, T_{ij})$; $Y^*_{av} = \Sigma_i \Sigma_j \, Y_{ij} / N_S$.

$SSX_1 = \Sigma_i \Sigma_j \, (X_{1ij} - X_{1av})^2$,

$SSX_2 = \Sigma_i \Sigma_j \, (X_{2ij} - X_{2av})^2$,

$SSY^* = \Sigma_i \Sigma_j \, (Y_{ij} - Y_{av})^2$,

$SX_1X_2 = \Sigma_i \Sigma_j \, (X_{1ij} - X_{1av})(X_{2ij} - X_{2av})$,

$SX_1Y^* = \Sigma_i \Sigma_j \, (X_{1ij} - X_{1av})(Y_{ij} - Y_{av})$,

$SX_2Y^* = \Sigma_i \Sigma_j \, (X_{2ij} - X_{2av})(Y_{ij} - Y_{av})$,

$D = SSX_1 \bullet SSX_2 - (SX_1X_2)^2$,

$\hat{Y}_{ij} = Y^*_{av} + \hat{S} \bullet (X_{1ij} - X_{1av}) + 11605 \bullet \hat{E}_A \bullet (X_{2ij} - X_{2av})$, and

$SSE^* = \Sigma_i \Sigma_j \, (Y_{ij} - \hat{Y}_{ij})^2$,

where i is summed from 1 to N, N is the number of stress tests, j is summed from 1 to s_i , s_i is the sample size of the i-th test, and $t_f(J_i \, T_i)$ is the failure time of the j-th sample in the i-th stress test.

7.2.2 Calculate the sample estimate of S from:

$$\hat{S} = \frac{SSX_2 \bullet SX_1Y^* - SX_1X_2 \bullet SX_2Y^*}{D} . \qquad (7.6)$$

7.2.3 Calculate sample estimate of E_A (in units of eV) from :

$$\hat{E}_A = \frac{1}{11605} \bullet \frac{SSX_1 \bullet SX_2Y^* - SX_1X_2 \bullet SX_1Y^*}{D} . \qquad (7.7)$$

7.2 When $t_f(J_i, T_i, j)$ or $t_f(J_{ij}, T_{ij})$ values are available from N stress tests (cont'd)

7.2.4 When there is interest in the confidence for $\hat{S}$ only, calculate the **individual**, two-sided confidence interval, $I_{SEf}(1-\alpha)$, for $\hat{S}$ with confidence coefficient 1-α from:

$$I_{SEf}(1-a) = \hat{S} \pm d_{SEf} = \hat{S} \pm t(1-\frac{a}{2};N_S-3) \bullet \sqrt{\frac{SSE^*}{N_S-3}} \bullet \sqrt{\frac{SSX_2}{D}}, \qquad (7.8)$$

where N_S is the total number of test parts used in the N stress tests and $t(1-\alpha/2;N_S-3)$ is the $1-\alpha/2$ percentile of the t distribution for N_S - 3 degrees of freedom.

7.2.5 When there is interest in the confidence for $\hat{E}_A$ only, calculate the **individual**, two-sided confidence interval, $I_{ESf}(1-\alpha)$, for $\hat{E}_A$ with confidence coefficient 1-α from:

$$I_{ESf}(1-a) = \hat{E}_A \pm d_{ESf} = \hat{E}_A \pm \frac{t(1-\frac{a}{2};N_S-3) \bullet \sqrt{\frac{SSE^*}{N_S-3}} \bullet \sqrt{\frac{SSX_1}{D}}}{11605}, \qquad (7.9)$$

where N_S is the total number of test parts used in the N stress tests and $t(1-\alpha/2;N_S-3)$ is the $1-\alpha/2$ percentile of the t distribution for N_S - 3 degrees of freedom.

7.2.6 When there is interest in the confidence intervals for both $\hat{S}$ and $\hat{E}_A$, calculate their simultaneous, two-sided confidence intervals [7], $I_{SEfs}(1-\alpha)$ and $I_{ESfs}(1-\alpha)$, according to the method of Bonferroni [7], by using α^* in eqs. 7.8 and 7.9, respectively, where $\alpha^* = \alpha/2$. Hence, use the $1-\alpha/4$ percentile of the t distribution, i.e. $t(1-\alpha/4;n-3)$, in these equations.

8 Procedure for calculating sample estimates of S, E_A, or both and their confidence intervals when when censrored data is used

8.1 If one or more of the stress tests used to determine sample estimates of S, E_A, or both, are halted **before** all the structures under test have failed, then the failure-time data from **all** tests are used to obtain sample estimates of t_{50} by procedures described in 5.1, 6.1, or 7.1, respectively. The methods for calculating these t_{50} values are described in 8.2 and 8.3.

