A Reliability Model for Connector Contacts

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Reader Aids —
Purpose: Tutorial, present a model
Special math needed for explanations: None
Special math needed to use results: None
Results useful to: Reliability and electrical-contact engineers

Abstract — **Connector contacts have a typical end-of-life behavior during accelerated life testing. Based on that behavior, a model is developed that predicts the change in resistance ΔR for an aging contact. The model shows that the duration of accelerated life tests can sometimes be reduced by up to 50%, resulting in substantial time and cost savings. Analysis of the model leads to several unexpected conclusions. For example, contrary to established practice, contact reliability cannot correctly be evaluated with ΔR, but the change in conductance ΔG must be used. The evaluation of contact reliability, using ΔR as a parameter, does not agree with a time-to-failure approach in which each individual contact is assumed to have a specific failure time. The agreement is restored by the use of ΔG ratios. The use of ΔG by itself leads directly to the conclusion that contact reliability evaluated at some point in a contact's life explicitly depends on the resistance R_0 of the contact when it was put into use. The measured R_0 should not include any bulk resistance due to wires or terminal structures. The method is useful in calculating acceleration factors for life tests—yielding, for example, an estimated acceleration of 295 for reactive-gas ambient testing over current cycling for contacts plated with a defective gold film. The model lends itself to use by the contact designer to verify the adequacy of specific designs.**

1. INTRODUCTION

In order to determine connector contact reliability, connectors are typically subjected to prolonged environmental life tests using, for example, high temperature and humidity, current cycling, or reactive gas ambients. Testing can place a great burden on the resources of businesses that are interested in reliable products but also in short development cycles and optimal cost of conducting business. This paper contributes towards these business goals by outlining a method for evaluating contact reliability that permits reducing test times and provides a consistent approach for reliability estimation. The method is based on the use of conductance G instead of resistance R.

It is shown that contact reliability depends on conductance-change ΔG and on the initial resistance, R_0, of a contact. The sequence followed in this paper is to derive the model equations and then apply them to contact resistance-change measurements in several ways:

1. Shortening of test times and estimation of contact reliability based on forecasting,
2. Estimation of reliability without forecasting at the end of accelerated life tests with known acceleration factors,
3. Estimation of acceleration factors for life tests.

Standard notation is given in "Information for Readers & Authors" at the rear of each issue.

2. MODEL DEVELOPMENT AND RELIABILITY—BY DATA PROJECTION

The approach is based on the observation that contact resistance changes in a characteristic manner for contacts during life testing. If testing is long enough, a contact typically reaches a final or end-of-life stage. This is illustrated in figure 1 for a tin/lead-plated (henceforth denoted as tin-plated) contact that was subjected to 3671 synchronous current and thermal cycles of 10 A ac and 110 V with thermal excursions between ambient and 55 °C. In figure 1, ΔR is plotted *vs* number of test cycles.

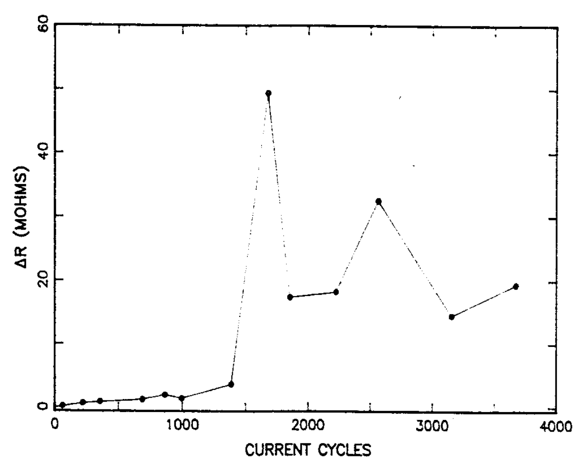

Figure 1. End-of-Life Stage of Tin-Plated Contact during 10 A Current/Thermal Cycling

Notation

ΔR	$R - R_0$
R	resistance at a given read-out time
G	$1/R$, conductance
$_0$	(subscript) implies the initial value

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Resistance was measured after equilibration-to-ambient with dry-circuit conditions, viz, at relatively low current (50 mA) and voltage (100 mV) using a 4-point measurement across the contact interface. The R is an average of two resistance measurements obtained by reversing the current for the second measurement. The characteristic end-of-life behavior, evident in figure 1, is that ΔR remains small for a prolonged time but then tends to increase rapidly within a relatively short time as the contact progresses towards an electric open. This point was reached at about 1600 current cycles for the contact in figure 1. The contact subsequently relaxed to an unstable equilibrium of $\Delta R = 30\ m\Omega$, probably due to continuing electric punch-through of any insulating layers. The reliability of an electric contact is usually evaluated in terms of ΔR. When ΔR exceeds an application-dependent limit (eg, 5 $m\Omega$), the contact is considered to have failed. It is clear from figure 1 that the time it takes the contact to fail (t_f) can also be used as a parameter with which to evaluate reliability.

The contact resistance plot shown in figure 1 is qualitatively similar to calculations by Greenwood [1] who constructed such a curve by plotting resistance *vs* the number of microscopic contact spots (a-spots) at the contact interface. The sharp upswing in resistance corresponds to the time when the number of a-spots has been reduced appreciably and most of the original conductive area is gone. The many ways by which this process happens have been dealt with by many authors, specifically with respect to contact hermeticity [2], surface contamination [3], temperature [4], and contact material [5, 6]. The primary modes of degradation lead to the destruction of the contact a-spots via: 1) ingress of an oxidizing or corrosive atmosphere, or corrosion products, or 2) by the diffusion of materials to the contact interface from the plating or bulk materials. For tin plating, these processes can be aggravated by fretting corrosion [7].

Although the ΔR in figure 1 is primarily gradual, a more abrupt mode of change is also possible; it occurs when the contact: 1) is moved on top of insulating or conductive regions by mechanical disturbance, or 2) experiences electric punch-through. This kind of abrupt resistance change is probably always present at a low level during testing and increases the variability of the data. This section works with the underlying gradual trend of resistance-change averaging through these disturbances. Thus, for the contact in figure 1, the gradual changes up to 1600 cycles can be approximated by a time-dependent function that has asymptotic properties near this end-of-life point. Such a function can be based on contact-degradation principles.

