

AMP

P351-93
Order No. 65761

Connector Design/Materials

and

Connector Reliability

by:
Robert S. Mroczkowski

AMP Incorporated
Harrisburg, PA 17105

Connector Design/Materials and Connector Reliability

by:
Robert S. Mroczkowski

INTRODUCTION

Connector reliability has taken on new significance as electronics, especially computers and telecommunications equipment, become more important in both business and everyday life. The reliability of a connector depends on two factors. First, the application, which determines the requirements - both environmental and functional - which the connector must meet. And, second, the design and materials of manufacture of the connector, which determine the degradation mechanisms. This paper will provide an overview of how these two factors interact to determine connector reliability in today's electronics equipment.

To provide a perspective on connector reliability some field history will be reviewed and a laboratory approach to estimating connector reliability will be proposed.

CONNECTOR OVERVIEW

The discussion begins with a simple question.

“What Is a Connector?”

This question can be answered in two ways, functionally and structurally. First a functional definition.

Connector Function

A connector provides a separable connection between two elements of an electronic system without unacceptable signal distortion or power loss.

There are two important parts to this definition, the “separable connection” and the “unacceptable” performance. Both depend on the connector application and its electrical and environmental requirements.

The separable connection is the reason for using a connector in the first place, to provide easy repair, upgrading, maintenance or interconnectability. Requirements on the separable interface include mating force limitations and meeting a specified number of mating cycles.

“Unacceptable” performance includes a large range of characteristics, but this discussion will concentrate on the resistance the connector introduces into the electronic system.

To provide an understanding of connector resistance, consider a “structural definition” of a connector, its design and materials of manufacture.

Connector Structure

Figure 1 provides a schematic illustration of a connector. Every connector includes:

- two permanent interfaces, the connections to the subunits which are to be connected,
- the contact springs in each half of the connector,
- the separable interface and
- the connector housing which maintains the location of the contacts and isolates them from one another electrically.

The insets in the figure illustrate the contact finish and the structure of the separable interface on a microscopic level. A brief description of each of these connector components is in order.

The Separable Contact Interface

The separable contact interface is the place where the two halves of the connector meet. For this discussion, it is sufficient to note two characteristics of the interface. First, the interface surfaces are rough on the microscale at which contact occurs as indicated on the lower inset in Figure 1. Second, a resistance, called constriction resistance, is introduced simply due to the restriction in contact area which occurs at the separable interface as

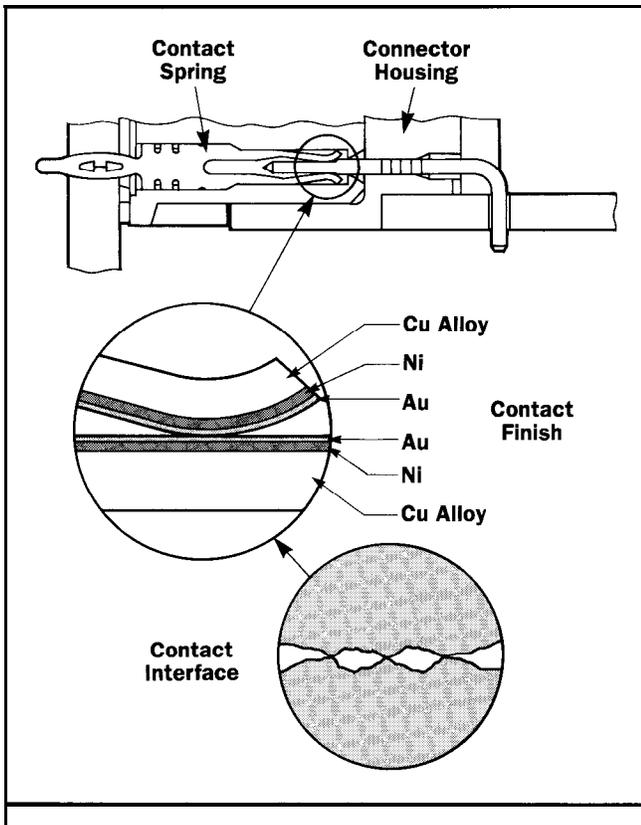


Figure 1. Schematic illustration of a typical connector indicating the major structural components. Insets illustrate the contact interface and contact finish.