8.2 For each stress test that was halted **after** all structures under test had failed, the sample estimate of t_{50} for complete data is the mean of the logarithms of the failure times.

8 Procedure for calculating sample estimates of S, E_A, or both and their confidence intervals when when censrored data is used (cont'd)

8.3 For each experiment that was halted before all parts under test had failed, the sample estimate of t_{50c} for censored data is obtained by the procedure in 8.4. This procedure follows that of method of JESD37 [2]. A method equivalent to JESD37 may be used.

8.4 The sample estimate of t_{50c} from censored data is obtained from the following calculations, where most of the terminology from JESD37 is retained.

8.4.1 Let s be the sample size of the test and K be the number of parts that had failed when the test was halted at time $t_{f\text{-}cen}$.

8.4.2 Calculate z_o, the standard normal value that corresponds to the 1 - K/s percentile of the standard normal distribution, by consulting a table for the standard normal cumulative distribution function. For example, $z_o(1\text{-}16/21) = z_o(0.238) = -0.7129$; and for a case of greater censoring: $z_o(0.45) = -0.1256$.

8.4.3 Calculate the following parameters, where $t_f(i)$ is the failure time of the i-th part of the K parts that failed under test:

$$a_{PR} = \frac{s}{K\sqrt{2p}} \exp\text{-}\left(\frac{z_o^2}{2}\right) \tag{8.1}$$

$$c_R = \ln(t_{f\text{-}cen}) \tag{8.2}$$

$$M = \frac{1}{K} \sum_{i=1}^{K} \ln(t_f(i)) \tag{8.3}$$

$$StdDev = \sqrt{\frac{\sum_{i=1}^{K} [\ln(t_f(i)) - M]^2}{K-1}} \tag{8.4}$$

$$\Delta = c_R - M \tag{8.5}$$

8.4.4 Calculate S_{RML}.

$$S_{RML} = \frac{1}{2} z_o \Delta + \frac{1}{2}\sqrt{z_o^2 \Delta^2 + 4 \bullet \left(\Delta^2 + \frac{K-1}{K} StdDev^2\right)} \,. \tag{8.6}$$

8 Procedure for calculating sample estimates of S, E_A, or both and their confidence intervals when when censrored data is used (cont'd)

8.4.5 Calculate S_{PRB}.

$$S_{PRB} = \sqrt{\frac{K-1}{K}\ StdDev^2 + a_{PR}(a_{PR} - z_o)\ S^2_{RML}}\ . \tag{8.7}$$

8.4.6 Calculate S_{PRU}.

$$S_{PRU} = \left(\frac{K}{K-1}\right)\bullet\left(\frac{1.8s + 5}{1.8s + 6}\right)\bullet S_{PRB}\ . \tag{8.8}$$

8.4.7 Calculate the sample estimate for t_{50c}.

$$\hat{t}_{50c} = \exp\left[\ M + a_{PR}\,S_{RML} + \left(\frac{0.98}{K} + \frac{0.068\,N}{K^2} - \frac{1.15}{s}\right)\bullet S_{PRU}\ \right]. \tag{8.9}$$

8.4.8 When sample estimates of t_{50c} for all censored tests have been calculated, use them with any sample estimates of t_{50} for complete data from 8.2 in procedures 5.1, 6.1, or 7.1 to calculate, respectively, sample estimates of S, E_A, or both, and their confidence intervals.

9 Measures for Linearity

9.1 The method depends on the assumption that Black's equation (3.2) is obeyed. There are several measures to assess the validity of this assumption.

9.2 Visual Inspection - When either current density or temperature is varied while the other variable is held constant, linearity can be assessed by a visual inspection of a plot of *ln* t_{50} as a function of *ln* J or of 1/T. When plotting t_{50} as a function of temperature, alternative scales, such as 1000/T or 1/*k*T, may be used. But, similar plots for *ln* t_f will generally not be as useful because of the much larger scatter of the *ln* t_f values for each current-density or temperature stress.

9.3 Correlation Coefficient - Linearity can be judged by how close the correlation coefficient is to unity. The sign of the coefficient is defined to match the sign of the slope of the line. Because the value of this coefficient is affected by the range of the variables and on the number of test parts, some caution is advised in the use of this measure. The correlation coefficient obtained from analyses of t_{50} data will be closer to unity than those for t_f data. Compare the values for these two cases in the sample calculations in Annex A, paragraphs A.1 and A.2.