Derivation of Function

At any time t, the conductance of a contact largely depends on the contact area available for conduction. The a-spots at the contact interface are approximated by circles with average radius r. The total conductance G is approximately proportional [8] to the number of a-spots q multiplied by r. The conductance of a single a-spot G_a decreases at a certain rate as the contact ages in proportion to the rate of change of r as shown in (1).

$$\delta G_a/\delta t \propto \delta r/\delta t. \tag{1}$$

Assume that $\delta r/\delta t$ = constant $\times\ t^p$, so that (1) becomes:

$$\delta G_a/\delta t = -mt^p. \tag{2}$$

$$G_a = -ct^n + G_{a0}. \tag{3}$$

G_{a0} is the initial a-spot conductance.

The total conductance for a contact is a sum of terms, similar to (3), for all a-spots. Assume that the exponent n is the same for all a-spots on this contact.

$$G = \sum_{k=1}^{q} -c_k t^n + G_{a0k} = -at^n + G_0 \tag{4}$$

The change in contact resistance is:

$$\Delta R = R - R_0 = (1/G) - (1/G_0). \tag{5}$$

Substitute for G from (4) and rearrange; the result is the expression for ΔR for a single contact:

$$\Delta R = R_0^2/[(1/at^n) - R_0], \text{ for } 0 < \Delta R < \infty. \tag{6}$$

Eq (6) describes a curve such as in figure 1 (as long as t is small enough that ΔR is bounded). As t increases, the expression on the left in the denominator becomes smaller and can drop to R_0. Consequently, the denominator can approach zero, and ΔR can go to infinity, viz, the end-of-life.

The R_0 in (6) should be the "true" initial contact resistance and should not include bulk resistance due to wires or terminal structure. In actuality, a measured R_0 is too large since it includes unavoidable bulk contributions. Therefore, one settles for the best feasible estimate. It is shown below that the effect of including extra resistance in R_0 is to make reliability or time-to-failure estimates optimistic, ie, they favor the contact manufacturer, in proportion to the resistance included.

After obtaining a best feasible R_0 estimate, values for the constants a and n in (6) are obtained by a regression fit to the ΔR test data. Eq (6) is linearized for regression analysis:

$$Y = \ln(a) + n\cdot\ln(t) = \ln(\Delta R) - \ln(R_0(R_0 + \Delta R)) \tag{7}$$

Because $\ln(\Delta R)$ can be negative,* the fit using (7) can pose difficulties. This can occur at the start of testing when ΔR's are small or negative due to measuring equipment limitations or ordinary fluctuations in R. Thus the measurement procedure and equipment were upgraded to allow a 15 $\mu\Omega$ repeatability as compared to a previous 100 $\mu\Omega$. Negative ΔR are accommodated by a software algorithm. □

*Negative ΔR's are either discarded or a subsequent readout point with low resistance is chosen as a new R_0 for calculating ΔR. Any negative ΔR's left after recalculating with the new R_0 are excluded from the fit. The exact R that is chosen as the new R_0 depends on how many data points are left for the regression fit after excluding negative values. The number of points left for the regression fit is to be a maximum for the new choice of R_0. Subsequent to the regression fit, the data are sorted according to the sign of the slope. Contacts with a negative slope (decreasing resistance over the duration of the test) are assigned to a population of immortals, as discussed below.

Figure 2 shows a regression fit based on the first 685 current cycles of the data shown in figure 1. The raw data are shown by the dashed line. The solid line is based on the linear regression fit obtained with (7). Two numerical fits are shown by the dotted and dotted-dashed lines. One fit is to all the data points and one to the data after excluding negative values. In this particular example no negative ΔR values were excluded, so that the two curves overlap.

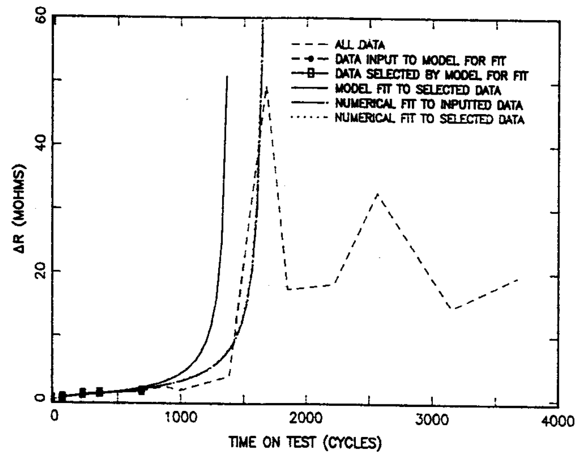

Figure 2. Actual & Projected Resistance Change *vs* Time for Current/Thermal Cycled Tin Contact

The non-linear numerical fit is computer-time intensive compared to the linear regression fit, and has an additional drawback. It is unduly influenced by outliers and isolated trends in the data – leading to erroneous projections. This is illustrated in figure 3 for a redundant dual contact with cracks in the nickel/gold plating that extend down to the beryllium-copper base metal. This sample had artificial perspiration (AP) applied to it and was kept in an office environment for more than a year. Figure 3 shows that the second readout point (at 24 hours) was selected by the model algorithm to be the new R_0. The regression fit (solid line), which is based on the first 570 hours of data, predicts a slightly earlier time-to-failure than the actual at 8300 hours. By comparison, the numerical fit (dotted and dashed-dotted lines) is unduly influenced by a temporary flat trend at the end of the data resulting in appreciable over-projection.

Usually, when the regression model fit is based on only the initial portion of the test data it yields a pessimistic time-to-failure that can advantageously be used to shorten test times. Such a fit results in a large slope and early estimated failure time because it is primarily based on the more rapid deterioration of the poor regions of contact at the contact interface. Thus, if the reliability goal is met, based on the early trend, then it would also be met were the entire history of the contact known. To illustrate these points, two examples of estimating reliability, based on trend lines, are given for gold- and tin-plated contacts.

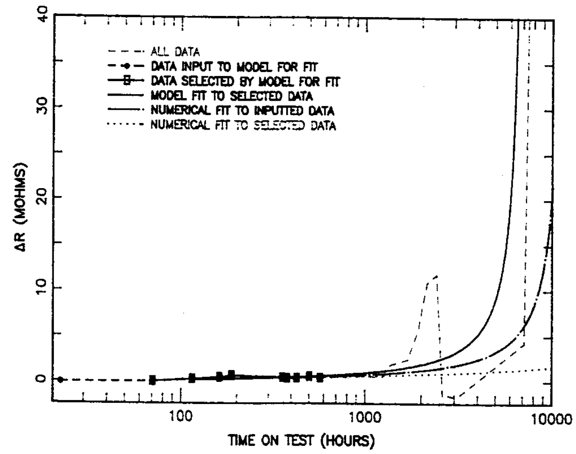

Figure 3. End-of-Life Stage of Nickel/Gold-Plated Contact with Damaged Plating and Artificial Perspiration at Room Ambient.

