Estimating the Reliability of Electrical Connectors

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Key Words — **Connector, Contact, Degradation mechanism, Reliability estimation, Reliability prediction.**

Reader Aids —
Purpose: Tutorial
Special math needed for explanations: Elementary statistical inference
Special math needed to use results: None
Results useful to: Reliability practitioners

Summary & Conclusions — **Some current approaches to estimating the reliability of electrical contacts and connectors are discussed. These approaches center on statistical analysis of test data, and consider the active degradation mechanisms, determination of appropriate environmental tests with corresponding acceleration factors and exposures, statistical analyses appropriate for the test data, and establishment of appropriate acceptance criteria. Each of these issues is treated separately; then multiposition connectors and Mil-Hdbk-217 are discussed.**

We deprecate reliability "predictions" based on generic databases and failure rate models, such as Mil-Hdbk-217. A reliability qualification program should consist of:

- **Determining an application-specific acceptance criterion for contact resistance. A criterion is also required for every other failure mode to be included in the qualification program.**
- **Developing a test program to address the anticipated degradation mechanisms operative in the application. Ranking of failure modes should be part of this process.**
- **Deriving acceleration factors, when possible, for the specified tests.**
- **Deciding on the statistical treatment appropriate to the data from the qualification program.**
- **Estimating the component reliability.**

All these steps depend heavily on engineering judgment. Both the connector manufacturer and the user should agree on the content and approaches to be specified in these steps, in particular, and the qualification program in general.

1. INTRODUCTION

The reliability of electronic assemblies depends on the reliability of the passive electrical connections between the active components, as well as on the reliability of the components themselves. Much of the increasing attention being given to reliability of electrical connectors focuses on the basic question, "How can the reliability of electrical contacts and connectors be meaningfully determined?" Some current approaches to answering this question are discussed. These approaches center on adequate statistical analysis of test data, based on proper consideration of the following issues:

1. The active degradation mechanisms must be identified and categorized by their importance for the application.
2. Appropriate environmental tests, with corresponding acceleration factors and exposures, must be determined for these degradation mechanisms.
3. The statistical approach to estimating reliability from the test data must be agreed upon.
4. An acceptance criterion appropriate for the application of interest must be established.

The level of knowledge and understanding available to address these issues varies appreciably. Each topic is considered in a separate section.

2. DEGRADATION MECHANISMS

Degradation, or failure, of a contact or connector can occur in many ways. For our purposes it is convenient to divide the mechanisms into two categories, intrinsic and extrinsic.

- Intrinsic degradation mechanisms are related to the design and materials of construction of the contact or connector. Examples are: corrosion, loss of normal force through stress relaxation, and excessive Joule heating leading to temperature-related degradation.
- Extrinsic degradation mechanisms are related to the application of the contact or connector. Examples are: contamination, degradation caused by use of the connector outside its rated temperature range (both ambient and enclosure-related) or by application of currents exceeding the product specification (in both single and distributed modes), and contact abuse resulting from improper mating practices (mating at excessive angles, pulling on cables, etc.)

Connector manufacturers can provide design features intended to protect against intrinsic degradation.

Extrinsic degradation can be controlled only by proper specification of product performance by the connector manufacturer and proper use of the available information by the user. This is a joint responsibility which merits attention. The connector manufacturer can include strain relief for cables, finishes on contacts, improved crimps, and other features intended to provide robustness against extrinsic degradation, but these can always be overcome through abuse or misapplication by the user. The concept of *user* includes the electrical equipment manufacturer as well as the ultimate user of the equipment. However, extrinsic degradation is not something which can be straightforwardly analyzed.

Our discussion is limited to a few aspects of intrinsic degradation, in order to provide an approach to connector reliability evaluation. It is important to distinguish between failure *modes* and failure *mechanisms.* A failure *mode* is the effect by which failure is observed; a failure *mechanism* is the physical, chemical, or other process which causes failure [1, pp 4-5].

Only one failure mode, increase in contact resistance, is discussed, although many others exist, both mechanical (broken latches, bent pins, etc.) and electrical (crosstalk, leakage between contacts, etc.).

Three failure (degradation) mechanisms are considered:

- corrosion
- stress relaxation
- plating wear.