9 Measures for Linearity (cont'd)

9.3.1 For cases where t_{50} values are analyzed, the correlation coefficient is defined by:

$$r = \sqrt{\frac{SSY - SSE}{SSY}} \ , \tag{8.1}$$

where SSE and SSY are defined according to the section used: 5.1, 6.1, or 7.1.

9.3.2 For cases where t_f values are analyzed, the correlation coefficient is defined by:

$$r^* = \sqrt{\frac{SSY^* - SSE^*}{SSY^*}} \ , \tag{8.2}$$

where SSE^* and SSY^* are defined according to the section used: 5.2, 6.2, or 7.2.

9.4 Residuals - If the assumption about linearity is valid, the observations of the $Y_i = \mathit{ln}\ t_{50}(i)$ values should scatter at random about the fitted straight line to the data in determining either S or E_A. This can be assessed by an examination of the least-squares residuals weighted by sample size, $s_i\ (Y_i - \hat{Y}_i)$, as a function of the independent variables X_{1i} or X_{2i}, respectively. These symbols are defined in the procedures (5., 6., and 7.). If the number of tests is small, as is expected to be usually the case, it will be difficult to detect anything but gross deviations from linearity.

NOTE — Among the properties of the least-squares residuals are that the sum of the weighted residuals is zero and the sum of the squared weighted residuals (SSE or SSE*) is a minimum.

10 Reporting

10.1 Minimum data to report

10.1.1 Sample estimates of n (i.e. -S) from 5.1.2.1 or 5.2.2, of E_A from 6.1.2.1 or 6.2.2, or of both from 7.1.2, or 7.2.2 and 7.2.3, depending on the input data.

10.1.2 Two-sided confidence interval(s) for n (i.e. -S) from 5.1.3 or 5.2.4, for E_A from 6.1.3 or 6.2.4, or for both from 7.1.3 and 7.1.4, or 7.2.4 and 7.2.5, depending on input data.

10.1.3 Confidence coefficient $(1 - \alpha)$ used in the calculation of confidence intervals.

10.1.4 Number of stress tests, N, and the total number of test structures, N_S (if needed in 10.1.2).

10 Reporting (cont'd)

10.1 Minimum data to report (cont'd)

10.1.5 If censored data is used, the values of K/s (in percent) for the stress tests conducted, where s is the sample size in a test and K is the number of parts failed when the test was halted.

10.1.6 For each test: the mean current-density stress (J_i) and the mean stress temperature (T_i) of the test lines .

NOTE — T_i is the sum of the ambient stress temperature and the temperature increase of the metal test line above ambient due to power dissipation in the test structure and elsewhere on the wafer or chip.

10.1.7 Sample estimates of t_{50} calculated for each stress test.

10.2 Additional recommended data and information

10.2.1 For each test: the range of current-density stress measured and the range of the stress temperatures calculated for the test lines.

NOTE — The stress temperature of a test line is the sum of the ambient stress temperature and the temperature increase of the metal test line above ambient due to power dissipation in the test structure and elsewhere on the wafer or chip.

10.2.2 Values for the individual failure times (t_f) of each test.

10.2.3 Method used to obtain the failure times and to measure joule heating of the test line.

10.2.4 A plot of $ln\ t_{50}(J_i)$ versus $ln\ J_i$, of $ln\ t_{50}(T_i)$ versus $ln\ (1/T_i)$, or of both, depending on the data analyzed in 9.2.

10.2.5 The correlation coefficient, r, (9.3.1) or the multiple correlation coefficient, r*, (9.3.2) for the t_{50} values.

10.2.6 A listing of the residuals for the t_{50} values (9.4).

11 References

[1] BLACK, J. R., "Current Limitations of Thin Film Conductors", Proceedings of the International Reliability Physics Symposium, 1982, pp. 300-306. IEEE Catalog No. 82CH17227-7.

[2] JEDEC Standard JESD37 Standard for Lognormal Analysis of Uncensored Data, and of Singly Right-Censored Data Utilizing the Persson and Rootzen Method.

[3] ASTM Standard F 1260M-96, Standard Test Method for Estimating Electromigration Median Time-To-Failure and Sigma of Integrated Circuit Metallizations, *Annual Book of ASTM Standards*, Vol. 10.04.

[4] EIA/JEDEC Standard No. 33-A, Standard Method for Measuring and Using the Temperature Coefficient of Resistance to Determine the Temperature of a Metallization Line.