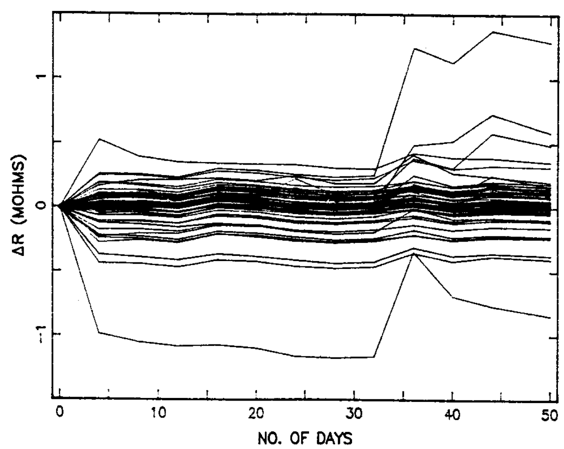

Figure 4. High $T+H$ for 56 Gold-Plated Terminals with Dual-Contact Design

Example 1

Figure 4 shows a plot of ΔR *vs* number of days at cyclic high $T+H$ for 56 gold-plated terminals similar to the one in figure 3. Resistance was measured every 4 days, after equilibration to room ambient. Figure 4 shows that some disturbances occurred at 32 days and at 40 days – resulting in a step-like increase in resistance at 36- and 44-day readouts. Figure 5 is an example of how reliability is estimated for these contacts based on calculated times-to-failure. It shows a 2-parameter Weibull probability plot constructed with calculated times-to-failure (time to reach 5 $m\Omega$). Time-to-failure for each contact was calculated from the regression fit (7) to the first 36 days of test data. Those contacts with a negative ΔR trend are included in figure 5 as censored data, viz, part of the immortal population. It is typical for this type of plot that the data segregates into early-failure

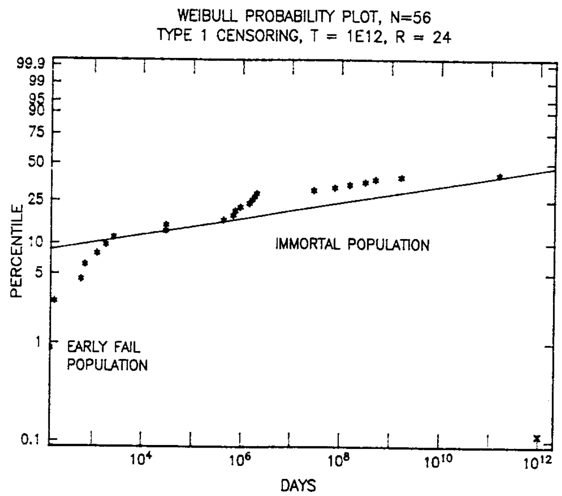

Figure 5. Projected Days-to-Failure for Gold-Plated Contacts

and immortal populations. The immortal population members are not of concern and failure is anticipated only from members of the early-failure population. A 3-parameter Weibull fit was, therefore, made to the early-failure population, with the results in table 1.

Table 1
Weibull Distribution Estimates

Regression Fit Interval (days)	Location Parameter (days)	Reliability at 50-day Test Endpoint
20	45.5	0.99706
24	38.8	0.98218
28	84.3	1
32	126.5	1
36	0.0	0.99660
40	151.5	1
44	92.5	1
50	136.1	1

Table 1 lists the Weibull location parameter and the reliability estimates for regression-fit intervals of various lengths. A location parameter is interpreted as that point before which failure is not anticipated. Reliability estimates were obtained from a plot such as in figure 5 for the 50-day endpoint of the $T+H$ test for the early-failure population. The early-failure and immortal populations were then combined on a relative basis to give the reliability numbers listed in table 1.

Table 1 is constructed during testing; thus it can be used dynamically as a decision table to determine when to stop testing. For example, after 20 days of testing, the reliability at 50 days is estimated as 0.99706. If the reliability goal is 0.999, then the decision is made at 20 days that testing should continue to the next scheduled readout at 24 days. By continuing this procedure, the decision can be made to stop testing after 28 days since the reliability goal has then been reached in a conservative manner. Thus a time saving of 22 days (44%) has been realized by using a projection method. An evaluation of the actual ΔR data at the 50 day point did verify that the reliability goal of 0.999 was met with respect to a 5 $m\Omega$ failure criterion. The deviation from a reliability of 1 at the 36-day interval is due to the fact that the data included a sudden increase in R as an endpoint for many contacts which resulted in an overly pessimistic regression fit. □