Each mechanism can lead to connector failure, directly or indirectly, through increased contact resistance. Corrosion of the contact interface causes an increase in contact resistance. Stress relaxation results in loss of contact normal force which in turn can lead to increased contact resistance, either directly or through increased susceptibility to mechanical or corrosive degradation. Plating wear can lead to increased contact resistance if wear-through occurs to the contact spring material which may be susceptible to corrosion.

These degradation mechanisms and the failure mode (increased contact resistance) associated with them are well-known factors in contact reliability. Thus, we have information relevant to our first concern, degradation mechanisms. Experience with the product, or with similar products or applications, allows us to categorize and rank the degradation mechanisms.

3. TEST METHODS & ACCELERATION FACTORS

The objective is to define a relationship between test methods, test data, and field experience. Simply put, we would like to be able to state that X days of exposure to test A are equivalent to Y years of service in application B. That is, we want an acceleration factor between the test exposure and field performance. Unfortunately, there are only a few tests for which such acceleration factors have been determined.

Examples

1. Corrosion testing via industrial mixed flowing gas (IMFG) exposures. The work done at Battelle Columbus Laboratories under Abbott [2; 3] provides a database from which an acceleration factor can be derived.

2. Stress relaxation via temperature life testing [4]. Acceleration factors developed for stress relaxation in pure copper do lead to conservative results when applied to copper-based alloys such as beryllium copper or phosphor bronze [5]. □

Other tests applied to electrical connectors include:

- temperature cycling with high humidity
- mating/unmating durability cycling
- mechanical shock and/or vibration
- salt spray
- fretting corrosion.

No acceleration factors are generally available for these tests. As a result, these are tests of *relative* performance; the resulting data indicate *only* the behavior of the connector system under the *tests*. They are not reliability tests yielding data on which estimates of behavior under *operating conditions* can be based [6; 7, p 4].

For those tests for which an acceleration factor is in hand, we can consider how to use appropriate test data to quantify reliability. Statistical approaches to reliability are our next concern.

4. RELIABILITY STATISTICS

We consider two kinds of data, variables and attribute. *Variables* data have a distribution to which a variety of statistical treatments can be applied; unfortunately, the distribution is rarely known. *Attribute* data assume that an item is in either of exactly two states (eg, good or not-good); the statistical treatment of such data is rather limited.

In a corrosion test, such as industrial mixed flowing gas, contact resistance is directly measured, and a statistical distribution can be fitted to the data. Alternatively, the contact resistance can be compared to some acceptance criterion and recorded as pass or not-pass. The statistical treatment of the data and the sample size needed for a given statistical confidence level generally vary appreciably for these two options.

One parameter which enters into both methods of data handling is the *acceptance* criterion applied to the data. For attribute data it appears directly. For variables data, it may appear, for example, in the estimate of a tolerance-limit factor, which in this context is a statistic (calculated from the test data and the known criterion) that reflects the relationship between sample size, reliability, and the statistical confidence with which the reliability may be stated, based on the test data. For variables data that follow a normal (Gaussian) statistical distribution, useful discussion and tables of tolerance-limit factors are given in [8]. In either case, the choice of *acceptance* criterion directly and appreciably influences the calculated reliability. How, then, should this value be selected?

5. ACCEPTANCE CRITERION

What is the appropriate value of contact resistance to use in calculating contact reliability? Consider two possibilities: the product specification and an application-related value. We suggest that the product specification contact resistance is not the proper choice. This value has a reliability aspect to it in the sense that the manufacturer has tested the product design to ensure that the specified contact resistance will be maintained in its intended range of applications. Thus the product specification value includes an "engineering safety/ignorance factor".

In a particular application, on the other hand, a user will have established a value of contact resistance at which the system ceases to function properly. The value might be over 100 $m\Omega$ in a signal application, or under 0.5 $m\Omega$ for a power contact.

The acceptance criterion for contact resistance should be based on this application-specific value and not the product-specification contact resistance. The requirement on statistical confidence limit and reliability should then be applied with this application-specific resistance value as the acceptance limit.

This statistical treatment and the "engineering safety/ignorance factor" approach are mutually exclusive. The statistical approach, based on an application-specific acceptance criterion, includes a "statistical safety/ignorance factor" by providing a lower statistical confidence bound on the reliability. To couple this with the "engineering safety/ignorance factor" inherent in the product specification acceptance criterion would impose one "safety/ignorance factor" on top of the other, and thereby place unduly restrictive requirements on contact-resistance stability.