[5] SCHAFFT, H. A., LECHNER, J. A., SABI, B., MAHANEY, M., and SMITH, R. C., "Statistics for Electromigration Testing", Proceedings of the International Reliability Physics Symposium, 1988, pp. 192-202. IEEE Cat. No. 88CH2508-0.

[6] DIXON, W. J., and MASSEY, Jr., F. J., *Introduction to Statistical Analysis*, 1982, pp. 242-243; and BROWNLEE, K. A., *Statistical Theory and Methodology in Science and Engineering*, John Wiley and Sons, Inc. 1960, pp. 274-275, 306-307.

[7] NETER, J. and WASSERMAN, W., *Applied Linear Statistical Models - Regression, Analysis of Variance, and Experimental Designs*, Richard D. Irwin, Inc., Homewood, IL, 1974, p. 147.

12 List of selected symbols

α Probability that the confidence interval estimate for a population mean does not include that mean.

A Materials-related constant in Black's equation (3.2).

B Constant involving A and E_A. $B = \ln A + E_A/kT$.

$\hat{B}$ Sample estimate of B.

C Constant involving A and n. $C = \ln A - n \ln J$.

12 List of selected symbols (cont'd)

$\hat{C}$ Sample estimate of C.

E_A Model parameter for temperature, T, in Black's equation and the activation energy for the electromigration process.

$\hat{E}_A$ Sample estimate of E_A.

i Running parameter from 1 to N, the number of stress tests.

j Running parameter from 1 to s_i, the sample size in i-th stress test.

J Current density in test line stressed in an electromigration stress test.

k Boltzmann's constant (8.617×10^{-5} eV/K).

n Model parameter for the current density, J, which is the absolute value of the exponent to which J is raised in Black's equation.

N Number of stress tests involved in determining model parameter(s).

N_S Number of test parts in N stress tests involved in determining model parameter(s).

s Sample size of a test (used in Section 8.).

s_i Number of test parts stressed in the i-th stress test.

S Slope of the line in a plot of *ln* t_{50} versus *ln* J of the linearized equation (3.3b) of Black's equation (3.1). S = -n.

$\hat{S}$ Sample estimate of the slope S.

T Temperature of the test line stressed in an electromigration stress test. This temperature is the sum of the local, ambient stress temperature and of the temperature increase of the test line due to power dissipation in the test structure and elsewhere on the wafer or chip.

t_f Failure time of a stressed test structure involved in an accelerated electromigration stress test.

t_{50} Median time to failure of the test structures stressed in an accelerated electromigration stress test.

ANNEX A Example Calculations

A.1 Using procedure 5.2 to calculate the sample estimate of S and of its confidence interval when failure times t (J ,j) are available from N stress tests. f i

A.1.1 A random number generator was used to develop the simulated *ln* t_f values listed in Table A.1A (on the following page) for five stress tests at different current-density stresses (1.0, 1.5, 2.0, 2.5, and 3.0 MA/cm^2) with different sample sizes (10, 10, 15, 15, and 20) from a population characterized by a slope S = - 2.0, a sigma = 0.3, and t_{50} values of 250, 111.1, 62.5, 40.0, and 27.78 h for the current densities used. For each test, the sample estimates of t_{50} and of sigma are given at the end of the string of t_f values.

A.1.2 Sample estimates of S (i.e. - n) and its two-sided confidence interval for a confidence coefficient of 0.9 are calculated. Their values and those of other parameters defined in 5.2.1 are listed in Table A.1B. To obtain a sum of residuals (see 9.4) to be zero required the use of double precision.

Table A.1B — RESULTS OF CALCULATIONS

Input Data: N = 5; N_S = 70; 1 - α = 0.9; t(1- α/2;N_S -2) = t(0.95;68) = 1.668

Sample Estimate of S = -2.018
Sample Estimate of the Variance of $\hat{S}$ = 0.01253677

2-Sided Upper 90% Confidence Limit for $\hat{S}$ = -1.831
2-Sided Lower 90% Confidence Limit for $\hat{S}$ = -2.205
δ_{Sf} = 0.187

Correlation Coefficient (r*) = - 0.90935

Sum of Residuals = 0.000000
SSE* = 8.20811
$\hat{B}$ = 5.47667
SSX_1 = 9.62827
SX_1Y^* = -19.431808

ANNEX A Example Calculations (cont'd)

Table A.1A — Input data from five simulated stress tests

STRESS TEST #1
$J_1 = 1.0$ MA/cm^2
Sample Size: $s_1 = 10$
Failure Times, *ln* t_f
5.070787
5.729231
5.150746
5.593572
5.317852
5.289805
5.217746
5.512861
5.976341
5.607882
$t_{50} = 231.987$ h;
s = 0.286