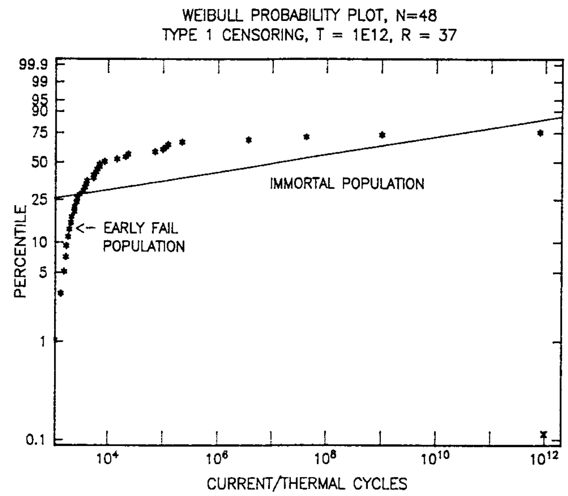

Figure 6. Cycles-to-Failure for Tin-Plated Contacts

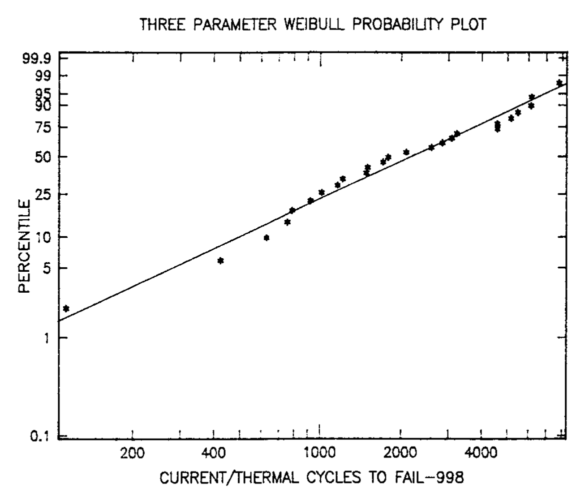

Figure 7. Tin-Plated Contact, Early-Failure Population

Example 2

This example is different from example 1 since it illustrates the procedure when contacts are projected to fail before the end of the test has been reached. Testing was done with 48 tin-plated contacts that were subjected to 3671 current & thermal cycles similar to the one discussed in figure 1. The regression fit interval is based on the data accumulated during the first 1382 cycles. Eventually, two failures occurred before the test specification endpoint of 3000 cycles. The failure after 1674 cycles is the contact shown in figure 1. Figure 6 is a 2-parameter Weibull plot of the time it took to reach 5 $m\Omega$ ΔR; the data are segregated into an early failure and an immortal population. The latter includes contacts that were censored because their regression line slope was nearly zero or negative. A three parameter Weibull probability fit of the early failure population is shown in figure 7 that gave a location parameter estimate of 998 cycles. From figure 7, the fraction of the early failure population anticipated to fail at 3000 current cycles is estimated as 48%. Thus, the decision that has to be made at the 1382 cycle readout point is whether to stop testing or whether to continue in order to verify the large probability for failure. In the latter case the two failures will be discovered. On the other hand, if the test is stopped, based on the high likelihood of failure, a 54% saving in test time is realized.

Reliability estimates based on data projection are appreciably affected by the behavior of individual contacts when it deviates from an ideal projection curve. This may be caused by appreciable differences in the rate of degradation for microscopic contact areas, thus violating the assumption that exponent n in (4) is the same for all of them. Or, for parallel and redundant contact designs, the various contact interfaces may have different physical properties and deteriorate at appreciably different rates. In either case, the presence of poor contact areas often results in an initially rapid change in resistance, followed by a slowing down as the higher integrity contact areas begin to predominate. When this happens, one can reassign R_0 to be a point at the start of the period of slow degradation in order to obtain a more realistic time-to-failure estimate. This is illustrated in figures 8 & 9 for a tin-plated contact.

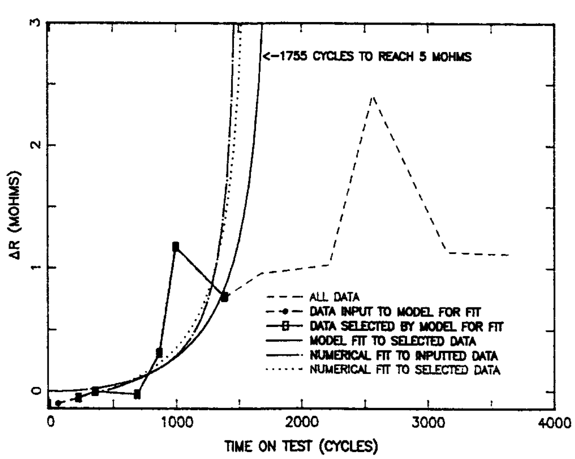

Figure 8. Actual & Projected ΔR *vs* Time for Current & Thermal Cycled Tin-Plated Contact

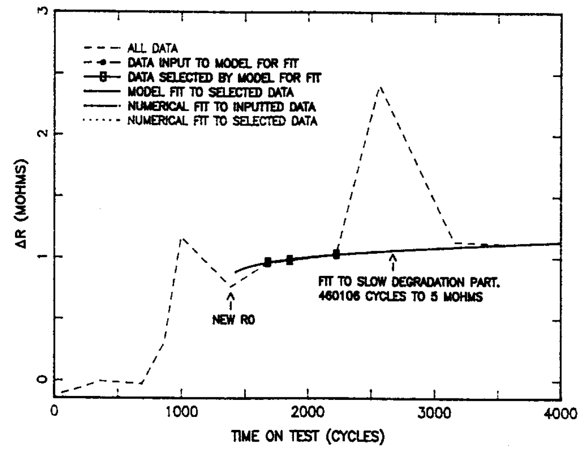

Figure 9. Actual & Projected ΔR *vs* Time for Current & Thermal Cycled Tin-Plated Contact

Figure 8 shows a fit that is conservative because it is made to the early time period of rapid change, with failure projected to occur at 1755 cycles. Figure 9 shows the fit to the slowly changing portion of the data between 1382 and 2300 cycles, with failure now predicted to occur after 460106 cycles. However, this kind of behavior need not occur, and the reliability estimate based on the initial data might have to be taken more seriously. For example, a comparison of figure 9 to the contacts in figures 2 & 3 shows that even though the latter are also of redundant design, there is no comparable levelling-off behavior at low resistance. In this case, the model is predictive of a realistic end-of-life because it represents an average behavior for those contacts that is maintained over time. □

An estimate of poor reliability based on data projection identifies a genuine weakness in the contact design that can have the consequence of failures during testing or in the field for large enough populations. In essence, it is not desirable to be dealing with a contact system for which much of the contact area is degraded early on and which has to rely for continued functioning on the remnant of a once healthy contact region, leaving the contacts in a precarious equilibrium. Thus, a projection method to weed out questionable designs in a short time is justified. A contact designer should try to produce contacts with an overall slow and stable rate of degradation. This model has the potential for helping contact designers evaluate whether such a goal has been achieved.

3. CONTACT RELIABILITY EVALUATION – WITHOUT DATA PROJECTION

The reliability of connectors and other components is often evaluated by subjecting them to an accelerated life test that is thought to be equivalent to a certain life in normal field usage. It is often convenient if the test data can be converted to a statistic that is (log)normally distributed. This permits estimating a

s-tolerance interval for the lives and a s-confidence interval to the distribution parameters and/or reliability. It frequently appears that ΔR is distributed in such a manner. This has resulted in the practice in our lab of obtaining estimates for high reliability connections by working with the distribution tails, considerably past the actual data. By using the s-tolerance interval method, relatively small sample sizes can be used for testing and the risk thus incurred can clearly be stated in statistical terms. However, based on (4)−(6), the assumption of (log)normality for the tails of the distribution of ΔR's is not justified, with the consequence that reliability estimates are in error. If the parameter used for estimating reliability is ΔG instead of ΔR, lognormality is introduced in its entirety, permitting the use of tail end regions and the calculation of high reliabilities.

When reliability is to be estimated at a final test readout point, there may be the tendency to include negative ΔR values in a lognormal fit by simply changing the negative to positive values. This procedure is not used here for the following reasons:

1. A decrease in resistance corresponds to an increase in conductive area which is a different physical process, and hence corresponds to a different failure mechanism, then the one underlying a resistance increase.