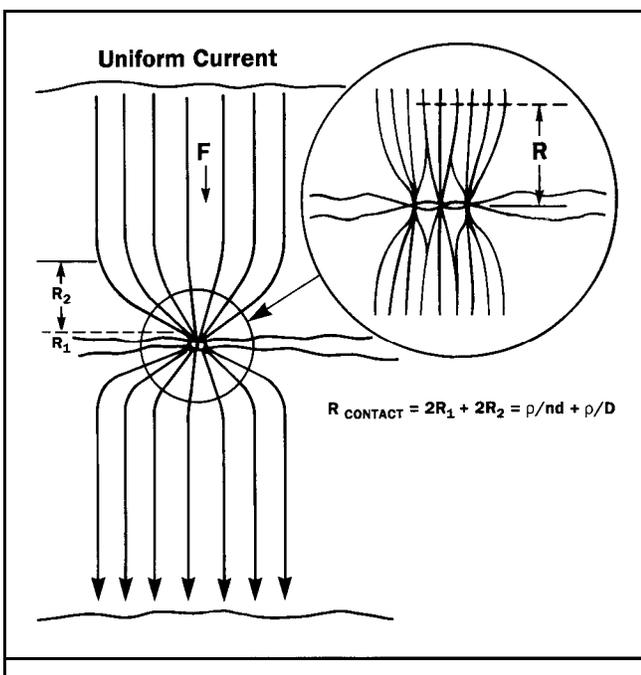


Figure 2. Schematic illustration of constriction resistance. Constriction resistance is a geometric effect.

illustrated in Figure 2. For a detailed discussion of contact interface structure see Williamson (1) and Mroczkowski (2).

An additional resistance may occur due to films at the interface. Films may affect contact resistance by introducing a series film resistance or by reducing the area of metallic contact as will be discussed.

One of the major objectives of connector design is to prevent film formation or disrupt existing films on mating of the connector. In addition, effective film management is a major criterion for selecting a contact finish because film formation is a source of connector degradation as will be discussed.

The Contact Finish - There are two reasons to apply a contact finish:

- . to protect the contact spring from corrosion and
- . to simplify film management.

The two major classes of contact finishes are:

- . noble metal (gold, palladium and alloys of these metals) and
- . non noble (primarily tin or tin/lead).

Both classes provide corrosion protection for the base metal springs. They differ, however, in the requirements for film management. Noble finishes minimize film formation, while for tin finishes the surface oxides are easily disrupted. Film management for noble metals requires preserving the nobility of the finish from external sources of degradation. For tin finishes mechanical displacement of the tin oxide is required and mechanical stability of the interface must be maintained to minimize the potential for reoxidation. Additional discussion of these concepts will be provided in a later section.

The Contact Spring

The contact spring provides both electrical and mechanical functions. Electrical requirements are minimal, basically the spring must be conductive. Mechanically, the spring provides the contact normal force which develops the separable interface and maintains interface stability over the application life of the connector. The contact spring must also provide a mechanism for the permanent connections of the connector to the subunits of which it is a part as mentioned previously.

The Connector Housing

The connector housing also performs electrical and mechanical functions. In this case however, the electrical function is insulative. The connector housing insulates the contacts in the connector from one another. Mechanically the housing locates the contact springs, to facilitate mounting and mating of the connector, and supports the springs mechanically. An additional function of the housing is to protect the contacts from the operating environment and from mechanical abuse.

Connector Resistance

To complete this brief overview of connector structure consider the sources of resistance in a connector.

As indicated in Figure 3, the connector resistance consists of:

- permanent connection resistances,
- the bulk resistances of the contact springs and
- the resistance introduced by the separable interface.

In a typical connector, the magnitudes of resistance for each of these contributions is of the order of:

- tens to hundreds of microohms for the permanent connections,
- a few to a few tens of milliohms for the spring bulk resistance and
- a milliohm or so for the separable interface contribution.

Note that the connection resistances are small compared to bulk contributions of the contact spring. The big difference, however, is that the connection resistances are variable. Degradation of connector resistance occurs at the separable or permanent interfaces due to loss in contact area by several mechanisms including corrosion, wear and loss in contact force.

Consider these degradation mechanisms in more detail.

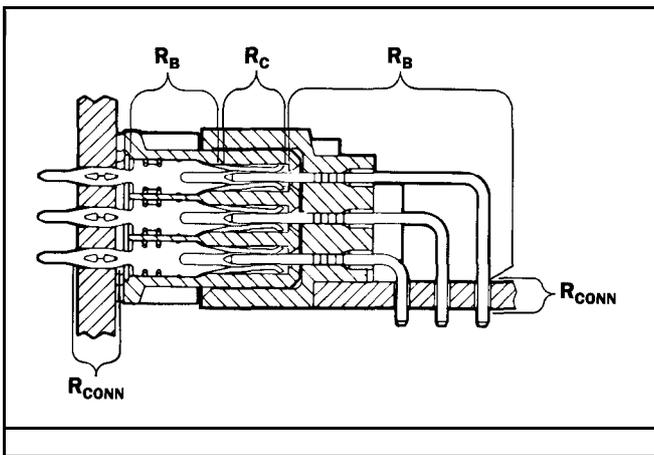


Figure 3. Schematic illustration of the components of connector resistance. Contributions from the permanent connection(s), spring bulk resistance and the contact resistance of the separable interface are indicated.

Connector Degradation Mechanisms

In this section, connector degradation mechanisms will be discussed in the context of connector materials and design.