STRESS TEST #2
$J_2 = 1.5$ MA/cm^2
Sample Size: $s_2 = 10$
Failure Times, *ln* t_f
4.629283
4.610377
4.591859
4.352696
4.647532
4.856495
4.794479
5.048316
4.702699
5.324223
$t_{50}= 116.256$ h;
s = 0.271

STRESS TEST #3
$J_3 = 2.0$ MA/cm^2
Sample Size: $s_3 = 15$
Failure Times, *ln* t_f
4.269233
3.925835
3.688546
4.102785
3.928148
4.350340
3.911164
3.969871
4.313139
4.210783
2.730517
3.702357
4.071662
4.205815
4.285730
$t_{50} = 53.396$ h;
s = 0.404

STRESS TEST #4
$J_4 = 2.5$ MA/cm^2
Sample Size: $s_4 = 15$
Failure Times, *ln* t_f
3.984736
3.475434
3.811593
4.262760
3.524077
3.825310
3.310381
3.714328
3.491235
4.217836
3.943266
3.652469
4.187853
3.312066
3.137638
$t_{50}= 41.405$ h;
s = 0.351

STRESS TEST #5
$J_5 = 3.0$ MA/cm^2
Sample Size: $s_5 = 20$
Failure Times, *ln* t_f
3.488092
3.189989
2.496679
3.161959
3.639703
3.314930
3.070728
3.342889
2.996146
3.551770
2.529699
3.600095
3.462303
2.603084
3.671518
3.285337
3.128409
3.410107
3.124379
3.507400
$t_{50} = 25.248$ h;
s = 0.354

ANNEX A Example Calculations (cont'd)

A.2 Using procedure 5.1 to calculate the sample estimate of S and its confidence interval when $t_{50}(J_i)$ values are given from N stress tests.

A.2.1 The values for $t_{50}(J_i)$ used in this example are taken from those calculated in A.1. These values and other input data taken from A.1 are listed in Table A.2A. The sample estimates of S and its two-sided confidence limits for a confidence coefficient of 0.9 are calculated. Their values and those of some of the other parameters listed in 5.1.1 are listed in Table A.2B.

A.2.2 The confidence interval for $\hat{S}$ is larger here, where t_{50} values are used, than it is in A.1, where t_f values are used. According to the note in 3.2.2, the confidence interval is expected to be approximately 41% larger. For this particular data set, the interval is almost 50% larger.

Table A.2A — Input data

$N = 5$; $N_S = 70$; $1\text{-}\alpha = 0.9$; $t(1\text{-}\alpha/2;N\text{-}2) = t(0.95;3) = 2.353$

i	J_i (MA/cm^2)	$t_{50}(J_i)$ (h)	s_i
1	1.0	231.987	10
2	1.5	116.256	10
3	2.0	53.396	15
4	2.5	41.405	15
5	3.0	25.248	20

Table A.2B — Results of calculations

Sample Estimate of S = -2.018
Sample Estimate of the Variance of $\hat{S}$ = 0.014231

2-Sided Upper Confidence Limit for $\hat{S}$ = -1.738
2-Sided Lower Confidence Limit for $\hat{S}$ = -2.299
δ_{S50} = 0.281

Correlation Coefficient (r) = - 0.99480
Weighted Residuals (see 9.4):
-0.29996
0.97432
-1.50034
1.43991
-0.61393
Sum of Weighted Residuals = 0.00000
SSE = 0.41107
SSX_1 = 9.62827

ANNEX A Example Calculations (cont'd)

A.3 Using procedure 7.2 to calculate the sample estimates of S and E_A and their confidence intervals when t_f (J_i ,T_i ; j) values are given from N stress tests.

A.3.1 Failure time data from 10 stress tests for different current-density and temperature stresses are used to calculate sample estimates for S and E_A. They are also used to calculate the two-sided intervals for $\hat{S}$ and $\hat{E}_A$ when considered individually and simultaneously. Their calculated values and those of other parameters defined in 7.2.1A are listed in Table A.3A. To obtain the sum of the residuals (see 9.4) to be zero required the use of double precision.