2. From a time-to-failure point of view, a negative ΔR at the end of a test is usually associated with a contact that has a ΔR trend line with a negative or nearly zero slope. The contact, therefore, belongs to the immortal population which is highly reliable and should be separated from and not included with the early failure population. There are two ways for separating the negative samples:

a. The model can be used to estimate a trend line and time-to-failure. The contacts are then separated according to which time-to-failure distribution they belong to. This is quite effective in removing contacts that have a negative ΔR at the end of the test.

b. In a more approximate but less data-treatment intensive manner, the data are sorted by assuming that contacts with negative ΔR automatically belong to the immortal population. This approach is used in this section.

The use of ΔG to estimate reliability is illustrated with the following test data. Two test fixtures with 24 tin-plated contacts each were subjected to current & thermal cycling similar to the contact shown in figure 1. A plot of ΔR *vs* number of cycles for all 48 contacts is shown in figure 10. The goal is to evaluate contact reliability with a (log)normal distribution at the worst readout point which occurred near 1600 cycles (one test fixture was read out at 1591 and the other at 1674 cycles; the data have been combined for the purpose of this analysis). Figure 10 shows that 2 of the contacts are in their end-of-life stage due to gradual deterioration, having reached 50 $m\Omega$ and 100 $m\Omega$ ΔR near 1600 cycles. Some of the contacts also display spike shaped increases of resistance due to temporary movement onto an insulating region, which is a different failure mode.

Figure 11 shows a normal probability plot of the ΔR data at the 1600 cycle point; the data cannot be described by a normal distribution. The same is true for a lognormal, Weibull, etc distribution of the positive ΔR values as shown in figure 12. These tin-plated contacts are evidently susceptible to appreciable fretting corrosion that gave rise to large ΔR values; for such contacts the (log)normal fit to ΔR fails for reasons that can be deduced from (6) & (7). The form of the equations implies for an individual contact that ΔR has the potential for diverging at a given point in time. This implies that the infinite population of ΔRs cannot be (log)normally distributed over the entire range of possible values of ΔR.

There is another basic flaw to the use of ΔR to evaluate reliability at a time that is related to the existence of a time-to-failure distribution for contacts. Such a distribution must be treated with a 3-parameter distribution. The location parameter implies that there exists a time period before which contact

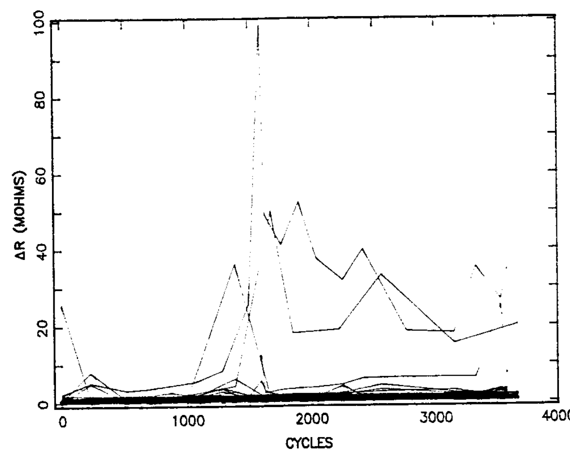

Figure 10. ΔR for 48 Tin-Plated Contacts [Current cycled at 10 A, and thermal cycled at 55 °C]

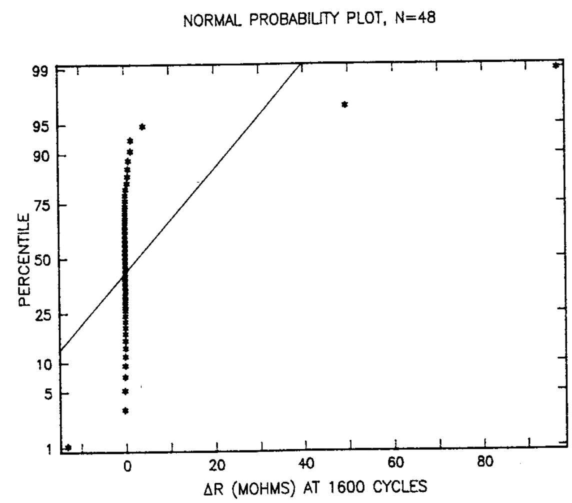

Figure 11. Current/Thermal Cycled Tin-Plated Contacts [Normal Distribution]

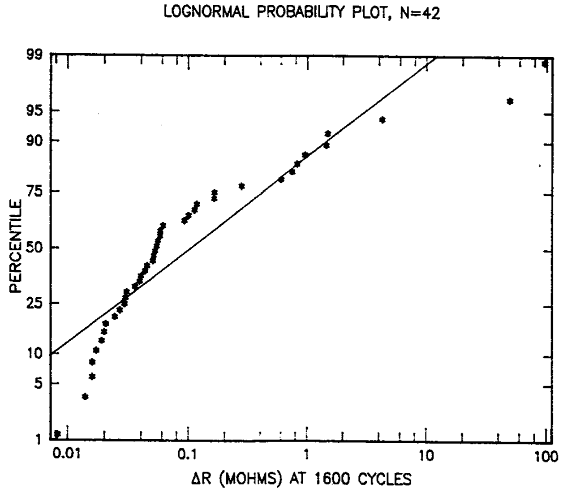

Figure 12. Current/Thermal Cycled Tin-Plated Contacts [Lognormal Distribution]

failure can not occur. This applies to the failure mode of gradual contact resistance change. Such a failure mode does not have a high probability of resulting in a failure very early in the test. An early failure is most likely due to a different failure mechanism. Because of the presence of the location parameter, there likewise must exist [9, pp 7–8] a location parameter on the ΔR axis at large ΔR since we now know that a short time-to-failure corresponds to a contact trend with large changes in R. However, when calculating a 3-parameter lognormal fit to ΔR, a location parameter will instead be calculated in a procedurally correct but technically incorrect manner at small ΔR.