Three degradation mechanisms will be considered:

- Corrosion
- Wear
- Loss of contact normal force.

Discussion of corrosion and wear involves contact finish properties, while loss in normal force depends on contact spring material selection and mechanical design.

Corrosion

Corrosion relates primarily to the contact interface and the contact finish. Corrosion increases contact resistance by two mechanisms:

- a series contribution due to films at the interface and
- a reduction in contact area due to penetration of corrosion products into the interface.

The series contribution occurs when mechanical disruption of the films is incomplete. The contact interface in such cases consists of parallel resistances of metallic and film covered regions. Loss in contact area can result from incomplete film disruption or from corrosion products encroaching into the contact area as the interface moves due to mechanical or thermal driving forces.

Three general types of corrosion must be considered:

- surface corrosion,
- corrosion migration and
- pore corrosion.

Surface Corrosion - Surface corrosion refers to formation of corrosion films over the entire surface of the contact such as tin oxide and oxides and chlorides on palladium and palladium alloys. Surface corrosion can cause contact resistance increases through either of the mechanisms previously mentioned depending on how effectively the films are disrupted on mating and the mechanical stability of the contact interface.

Corrosion Migration - Corrosion migration refers to the movement of corrosion products from sites away from the contact interface into the contact area. Such sites include contact edges and defects in the contact finish. It is important to note that corrosion migration is very sensitive to the operating environment. Abbott (3) has shown that corrosion migration is of concern predominately in environments in which sulfur and chlorine are present.

Pore Corrosion - When the defect site from which corrosion migration occurs is a pore, a small discontinuity in the contact finish, the corrosion mechanism is referred to as pore corrosion. Pores themselves do not affect contact resistance. Only if the pores become corrosion sites is contact resistance degraded.

Corrosion the Finish

The effects of operating environments on contact resistance

depend on the contact finish. For precious metal finishes all of the mechanisms described above are active. For tin contact finishes, surface corrosion is the dominant mechanism, but with a specific kinetics, fretting corrosion. The finishes will be considered separately.

Precious Metal Finishes - Figures 4 through 10, after Mroczkowski (4), summarize the effects of corrosion, due to mixed flowing gas exposures, on contact resistance for precious metal plated coupons. The test environment used was intended to simulate exposure to an industrial environment of moderate severity (3). These data are NOT from connectors, but from coupons exposed to the environment and then probed with a hemispherical soft gold probe. Three precious metal platings were evaluated, gold, palladium and an 80 palladium - 20 nickel alloy. The precious metal plating thickness was nominally 0.75 microns for all finishes. All coupons had a nickel underplate of nominal thickness 2.5 microns.

Figure 4 shows the effects of the mixed flowing gas environment on the gold/nickel sample, the curves shown are the average of nine individual probe readings. The test environment results in significant degradation in contact resistance in 48 hours despite the fact that gold is inert to the gases in the test environment. The effects of the corrosion processes on contact resistance can be understood from consideration of Figures 5 through 10.

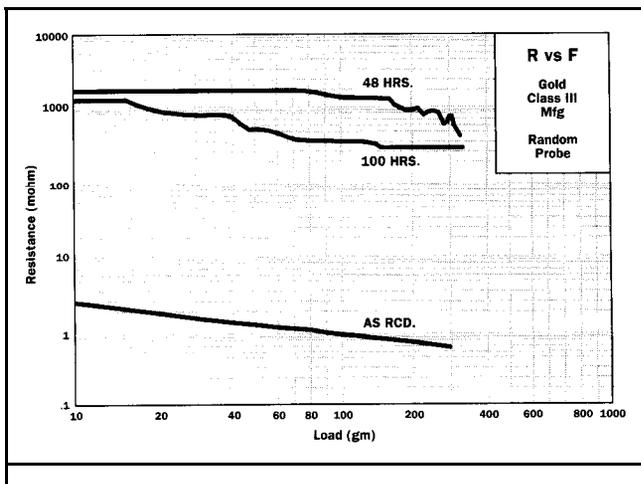


Figure 4. Plot of Contact Resistance versus Normal Force for gold/nickel coupons exposed to a test atmosphere intended to simulate an industrial environment. Data for 0, 48 and 100 hour exposures are presented. These data were obtained by random probing of the coupon with a hemispherical soft gold probe.

Figure 5 is a photomicrograph of the gold surface after exposure to the test environment. The migration of pore corrosion products is evident as haloes around the pore sites, the pore density on these coupons is higher than that typical of connector finishes. Figure 6 shows the individual probe point contact resistance data from the 100 hour exposure in Figure 4. Note that 3 of the 9 individual curves show little effect of the corrosive environment on the gold surface. These data support the claim that the gold is inert, contact resistance degradation occurs due to corrosion migration, in this case from pore sites.