A.3.2 The stress conditions and the failure times of the 10 stress tests are listed in Table A.3B. For each test shown in the table, the sample estimates of t_{50} and sigma are given at the end of the string of t_f values. Additional input data used in the calculations are:

> $N = 10$; $1- \alpha = 0.9$; $N_S = 181$
> For individual percentile: $t(1- \alpha/2;N_S -3) = 1.653$
> For simultaneous percentile: $t(1- \alpha/4;N_S -3) = 1.973$

Table A.3A — Results of calculations

Sample Estimate of S = -2.323

Individual Upper Confidence Limit for $\hat{S}$ = -2.016
Individual Lower Confidence Limit for $\hat{S}$ = -2.629
δ_{SEf} = 0.307
Simultaneous Upper Confidence Limit of $\hat{S}$ = -1.956
Simultaneous Lower Confidence Limit of $\hat{S}$ = -2.689
δ_{SEfs} = 0.367

Sample estimate of E_A = 0.407

Individual Upper Confidence Limit for $\hat{E}_A$ = 0.438
Individual Lower Confidence Limit for $\hat{E}_A$ = 0.376
δ_{ESf} = 0.031
Simultaneous Upper Confidence Limit for $\hat{E}_A$ = 0.444
Simultaneous Lower Confidence Limit for $\hat{E}_A$ = 0.370
δ_{ESfs} = 0.037

X_{1av} = 0.743035; X_{2av} = 0.002345; Y^*_{av} = 1.561158;
SSX_1 = 5.342524; SSX_2 = 0.000004; SX_1X_2 = 0.00127048;
SX_1Y^* = -6.412212; SX_2Y^* = 0.0153759; SSY^* = 117.690633;
D = 0.00001913093; Sum of Residuals = 0.000000;
SSE* = 30.228027;
Multiple Correlation Coefficient, r* = 0.86207

ANNEX A Example Calculations (cont'd)

Table A.3B — Input data from ten stress tests

STRESS TEST #1
$J = 2.0\ MA/cm^2$;
$T = 458\ K$; $s_1 = 19$
Failure Times, t_f (h)

1.246
1.264
1.717
1.899
1.958
2.284
2.298
2.401
2.415
2.446
2.519
2.599
2.616
2.761
3.264
3.274
3.984
3.986
3.987

t_{50} =2.446 h; s=0.337

STRESS TEST #2
$J = 2.0\ MA/cm^2$;
$T = 413\ K$; $s_2 = 18$
Failure Times, t_f (h)

3.040
3.215
4.262
5.376
6.016
6.651
6.680
6.766
6.934
7.138
7.516
7.620
8.421
9.002
9.242
11.815
14.092
14.417

t_{50} = 7.067 h; s=0.428

STRESS TEST #3
$J = 2.0\ MA/cm^2$;
$T = 433\ K$; $s_3 = 19$
Failure Times, t_f (h)

2.009
2.151
2.486
2.972
3.155
3.256
4.086
4.088
4.090
4.287
4.491
4.851
4.926
5.512
5.967
6.477
6.838
7.099
7.369

t_{50} = 4.227 h; s=0.394

STRESS TEST #4
$J = 2.53\ MA/cm^2$;
$T = 413\ K$; $s_4 = 19$
Failure Times, t_f (h)

1.132
3.320
3.402
3.506
3.521
3.762
4.134
4.265
4.338
4.430
4.932
5.309
6.462
6.469
6.941
6.959
6.998
7.824
9.337

t_{50} =4.680 h; s=0.467

STRESS TEST #5
$J = 2.53\ MA/cm^2$;
$T = 433\ K$; $s_5 = 19$
Failure Times, t_f (h)

1.166
1.171
1.289
1.428
1.572
2.204
2.429
2.699
2.853
3.118
3.438
3.518
3.872
4.346
5.035
5.100
5.371
5.394
8.795

t_{50} =2.916 h; s=0.589

STRESS TEST #6
$J = 2.53\ MA/cm^2$;
$T = 373\ K$; $s_6 = 19$
Failure Times, t_f (h)

7.534
9.759
9.857
12.293
12.321
12.413
12.625
12.807
12.998
13.491
16.201
17.061
17.151
17.648
18.068
20.158
20.377
22.845
23.658

t_{50} =14.582 h; s=0.306

ANNEX A Example Calculations (cont'd)

Table A.3B — Input data from ten stress tests (cont'd)

STRESS TEST #7
J = 1.67 MA/cm^2 ;
T = 413 K; s_7 = 16
Failure Times, t_f (h)

8.353
8.686
9.331
10.045
10.303
11.524
12.496
13.054
13.069
13.706
13.878
14.328
19.428
22.641
23.446
25.246

t_{50} =13.503 h; s=0.352

STRESS TEST #10
J = 2.53 MA/cm^2 ;
T = 458 K; s_{10} = 19
Failure Times, t_f (h)