6. ESTIMATING RELIABILITY OF MULTI-POSITION CONNECTORS

The above discussion is concerned with contact reliability, and with contact resistance as a degradation mode. Our ultimate concern is with connector reliability, which would generally include several contacts and degradation modes. A methodology for translating contact reliability, as determined for the desired range of degradation mechanisms, into connector reliability is required. The issue is complicated by two interacting factors:

1. The resistance data are obtained for individual contacts
2. The effect of the test on contact resistance is influenced by the fact that the contacts are, generally, in a connector.

In other words, we are including the effects of connector housing design on contact resistance, so we are not, strictly speaking, measuring contact reliability. The contact reliability may not be the same in a different housing geometry or configuration.

6.1. *The Contacts in a Connector Perform Statistically Independently*

Assumptions

1. All the degradation mechanisms and individual contact reliabilities are statistically independent.
2. A failure in any position in the connector results in connector failure.

The contact reliability is the product of the reliabilities for the individual degradation modes as determined from the appropriate test data. The connector reliability, in turn, is the previously determined contact reliability raised to a power equal to the number of positions in the connector. For example, the reliability for a 16-position connector which is to be qualified for 5 degradation mechanisms is:

$$R = [R(t_1)R(t_2)R(t_3)R(t_4)R(t_5)]^{16}. \quad (6\text{-}1)$$

Notation

- $R(t_n)$ contact reliability as determined for test n with respect to degradation mechanism n; we are not concerned here with the exact form of $R(t_n)$.
- R_c contact reliability for the special case of i.i.d. contact lives.

If $R(t_n) = R_c$ (independent of n), then the connector reliability is:

$$R = [R_c^5]^{16} = R_c^{80}. \quad (6\text{-}2)$$

This 80[th] power dependence appreciably impacts at least two aspects of qualification programs: cost and contact-reliability requirements. For a connector unreliability of the order of 10^{-4}, the contact unreliability requirement is of the order of 10^{-6}. Achieving an unreliability of this magnitude is one problem, an important one indeed, but another is verifying that it has been achieved. The sample size for such a verification could be very large, and would impact program cost.

6.2. *Using Asymptotic Extreme-Value Distributions*

Assumptions

1. The degradation mechanisms and individual contact reliabilities are not necessarily all statistically independent.
2. A failure in any position in the connector results in connector failure.

Connector failure depends only on the extreme value of the performance measurements over all contacts in the connector, eg, the shortest time to failure for any of the contacts, or the maximum increase in contact interface resistance for any of the contacts. The procedure described here depends on measuring the extreme values directly, and fitting (what can be a relatively small number of) them to an asymptotic distribution for extreme values. The connector population reliability is then estimated directly from this fitted distribution, without any attempt to estimate reliability of the contacts individually.

For a great many statistical distributions which apply to a variety of physical phenomena, the distribution of the extreme value (minimum or maximum) among N measurements tends to one of only three types of asymptotic distributions as N goes to infinity.

These asymptotic distributions differ both in the domain of the extreme-value variable and in the form of the upper tail (for maximum extremes) or lower tail (for minimum extremes) of the parent (original) distribution [9, p 192]. These asymptotic distributions are each of a fairly simple form and are each expressible in a parameter-free standardized form, analogous to the standardized normal distribution. Thus, numerical tables and/or appropriate probability graph papers are available for them.

If measurements of either time-to-failure or some continuous performance characteristic (eg, change in contact resistance) are made on all contacts of a few connectors (eg, 4 to 10) subjected to reliability testing, and the appropriate extreme value for each connector is determined, then these relatively few extreme measurements can be used to estimate the population reliability of the connectors relative to the acceptance criterion. For further discussion and examples, see [9, pp 185-199; 10; 11; 12, pp 63-81; 13, pp 40-45, 152-159, 295-308; 14, chapter 11].

Extreme caution should be used in extrapolating any distribution to values outside the range of the data. The statistical uncertainty (assuming the model is correct) in the answer should be calculated, and the engineering uncertainty (because the model might not be correct) should be estimated by any reasonable method available, eg, by comparing results from parametric and nonparametric (distribution-free) analyses.