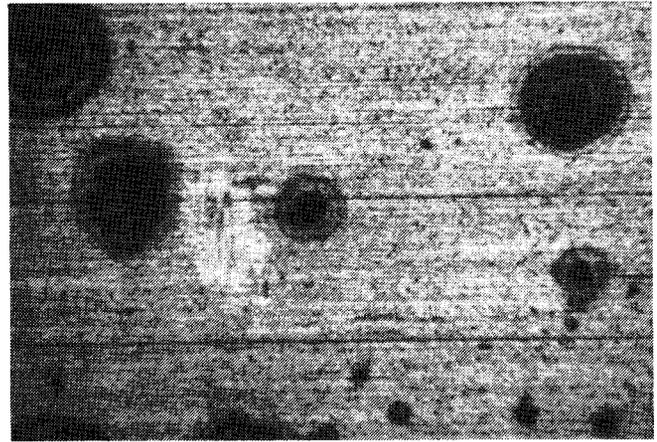


Figure 5. Photomicrograph (100X) of pore corrosion haloes on the coupons producing the data in Figure 4. One of the probe sites is visible in the photomicrograph.

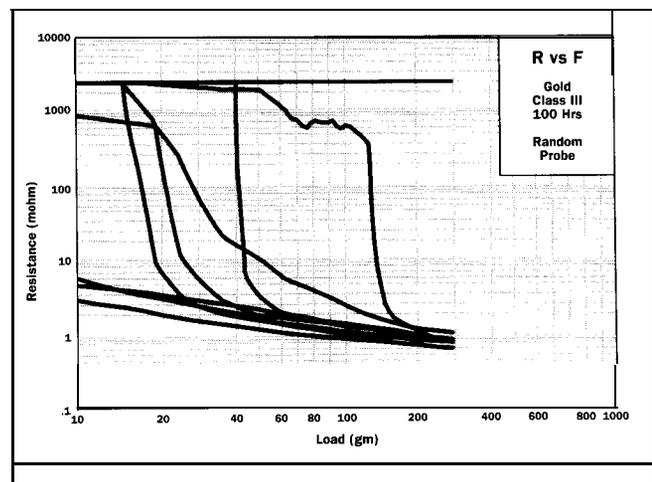


Figure 6. Plot of Contact Resistance versus Normal Force of the individual readings of the 100 hour exposure in Figure 4. These data indicate the effects of pore corrosion on contact resistance.

Figures 7 and 8 show data for palladium/nickel coupons. These data are similar to that for gold. Figure 9, contains data obtained by probing the sample selectively to avoid, as much as possible, the effects of pore corrosion. Figure 9a, for gold exposed for 100 hours, indicates the relative inertness of the gold, the contact resistance distribution is similar to that of the as received coupons. The palladium data, Figure 9b, shows the effects of general surface corrosion of palladium after 100 hours exposure. The average contact resistance has increased and the distribution has broadened. Palladium is not as inert as gold. For this reason, among

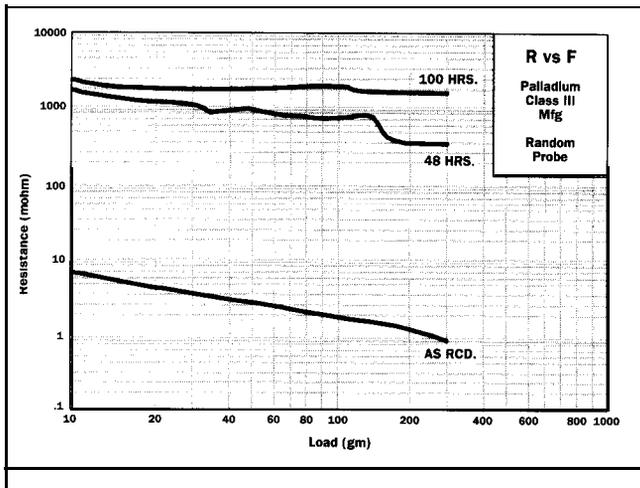


Figure 7. Plot of Contact Resistance versus Normal Force for palladium/nickel coupons exposed to a test atmosphere intended to simulate an industrial environment. Data for 0, 48 and 100 hour exposures are presented. These data were obtained by random probing of the coupon with a hemispherical soft gold probe and are the analog to Figure 4.

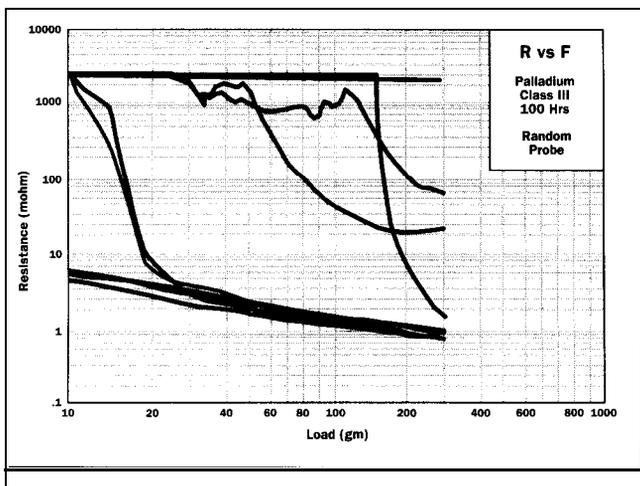


Figure 8. Plot of Contact Resistance versus Normal Force of the individual readings of the 100 hour exposure in Figure 7. These data indicate the effects of pore corrosion on contact resistance.

others, palladium, and palladium alloy, contact finishes generally include a gold topcoat, a tenth micron or so, as a protective surface.