0.773
0.800
0.923
0.956
1.054
1.102
1.152
1.179
1.348
1.388
1.394
1.431
1.562
1.854
1.883
1.904
1.966
2.300
2.798

t_{50} = 1.375 h; s = 0.358

STRESS TEST #8
J = 1.67 MA/cm^2 ;
T = 433 K; s_8 = 19
Failure Times, t_f (h)

3.143
3.589
4.144
4.144
4.471
5.246
5.709
6.259
6.354
6.699
7.064
7.506
7.740
7.885
8.866
8.969
9.657
10.234
10.333

t_{50} = 6.355 h; s = 0.362

STRESS TEST #9
J = 1.67 MA/cm^2;
T = 458 K; s_9 = 14
Failure Times, t_f (h)

1.860
2.052
2.767
3.298
3.387
3.626
3.869
4.011
4.224
4.534
4.695
7.211
8.564
8.752

t_{50} = 4.053 h; s = 0.466

ANNEX A Example Calculations (cont'd)

A.4 Using procedure 7.1 to calculate sample estimates of S and E_A and their confidence intervals when t_{50} (J_i ,T_i) values are available from N stress tests.

A.4.1 The values for t_{50} (J_i ,T_i) are taken from those calculated in A.3 for ten stress tests. The stress conditions, sample sizes, and sample estimates of t_{50} (J_i ,T_i) are listed in Table A.4A, as are other input data.

A.4.2 The input data are used to calculate sample estimates for S and E_A , and to calculate the two-sided 90% confidence intervals for $\hat{S}$ and $\hat{E}_A$ when they are considered individually and simultaneously. The results of these calculations are listed in Table A.4B.

A.4.3 The confidence intervals for $\hat{S}$ and $\hat{E}_A$ are larger for this case (where t_{50} values are used) than in A.3 (where t_f values are used). The ratio of the calculated intervals are:
$\delta_{SE50} / \delta_{SEf}$ = 0.336/0.307 = 1.09 and $\delta_{ES50} / \delta_{ESf}$ = 0.034/0.031 = 1.10. The ratio is smaller than that found in A.2.2 because here the number of experiments, N, is larger.

Table A.4A — INPUT DATA

N = 10; N_S = 181; 1 - α = 0.9
For individual percentile: t(1 - α/2;N-3) = 1.895
For simultaneous percentile: t(1 - α/4;N-3) = 2.365

i	J_i (MA/cm^2)	T_i (K)	t_{50} (J_i ,T_i) (h)	s_i
1	2.0	458	2.446	19
2	2.0	413	7.067	18
3	2.0	433	4.227	19
4	2.53	413	4.680	19
5	2.53	433	2.916	19
6	2.53	373	14.582	19
7	1.67	413	13.503	16
8	1.67	433	6.355	19
9	1.67	458	4.053	14
10	2.53	458	1.375	19

ANNEX A Example Calculations (cont'd)

TABLE A.4B - RESULTS OF CALCULATIONS

Sample Estimate of S = -2.322

Individual Upper Confidence Limit for $\hat{S}$ = -1.987
Individual Lower Confidence Limit for $\hat{S}$ = -2.658
δ_{SE50} = 0.336
Simultaneous Upper Confidence Limit of $\hat{S}$ = -1.903
Simultaneous Lower Confidence Limit of $\hat{S}$ = -2.741
δ_{SE50s} = 0.419

Sample Estimate of E_A = 0.407

Individual Upper Confidence Limit for $\hat{E}_A$ = 0.441
Individual Lower Confidence Limit for $\hat{E}_A$ = 0.373
δ_{ES50} = 0.034
Simultaneous Upper Confidence Limit for $\hat{E}_A$ = 0.449
Simultaneous Lower Confidence Limit for $\hat{E}_A$ = 0.364
δ_{ES50s} = 0.042

X_{tav} = 0.743035; X_{2av} = 0.002345; Y_{av} = 1.561208;
SSX_1 = 5.342524; SSX_2 = 0.00000388300; SX_1X_2 = 0.00127048;
SX_1Y = -6.411573; SX_2Y = 0.0153741; SSY = 88.525456;
D = 0.00001913093; SSE = 1.08217

Weighted Residuals (see 9.4):
-0.38061
-1.47152
-1.29024
0.98857
2.02791
-0.70021
2.35121
-1.49970
0.92676
-0.95216
Sum of Weighted Residuals = 0.00000
Multiple-Correlation Coefficient (r) = 0.99387

ANNEX A Example Calculations (cont'd)

A.5 Using procedures 8. and 7.1 to calculate sample estimates of S and E_A and their confidence intervals when censored data is used.