6.3. *An Example*

Four 25-position connectors are subjected to industrial mixed flowing gas testing, with resulting maximum changes in contact resistance of:

0.150, 0.153, 0.170, 0.176 $m\Omega$,

in ascending order. (Each of these values is the largest change observed among the 25 contacts in a connector). A plot of these 4 values on type-I asymptotic extreme-value probability paper is shown in figure 1.

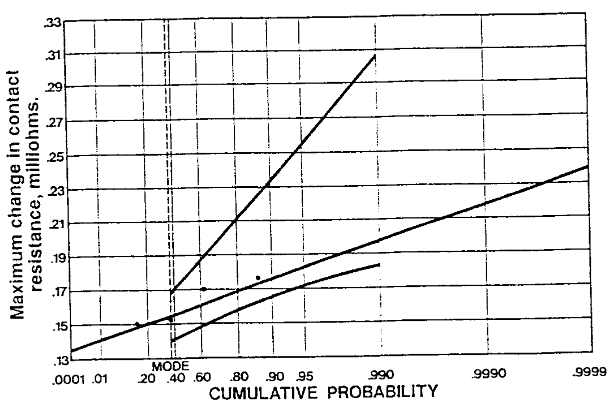

Figure 1. Extreme-Value Probability Plot.

The cumulative probability plotting positions used in figure 1 are $(i-0.44)/(n+0.12)$, where i is the rank of sample order statistic i and n is the sample size. These plotting positions are recommended by King [15, 16], who attributes them to Cunnane [17].

Procedures for estimating distributional parameters, for calculating statistical confidence limits, and for testing goodness-of-fit, for 2-parameter Weibull distributions and for type-I asymptotic extreme-value distributions, were developed by N. R. Mann (primarily) and others. These and related procedures are discussed and illustrated with numerical examples, and necessary tables are provided along with references to the original papers, in [13, chapter 11 and appendixes 8-13].

Appropriately applying these procedures to the 4 given data values provides the following results:

1. There is no statistically significant basis to reject the null hypothesis that these data came from a type-I asymptotic maximum-extreme-value distribution, even at the 25% level of statistical significance.
2. The best linear invariant estimates of the mode, w, and scale parameter, b, of the corresponding type-I asymptotic maximum-extreme-value distribution are $\tilde{w} = 0.155\ m\Omega$ and $\tilde{b} = 0.00914\ m\Omega$, respectively.
3. Corresponding 90% (2-sided, symmetric) statistical confidence intervals are ($0.142\ m\Omega < w < 0.169\ m\Omega$) and ($0.00598\ m\Omega < b < 0.03266\ m\Omega$), respectively.
4. Point estimates and 90% statistical confidence intervals for some percentile points of the distribution are:

Cumulative Probability	Estimated Percentile Point, $m\Omega$	90% Statistical Confidence Interval for the Percentile Point, $m\Omega$
0.0001	0.135	
exp(−1)=0.3679	$\tilde{w}$=0.155	(0.142, 0.169)
0.90	0.176	(0.166, 0.232)
0.95	0.183	(0.171, 0.255)
0.99	0.197	(0.181, 0.307)
0.9999	0.240	

Plotting each estimated percentile point *vs* its corresponding cumulative probability produces the fitted straight line in figure 1. Plotting the statistical confidence intervals produces the 90% statistical confidence band in figure 1.

This example demonstrates some of the difficulties that can occur in such analyses:

1. The fitted line, based on the estimated values of the distribution parameters, may not be the line of apparent best fit.
2. Much more serious is the excessive width of the statistical confidence band, which reflects the small sample size ($n = 4$). If a sample of 10 connectors had yielded the same estimates, $\tilde{w}$ and $\tilde{b}$, then, eg, the 90% statistical confidence interval for the 99-percentile point would have been ($0.185\ m\Omega$, $0.234\ m\Omega$) instead of ($0.181\ m\Omega$, $0.307\ m\Omega$) as found from our sample of 4. However, each of these sample values is costly, since (in this example) each one requires the preparation and measuring of 25 contacts. Some compromise between testing expense and acceptance criterion for the test results is needed. □