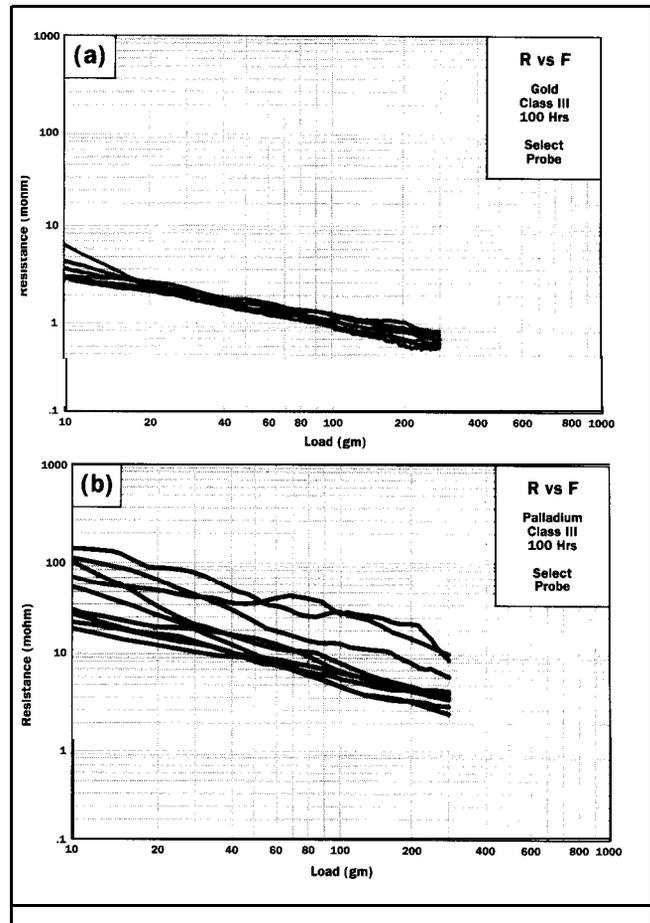


Figure 9. Plot of Contact Resistance versus Normal Force for gold/nickel, Figure 9a, and palladium/nickel, Figure 9b, coupons exposed for 100 hours to a test atmosphere intended to simulate an industrial environment. These data were obtained by selective probing to avoid the effects of pore corrosion haloes, shown in Figure 5, on contact resistance. The data indicate the different corrosion susceptibility of the gold and palladium in the test environment.

Figure 10 contains the same type of data for the precious metal alloy 80 Palladium - 20 Nickel. In this case the contact resistance degradation curves are similar regardless of whether the probing is random or selective. This is due to the reaction of the nickel in the alloy with the test environment resulting in general surface corrosion. Alloying of precious metals can impact environmental performance when alloying constituents include base metals.

In summary, contact resistance degradation of precious metal finishes arises from a combination of surface corrosion and corrosion migration. For gold finishes, corrosion migration is dominant while for palladium and palladium alloy finishes surface corrosion is also active.

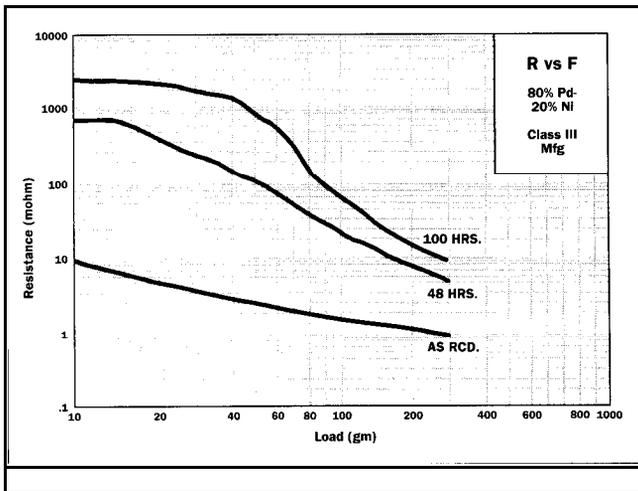


Figure 10. Plot of Contact Resistance versus Normal Force for palladium-nickel (80-20)/nickel coupons exposed to a test atmosphere intended to simulate an industrial environment. Data for 0, 48 and 100 hour exposures are presented. These data were obtained by random probing of the coupon.