A.5.1 Consider the ten experiments described in A.3 used to calculate sample estimates of S and E_A (and of their confidence intervals) with procedure 7.2. In this example, it is assumed that experiments #2, #6, #7, and #8 had been halted before all test parts had failed. The times that these experiments were halted, for the sake of this example, are: 7.5 h, 13.5 h, 13.5 h, and 7.5 h.

A.5.2 The sample estimates of t_{50} for these four experiments are calculated with the censored data by the method described in section 8. The input data and results of the calculations are listed in Table A.5A.

TABLE A.5A — CALCULATIONS OF t_{50c} FOR EXPERIMENTS 2, 6, 7, AND 8

Exps.	2	6	7	8
s	19	16	19	18
K	11	9	10	10
$t_{f\text{-}cen}$(h)	7.5	13.5	13.5	7.5
z_O	-0.1991	-0.1573	-0.0660	-0.1398
α_{PR}	0.67556	0.70051	0.75634	0.71111
c_R	2.0149	2.60269	2.60269	2.01490
M	1.60942	2.36293	2.43774	1.68135
StdDev	0.27226	0.17234	0.18415	0.32427
S_{RML}	0.44279	0.27139	0.23489	0.43104
S_{PRB}	0.42806	0.26581	0.25463	0.45504
S_{PRU}	0.45915	0.29045	0.27588	0.49243
t_{50c}(h)	**6.866**	**13.036**	**13.864**	**7.468**
t_{50}(h) †	7.468	13.864	13.036	6.866

† t_{50} values from A.3 where complete data was used.

A.5.3 The sample estimates of t_{50} for the remaining experiments are obtained from the exponential of the mean of the *ln* t_f values for each experiment.

A.5.4 The sample estimates of S and E_A are obtained by the use of procedure 7.1 with sample estimates of t_{50} from the complete data of six experiments and with sample extimates of t_{50c} from the censored data of four experiments. The input data to these calculations are listed in Table A.5B. The results of the calculations are shown in Table A.5C.

ANNEX A Example Calculations (cont'd)

TABLE A.5B — INPUT DATA

$N = 10$; $N_S = 131$; $1 - \alpha = 0.9$
For individual percentile: $t(1- \alpha /2;N-3) = 1.895$
For simultaneous percentile: $t(1- \alpha /4;N-3) = 2.365$

i	J_i (MA/cm^2)	T_i (K)	$t_{50}(J_i,T_i)$ (h)	s_i
1	2.0	458	2.446	19
2	2.0	413	6.866*	10†
3	2.0	433	4.227	19
4	2.53	413	4.680	19
5	2.53	433	2.916	19
6	2.53	373	13.036*	10†
7	1.67	413	13.864*	9†
8	1.67	433	7.468*	11†
9	1.67	458	4.053	14
10	2.53	458	1.375	19

* t_{50c} value
† number of parts (K) that had failed when the test was halted.

ANNEX A Example Calculations (cont'd)

TABLE A.5C — RESULTS OF CALCULATIONS (With Censored Data)

Sample Estimate of S = -2.351
Individual Upper 90% Confidence Limit for $\hat{S}$ = -2.058
Individual Lower 90% Confidence Limit for $\hat{S}$ = -2.643
δ_{SE50} = 0.292
Simultaneous Upper 90% Confidence Limit of $\hat{S}$ = -1.986
Simultaneous Lower 90% Confidence Limit of $\hat{S}$ = -2.716
δ_{SE50s} = 0.365

Sample Estimate of E_A = 0.405
Individual Upper 90% Confidence Limit for $\hat{E}_A$ = 0.436
Individual Lower 90% Confidence Limit for $\hat{E}_A$ = 0.373
δ_{ES50} = 0.032
Simultaneous Upper 90% Confidence Limit for $\hat{E}_A$ = 0.444
Simultaneous Lower 90% Confidence Limit for $\hat{E}_A$ = 0.365
δ_{ES50s} = 0.039

X_{1av} = 0.757703; X_{2av} = 0.002319; Y_{av} = 1.411972;
SSX_1 = 4.186958; SSX_2 = 0.00000266843; SX_1X_2 = 0.00085550;
SX_1Y = -5.827172; SX_2Y = 0.0105150; SSY = 63.711530;
D = 0.00001044074; SSE = 0.65249

Weighted Residuals (see 9.4):
-0.62902
-0.33696
-1.47886
0.98048
1.96679
-0.81290
0.89523
-0.18334
0.67165
-1.07306
Sum of Weighted Residuals = 0.00000
Multiple-Correlation Coefficient (r) = 0.99487

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