The techniques in this example are developed assuming the original data came from a 2-parameter Weibull distribution with scale parameter δ and shape parameter β; denote these data values by t_i for $i = 1, 2, \ldots, n$. The data values (t_i) are transformed into new values (say, x_i) by $x_i = \ln(t_i)$. The x_i-values then follow a type-I asymptotic minimum-extreme-value distribution with mode $u = \ln(\delta)$ and scale parameter

$b = 1/\beta$. The calculations are carried out using the x_i-values. Since our data values (say, y_i) follow a type-I asymptotic maximum-extreme-value distribution, transforming them into corresponding values of x_i is accomplished through multiplication by -1. Since the x_i-values must be used in ascending order during the calculations, the order of our y_i-values must be reversed. Thus, $x_i = -y_{n+1-i}$ for $i = 1, 2, \ldots, n$. The estimates of the mode, u, and scale parameter, b, of the distribution of the x_i-values yield estimates of the mode, w, and same scale parameter, b, of the distribution of the y_i-values, with $w = -u$.

7. FAILURE-RATE PREDICTIONS BASED ON MIL-HDBK-217

The preceding discussion presents some of the pertinent issues in estimating the reliability of electrical connectors from appropriate test data. No mention has been made of procedures for "predicting" failure rate based on Mil-Hdbk-217 or similar generic models and databases. We strongly oppose the use of such models and databases, for the following reasons.

1. The intent of Mil-Hdbk-217 is to provide a basis for "predicting" failure rate *before* hardware is available for testing. These "predictions" are calculated using failure rate models and adjustment factors based on:

- historical field data acquired from a variety of sources over some period of time and under various levels of statistical control and verification,
- unspecified laboratory data.

The sources, the time frame, the corresponding levels of statistical control and verification of the data, and the manipulations applied to the data to derive the failure rates and adjustment factors, are not described in Mil-Hdbk-217 (or any other public document). Thus, we have no way of knowing the quantity, nor the pedigree (source, history, quality, etc.) of the data, nor the political factors, upon which Mil-Hdbk-217 is based.

The failure rate models and adjustment factors in Mil-Hdbk-217 take into account these characteristics of the connector/application:

- number of active contacts in the connector
- contact gauge
- current per contact
- number of mating/unmating cycles per 1000 hours
- insert material.

However, no consideration is given to such critical design parameters as contact normal force, contact wipe distance, strain relief, contact base metal and plating, and contact density. All of these can appreciably affect connector reliability.

2. The current version (E) of Mil-Hdbk-217 is dated 1986 October 27; revision D was dated 1982 January 15. The *Foreword* of revision E lists the changes from revision D; no mention is made of any failure rate models or adjustment factors for connectors. The inescapable conclusion is that the models and adjustment factors for connectors in revision E do not reflect in any way the changes in connector technology since 1981 or earlier. This obsolescence is evident, eg, in the list of insert materials given in Table 5.1.12.1-3.

3. The adjustment factors in Mil-Hdbk-217 for *Use Environment* span 27 different environments (Tables 5.1.1-3, 5.1.12.1-6, 5.1.12.1-7, 5.1.12.2-4, 5.1.12.2-5, and 5.1.12.3-1). It seems unlikely that sufficient field data could have been obtained for all of these environments to justify any great precision or accuracy in the resulting adjustment factors. Indeed, pages 4-2 and 4-3 of Mil-Hdbk-217E state:

> "... part reliability in the field use of equipment is difficult to examine due to the lack of suitable data being acquired. Thus, it can be seen that derivation of failure rates (being mean values) is empirically difficult and obtaining valid confidence values is practically precluded because of lack of correlation.
>
> "The use of failure rate data, obtained from field use of past systems, is applicable on future concepts depending on the degree of similarity existing both in the hardware design and in the anticipated environments. Data obtained on a system used in one environment may not be applicable to use in a different environment, especially if the new environment substantially exceeds the design capabilities. Other variants that can affect the stated failure rate of a given system are: different uses, different operators, different maintenance practices, different measurement techniques or definitions of failure. When considering the comparison between similar but unlike systems, the possible variations are obviously even greater.
>
> "Thus, a fundamental limitation on reliability prediction is the ability to accumulate data of known validity for the new application. Another fundamental limitation is the complexity of prediction techniques ..." [18, pp 4-2 & 4-3].

For these reasons, we see no basis for correlation of the results of Mil-Hdbk-217 failure-rate "predictions" to specific products [19].

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