Corrosion and the Connector Housing - Before leaving the subject of corrosion in precious metal finishes, comments on the importance of the connector housing in protecting the contacts from the environment are in order. The data discussed in the previous section referred to coupon data and indicate the effect of the environment on the materials of the contact system. Corrosion mechanisms affecting contact materials are active in typical connector operating environments. Connector degradation through corrosion, however, is not common. Figure 11 (4) shows contact resistance performance for gold over nickel (1 micron gold over 2.5 microns nickel) plated connectors exposed, unmated and mated, to the same environment as the coupons discussed previously. Note that the unmated exposures result in significant contact resistance degradation, illustrating the effect of the environment on the contact materials. Mated exposures, however, show little effect on contact resistance. This difference in performance is attributed to the shielding effect of the housing in restricting access of the environment to the contact interface.

Tin Contact Finishes - As mentioned previously, tin finishes are subject to a different corrosion degradation mechanism, fretting corrosion. Tin is resistant to surface corrosion in that a protective oxide film forms on the tin surface which limits further corrosion of the tin. This oxide film does not affect contact resistance since it is easily disrupted on mating of the connector. The disruption of tin oxide is schematically illustrated in Figure 12a (2). The tin oxide, being thin, hard and brittle, fractures under the application of contact normal force. The load is transferred to the tin which, being soft and ductile, flows to enlarge the cracks in the oxide and extrudes through the cracks to establish the desired metallic interface. This mechanism explains the utility of tin finishes despite the presence of a surface oxide.

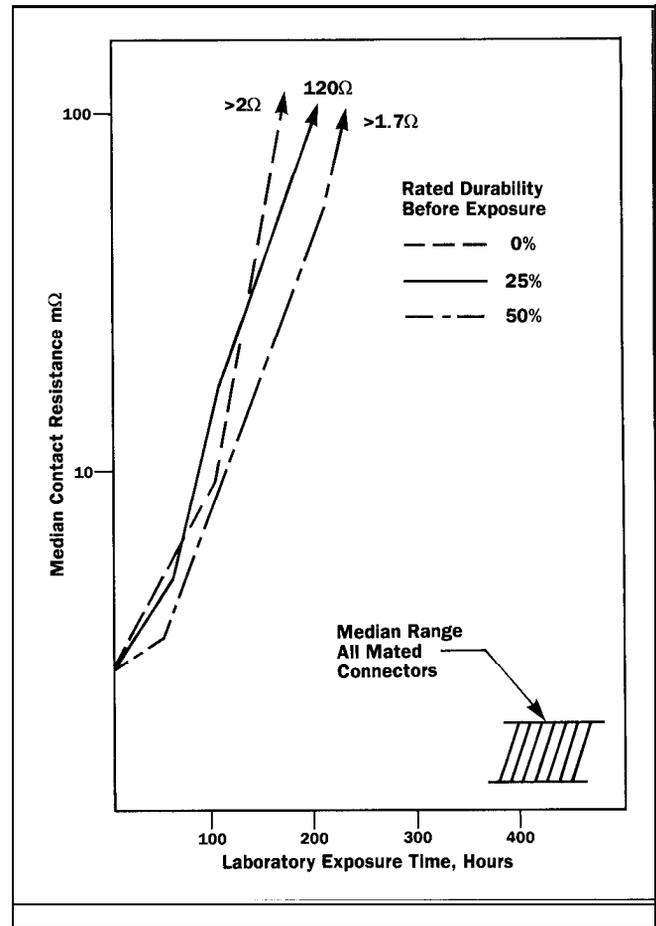


Figure 11. Contact Resistance versus Exposure time for gold/nickel plated connectors exposed to a test atmosphere intended to simulate an industrial environment. Data for unmated and mated exposures are shown. Some of the connectors were durability cycled as indicated in the legend on the plot.

Unfortunately the oxide forming tendencies of tin remain active, and if the contact interface moves, as shown in Figures 12b through 12d, contact resistance increases steadily. This degradation mechanism is known as “fretting corrosion”. “Fretting” refers to the small motions, hundredths to tenths of a millimeter, which occur randomly due to mechanical disturbances or thermal expansion mismatches. “Corrosion” refers to the reoxidation of the tin surface as it is exposed during the fretting. Fretting corrosion can result in rapid contact resistance degradation and is the dominant degradation mechanism for tin contact finishes.

Summary

Corrosion is an important degradation mechanism in connectors. The two basic classes of contact finishes, precious metal and tin differ in the kinetics of corrosion. Gold finishes degrade through ingress of corrosion products from various sources on the contact spring to the contact area.

For corrosion migration to be active, however, the operating environment must contain sulfur and chlorine. Palladium and palladium alloys are more sensitive to general corrosion than is gold.