It is necessary to bring the evaluation of reliability using ΔR into accord with the time-to-failure approach. This can be achieved by working with the inverse of R, viz, G. In that case, a location parameter is appropriately calculated at large R (small G). However, straightforward conductance does not lend itself to the evaluation of contact reliability. Rearrange (6) and take the logarithm of both sides:

$$\ln(\Delta G) = \ln(\Delta R) - \ln(R_0(\Delta R + R_0))$$

$$= n \cdot \ln(t) + \ln(a). \tag{8}$$

The $\ln(\Delta G)$ instead of $\ln(\Delta R)$ can now be used to calculate reliability. When that is attempted, however, there is no longer available a meaningful, unique, population failure criterion corresponding to a unique ΔR failure criterion (eg, 5 $m\Omega$) but only an individual criterion for each contact. This is evident from (8) which shows that a ΔG failure criterion, ΔG_f, calculated by substituting a ΔR failure criterion for ΔR in (8), depends on an individual R_0 for each contact. To obtain a unique population failure criterion, the ratio $\Delta G_f/\Delta G$ is calculated for each individual contact and the positive ratios are plotted on lognormal probability paper using a 3-parameter fit. Negative ratios are assigned to the immortal population. The use of a ratio results in a unique population failure criterion which is always 1. Reliability can now be estimated as being that fraction of the contact population that has $\Delta G_f/\Delta G > 1$. A 3-parameter fit must be used when calculating with $\Delta G_f/\Delta G$ in accordance with a time-to-failure approach because it consistently provides the best fit to the data. Figure 13 illustrates the result of this procedure when applied to the data that is shown in figure 12. Figure 13 shows by comparison to figure 12 that large delta R values are now easily accommodated (they are now on the left side of the plot) and that an excellent probability plot is obtained.

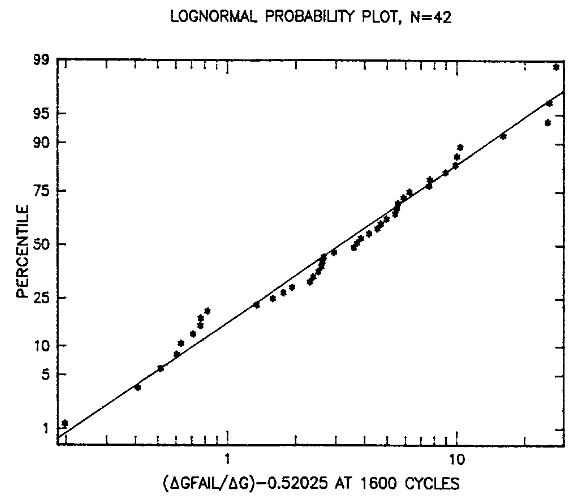

Figure 13. Current/Thermal Cycled Tin-Plated Contacts

The use of ΔG brings out the fact that the reliability of a contact directly depends on the value of its R_0. This is evident from (8) and by the following argument. $\Delta G = -(1/R) \times (\Delta R/R_0)$. The term on the right is the relative change in R_0 per ohm of final contact resistance at the end of the life test. This number should be kept as low as possible for a high reliability connection. A given ΔR distribution therefore implies various reliabilities, depending on the underlying R_0 distribution. For two populations with similar ΔR distributions but dissimilar R_0 distributions, the contact system with smaller R_0's is less reliable because it has degraded faster. This fact is, however, not accounted for in the ΔR distribution. Such a distribution will yield the same reliability number regardless of the underlying R_0 values. That is not the case when ΔG ratios are used as shown below.

Because the reliability depends on R_0, errors in the measurement of R_0 affect the estimate. One important contributor to this error is extraneous bulk resistance, R_b. It affects the ΔG ratio as shown in (9).

$$\ln(\Delta G_f/\Delta G) = \ln\{[\Delta R_f(\Delta R + R_0 + R_b)]/[\Delta R(\Delta R_f + R_0 + R_b)]\} \tag{9}$$

Using (9), the effect of R_b on the reliability estimate for the tin-plated contacts shown in figure 10 is summarized in table 2. The measured R_0 ranged from 0.1 to 2.11 $m\Omega$ with an average of 0.38 $m\Omega$. Table 2 shows the change in the reliability estimate as R_b increments are added to R_0 for failure criterion of 2 $m\Omega$ or 5 $m\Omega$.

Table 2.
Reliability (for Lognormal Fit to ΔG Ratio) with Failure Criterion of –

R_b ($m\Omega$)	2 $m\Omega$	5 $m\Omega$
0.0	0.90581	0.94506
0.2	0.93048	0.95922
0.4	0.93786	0.96193
1.0	0.94606	0.96825
2.0	0.94921	0.97450
5.0	0.94929	0.97963

Table 3
Reliability Estimates for High T + H Test of Contacts

Test	Procedure
Event 0:	Initial Insertion, R_0 read
Event 1-10:	1 Insertion and R read per event
Event 11:	10 days of T+H, R read
Event 12:	Disturb, R read
Event 13:	10 days of T+H, R read
Event 14:	Disturb, R read
Event 15:	10 days of T+H, R read
Event 16:	Disturb, R read
Event 17:	Insertion, R read
Event 18:	10 days of T+H, R read
Event 19:	Disturb, R read
Event 20:	10 days of T+H, R read
Event 21:	Disturb, R read
Event 22-24:	1 Insertion and R read per event

At Event	Location Param. (ΔG Ratio)	Unreliability (ΔG Ratio)	Unreliability (ΔR Lognormal)
ΔR Failure Criterion: 5 $m\Omega$			
15	0.0	0.00229	0.00169
20	0.2625	0.00599	0.00897
21	0.1850	0.01392	0.01770
23	0.1992	0.03456	0.05321
ΔR Failure Criterion: 150 $m\Omega$			
15	0.0	0.00022	3.8×10^{-8}
20	0.7059	0.00004	5.9×10^{-8}
21	0.4945	0.00041	2.1×10^{-6}
22	0.3020	0.00227	1.2×10^{-4}
23	0.5026	0.00247	1.6×10^{-4}
ΔR Failure Criterion: 1000 $m\Omega$			
15	0.0	0.00020	5.7×10^{-12}
20	0.7422	0.00002	3.6×10^{-12}
21	0.5198	0.00031	7.5×10^{-10}
22	0.3161	0.00195	7.6×10^{-7}
23	0.5259	0.00199	9.9×10^{-7}

Table 2 shows that reliability becomes larger with added R_b, an effect that is more pronounced for a small failure criterion. This fact can be useful in arriving at an opinion concerning the reliability of a contact system even though a good R_0 estimate is not available. For example, the test sequence shown in table 3 involved subjecting 400 gold-plated contacts to 50 days of cyclic high $T+H$ with periodic mechanical disturbance (durability cycling). The disturbance consisted either of a partial or full insertion/withdrawal cycle. No R_0 measurement was available. Based on some knowledge of the contact system, a constant R_b estimate was obtained by examining the R_0 values of all contacts after the first durability cycle, finding the lowest value, 25 $m\Omega$, and then using 20 $m\Omega$ as an approximate R_b. It was estimated that important residual bulk resistance remained for most contacts after subtraction of the 20 $m\Omega$ from their R_0. Thus, any reliability estimates would be known to be optimistic and favor the contact manufacturer. The estimates in table 3 are for some representative readout points and for the 3 failure criteria of 5, 150, 1000 $m\Omega$. A comparison is also made to estimates obtained with a lognormal fit to ΔR. The ΔG ratio method was robust enough to yield good probability plots even though it was applied to readouts after disturbances that incorporate step-function type changes in R. Durability cycling tends to produce 3 weakly-separated contact populations that in this instance were averaged together. The populations are centered at low ΔR (for contacts that become more conductive), mid ΔR, and high ΔR (for contacts that become more insulating.)