Tin finishes degrade through fretting corrosion, which requires oxygen and motion and, therefore, can occur in any operating environment. The key factor in environmental severity for tin is the driving force for contact motion. Differential thermal expansion is the most common driver for fretting.

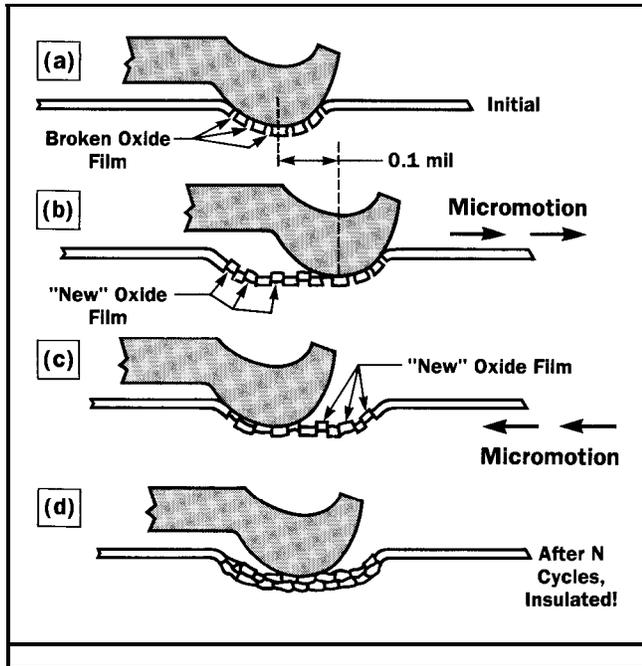


Figure 12. Schematic illustration of the mechanism of contact formation in tin finished connectors, Figure 12a. Figures 12b through 12d illustrate the mechanism of fretting corrosion.

Wear

The second degradation mechanism to be discussed is wear. It is important to note that the significance of wear is that it increases corrosion susceptibility by removing the protection provided by the contact finish.

Wear as a degradation mechanism in connectors takes its importance from the separability requirement on the connector. Cycle life requirements on connectors range from a few cycles to several hundred in typical applications with a few thousand being required in some special cases. Wear is a result of the connector mating and is dependent on the design and materials of manufacture of the connector and the required number of mating cycles the connector must support.

This paper will provide only a brief overview of connector wear. A simple equation, due to Rabinowitz (6), to predict wear is

$$V = kLx/H \quad (4)$$

where V is the wear volume, the volume of material removed, k a wear coefficient, L the load, x the wear distance and H the hardness of the surfaces in contact.

With respect to connector design the parameters in this equation translate to the following:

- L , the contact normal force
- H , the "finish hardness"
- x , the engagement length of the connector
- k , a "wear coefficient" which includes finish characteristics and the state of lubrication of the mating surfaces
- V , wear volume. The distribution of the wear volume is dependent on the geometries of the mating surfaces.

The role of normal force is straightforward, wear increases with normal force. This is one reason for minimizing normal force as will be discussed in a later section.

The finish hardness is more complex, especially in precious metal finished connectors. The effective hardness depends on both the precious metal hardness/thickness and that of the nickel underplate. The nickel underplate can significantly enhance connector durability as discussed by Antler and Drozdowicz (7).

The engagement length is also straightforward, although it is important to consider localization of the wear such as occurs in a receptacle to post connector, the wear on the receptacle is localized while that on the post is distributed.

The "wear coefficient" is complex in that it includes the surface roughness and the state of lubrication, both of which are variable. Surface roughness may change significantly during the wear process. The state of lubrication varies from atmospheric "contamination" to the application of special contact lubricants. Lubrication is possibly the most important means of improving durability of connectors.

A discussion of wear mechanisms and kinetics is beyond the scope of this paper. For detailed discussion of connector wear and lubrication see the review article by Antler (8).

Summary

Noble metal finishes provide much higher durability life than tin finishes. This is due to two main factors, higher hardness for the precious metals, and a lower normal force requirement. Normal forces for tin connectors are typically higher than for precious metal to provide the mechanical stability necessary to minimize tendencies towards fretting corrosion.

Loss in normal force

Loss in contact normal force is the final degradation mechanism to be discussed. But first, it is important to provide a basic understanding of the function of normal force in a connector.

Contact Normal Force

Normal force is important in two distinct functions, establishing the original contact interface and maintaining its stability over the application lifetime of the connector. The normal force required to establish the contact interface are relatively small. Figure 13 (9) shows a plot of contact resistance versus normal force for gold contact finishes. Note that a contact resistance of the order of 3 milliohms can be achieved with normal forces in the range of 25 to 30 grams. The majority of the normal force, typically of the order of 100 grams, is to ensure mechanical stability of the contact interface. Insufficient normal force allows for disturbance of the contact interface which renders it susceptible to the ingress of corrosion products and resultant increases in contact resistance.