Table 3 shows that the unreliability of this gold-plated contact system is poor, ranging from 0.03456 to 0.00229 for a 5 $m\Omega$ failure criterion. Since these estimates are optimistic because of the included bulk resistance, then this contact system is not acceptable. Thus, it is possible to decide, even though measurements of R_0 were not available. A comparison of unreliability *vs* failure criterion shows, for the 5 $m\Omega$ failure criterion, that the estimate based on ΔR is reasonably close to the estimate based on ΔG. However, as the failure criterion is moved into the tail of the distribution to 150 $m\Omega$ and 1000 $m\Omega$, the estimate based on ΔR becomes unrealistic. For example, the optimistic estimated fraction defective for event 22 for a failure criterion of 150 $m\Omega$ when based on ΔG is $1-0.99773 = 0.23\%$. This compares well to an actually observed 0.75%. When the estimate is instead based on the lognormal fit to ΔR, it is an unrealistically small 0.012%.

Table 3 shows that there is no appreciable improvement in the ΔG reliability estimate from increasing the failure criterion beyond 150 $m\Omega$ to 1000 $m\Omega$. This is a realistic consequence of the estimate's dependence on the initial state of the conductive contact region via the inclusion of R_0. A 150 $m\Omega$ ΔR in relation to a low R_0 implies that:

- the rate of degradation was very high
- most of the initial conductive contact area is destroyed,
- the contact is in its asymptotic end-of-life stage,
- only small additional changes in the contact area are needed to produce very large changes in resistance (or an open).

This picture is not appreciably different if the failure criterion is increased to 1000 $m\Omega$ or more. This element of realism is missing when reliability is evaluated using ΔR alone, with important consequences. For example, there may be the tendency, especially for low-current signal applications, to select a large failure criterion in order to accommodate marginal test results. It is now clear that this will not appreciably improve the probability of survival of the contact system. Further, since permitting a large failure criterion places one into the high-risk end-of-life domain of a contact's existence, one has to be very certain about the acceleration factors of the tests. With that knowledge being uncertain, there is an appreciable risk of contact failure in the field since there is no safety margin in the failure criterion by way of keeping it small.

The use of ΔG for calculating reliability opens up new possibilities for looking at test results. Based on test data of gold- and tin-plated samples examined with the ΔG approach so far, there is a consistent physical correlation such that a low starting contact resistance is associated with a high rate of degradation and a large ΔG by the end of a test. This correlation might be a general rule for some contact systems such that a low R_0 corresponds to a large conductive contact region with weak contact pressure and the associated potential for a high rate of degradation. This effect is directly manifested by a correlation plot of ΔG at the end of a test *vs* R_0 (figure 14) and by a plot of ΔG *vs* time shown in figure 15.

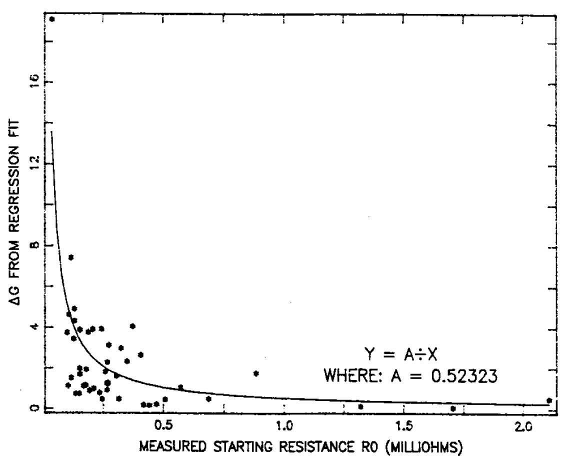

Figure 14. Correlation of Calculated ΔG with R_0 [For Tin-Plated Contacts in Figure 10.]

Figure 15 is a double log plot of calculated ΔG *vs* readout time for the tin-plated contacts shown in figure 10. The slope of the trend lines is approximately correlated with early ΔG such that it is positive for small ΔG and becomes negative for large ΔG. This relationship is reversed as time progresses, resulting in a plot with the trend lines crossing and forming nodal points about one third through the test. Rate of change of contact area and poor contact-pressure are involved such that a small early ΔG corresponds to contacts with a small R_0 and hence large conductive area. Such contacts show relatively little change in conductance early in the test while deteriorating at a fast rate and exhibiting a steep slope as testing progresses.

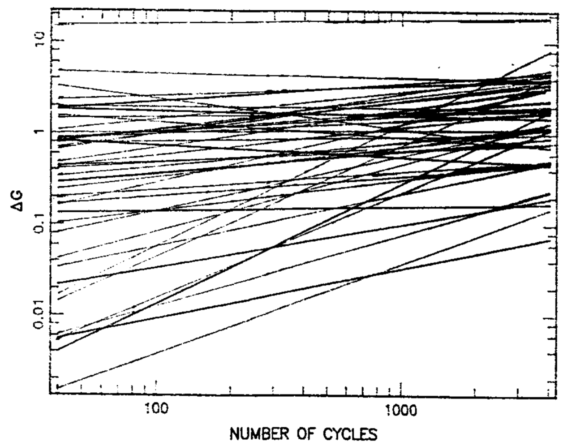

Figure 15. Calculated ΔG for Current & Thermal Cycled Tin-Plated Contacts

4. THE GENERAL MODEL

Changes in conductance in response to temperature, humidity, and contact force are not treated explicitly in previous sections. Their effect is implicitly incorporated in the constant m in (2). A more general form of (2) is given in (10); the integral of (10) is (11).

$$\delta G_a/\delta t = bF_0^w t^p \exp[-(E/kT) + \mathrm{BU}] \quad (10)$$

$$G = G_0 + ct^n \exp[-(E/kT) + \mathrm{BU}] \quad (11)$$

Notation

b, B	constants
w	an exponent that depends on the data
F_0	initial contact force
t	time
E	activation energy
U	relative humidity
T	absolute temperature
k	Boltzmann's constant (8.623×10^{-5} ev/K
c	a constant that incorporates the contact force.

Contact force is incorporated in (10) as a constant by using the initial contact force and ignoring any changes with time. This is partly justified based on known [2] contact resistance *vs* load behavior where the contact resistance remains approximately constant as the load is decreased over an appreciable range. However, the discussion in section 3 with regard to the correlation of ΔG and R_0 in an accelerated environment suggests that there might nevertheless be an increased opportunity for corrosion should the load change appreciably with time.

Eq (11) can be converted to (6) except that a has the expanded meaning:

$$\Delta R = R_0^2/[(1/at^n) - R_0], \text{ for } \Delta R > 0. \quad (12)$$

$$a \equiv c_1 F_0^w \exp[-(E/kT) + \mathrm{BU}]$$

Eq (12) is useful for calculating acceleration factors for life tests. An example for current cycling is provided below for gold-plated contacts of the type in figure 3. In this treatment of current cycling, the dependence of contact aging on current is implicitly taken into account by using the contact temperature rise due to Joule heating rather than by using an expression explicitly dependent on current. The temperature rise was measured by placing a thermocouple next to a contact at the center of a connector during operation. Based on calculating projected times to failure with (12) and a Weibull distribution fit to those projected times to failure, (13) was obtained.

For 3 A current, a contact temperature of 27.4°C, and $\alpha = 25449.4$ power-on hours —

$$\ln 25449.4 = b + H/[k(273°\mathrm{C} + 27.4°\mathrm{C})] \quad (13)$$

Notation

H	apparent activation energy $= E/n$
n	0.6 (from the data)
α	scale parameter of the Weibull distribution

The test conditions were:

- known porous gold plating
- artificial perspiration applied by dipping
- a current cycle of 10 min on, 20 min off
- 15 $m\Omega$ failure criterion.

For 8 A current, a contact temperature of 58.1°C, $\alpha = 11056.5$ power-on hours —

$$\ln 11056.5 = b + H/[k(273°\mathrm{C} + 58.1°\mathrm{C})] \quad (14)$$

Solve (13) & (14) for b, E, H; the result is:

$$\ln(\alpha) = 1.153 + 0.233/[k(273°\mathrm{C} + T_a + T_b)] \quad (15)$$

Notation

T_a	ambient temperature (°C)
T_b	Joule bulk temperature rise (°C)

Substituting in (15) for no current flow ($T_b = 0$) and a lab ambient of 21.5°C, the scale parameter is extrapolated to be 30.5 k hours. This is reasonably close to a value of 46.6 k hours that was calculated for the room ambient control to this experiment, given the approximations and uncertainties involved.

The above approach for current cycling assumes that the current is not excessive for the size of the contact, so that any effects due to local heating at the individual microscopic a-spots, denoted as super-temperature rise [8], can be neglected in favor of bulk heating.

Additional kinds of tests for which acceleration factors were obtained are listed in table 4. The acceleration factors were calculated by taking ratios of the Weibull scale parameters. These results were obtained for 1 connector per test cell with 12 contacts per connector and are, therefore, only rough estimates based on a small sample size. Some of these tests were however subsequently repeated with larger sample sizes of between 48 and 96 contacts per test cell; the results were surprisingly similar.

Table 4
Testing for Acceleration Factors

Test	
1	Ambient control with artificial perspiration (AP)
2	IBM G1T Reactive gas flow test [11]
3	3 A current cycling
4	3 A current cycling with AP
5	8 A current cycling
6	8 A current cycling with AP
7	Cyclic high temperature and humidity (4-4-16 test)
8	Cyclic high temperature and humidity with AP

Weibull Parameters (3-parameter distribution)
[The distribution was fit to projected times to failure.]

Test	Shape	Scale	Location
1	0.4370	47420	2881 hours
2	0.9527	1434	81 hours
3	0.3497	112321	1916 power-on hours
4	0.4506	26532	1101 power-on hours
5	0.5026	36945	1007 power-on hours
6	0.3569	8445	679 power-on hours
7	0.4975	55820	3578 hours
8	0.3972	266428	5880 hours

Test	Relative Acceleration-Factors*				
	1	2	3	4	5
1	3.0			1.0	1.04
2	98.2**				33.7
3	1.0				0.3 power-on hours used
4	5.5	1.0		1.8	1.9 power-on hours used
5	4.4		1.0		1.5 power-on hours used
6	12.7	2.3	2.9	4.2	4.4 power-on hours used
7	2.9				1.0
8	0.5				0.2

*Acceleration factors in each column are relative to the test marked with a factor of 1.0

**The acceleration factor for the reactive gas flow test relative to 3 A current cycling is 295 if number-of-current-cycles rather than power-on-time is used.

Because of the uniformity of the shape parameters for all the tests shown in table 4 (except for the reactive gas flow test), an average shape parameter was calculated and used in obtaining acceleration factors, ie, the data and average shape parameter were used to recalculate the scale and location parameters.

The acceleration factors in table 4 are relative to the test marked with a factor of 1.0 in each column. For example, in column 2, the test 4 (3 A current cycling with artificial perspiration) is marked with 1.0. Thus, comparing test 6 in column 2 (8 A with artificial perspiration) to test 4 shows that an increase in current to 8 A for the artificial perspiration test samples results in an acceleration factor of 2.3. By comparison, an acceleration factor of 4.4 is obtained when the current is increased to 8 A for the non artificial-perspiration samples (test 5 *vs* test 3 in column 1). The acceleration due to adding artificial perspiration is found by comparing tests 4 & 3 in column 1 for the 3 A samples and tests 6 & 5 in column 3 for the 8 A samples. The relative acceleration produced by artificial perspiration is 5.5 for the 3 A, and 2.9 for the 8 A samples.

The acceleration factor relative to one of the least severely stressed test cells, 3 A current cycling, is largest for the G1T [11] reactive gas flow test. Samples from that test investigated by SEM/X-ray (EDXS) methods showed the presence of chlorine compounds at the contact interface, which is interpreted to be due to a reaction with the exposed copper through the damaged plating. As anticipated, contact deterioration is accelerated by: an atmosphere containing chlorine and sulfur, high temperature and humidity, increased current, and artificial perspiration. The connector with AP in the 50-day high $T+H$ test was an exception though, showing the least acceleration. The gold contacts typically exhibited a great capacity for periodically improving in contact resistance during a test. This was especially true for the G1T test and was possibly due to mechanical disturbance by sample transport to the measurement station. I believe that averaging such test data is the primary reason for the difference in Weibull shape parameter for that test cell.

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