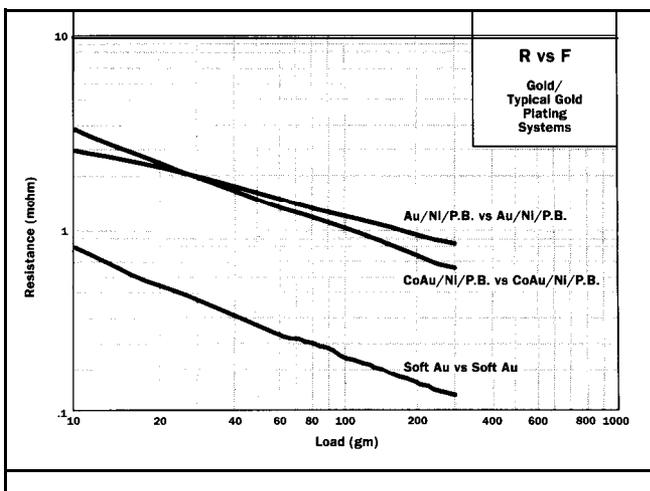


Figure 13. Contact Resistance versus Normal Force for gold/nickel and wrought gold contact interfaces.

In general, high normal force is undesirable since it increases mating forces, stresses on the contact springs/housings and wear (9). For these reasons establishing a minimum normal force requirement is an important design consideration. If normal force is to be minimized, however, ensuring the stability of normal force becomes important, which is why loss of normal force becomes an important degradation mechanism.

Contact normal force is generated by deflection of the contact spring as schematically illustrated in Figure 14. The important material and dimensional parameters affecting normal force are illustrated in the following equations.

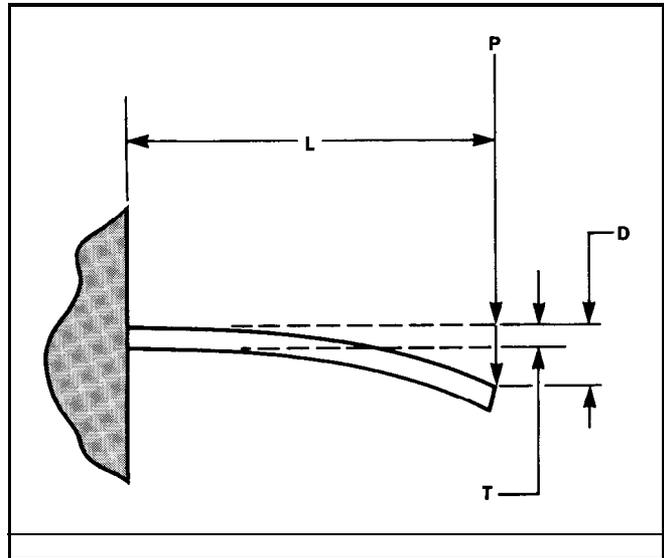


Figure 14. Schematic illustration of a cantilever beam and equations for calculating the normal force generated by deflection of the beam.

For a cantilever beam the force deflection equation takes the form

$$F = (D/4) E W(L/T)^3 \quad (1)$$

where F is the force resulting from a beam deflection D , E is the Young's modulus of the spring material, and W , L and T represent the width, length and thickness of the beam respectively. Many contact spring configurations fit or approximate this cantilever geometry.

A second equation relates the stress in the beam to its deflection.

$$S = 3D/2 E T^2/L \quad (2)$$

where S is the stress and the other variables are the same as in Equation (1).

Combining Equations (1) and (2) we obtain:

$$F = 1/6 S T^2 (W/L) \quad (3)$$

This equation shows that the normal force, F is determined by the stress induced in the spring due to the deflection.

Mechanisms for Loss of Normal Force

Equations 1 and 3 provide a means for understanding the two major mechanisms leading to loss of normal force, permanent set and stress relaxation.

Permanent Set - Permanent set refers to a permanent deflection of the contact beam due to overstressing the beam. Equation 1 illustrates the importance of permanent set as a mechanism for degradation of normal force. Normal force varies directly with deflection. A set in the spring will decrease the deflection and, therefore, the normal force.

Permanent set is a result of overstressing the contact spring. The overstress may be a result of improper design, the designed in beam deflection results in plastic deformation of the spring, or mating abuse, improper mating angle results in plastic deformation. In either case, normal force will be reduced by the reduction in beam deflection on subsequent matings. Proper materials selection and contact design can minimize or eliminate plastic deformation under proper application conditions. Abusive mating can be moderated by design features in the contact spring and connector housing, but proper application instructions and trained users are critical to minimizing abuse.

Stress Relaxation - Equation 3 illustrates the effect of stress relaxation on loss in normal force. Normal force is directly proportional to the stress in the beam. Stress relaxation is defined as a time/temperature dependent loss in stress under constant deflection. In other words, the stress in a deflected contact spring will decrease with time/temperature resulting in a loss in normal force. The effect of stress relaxation on connector performance is controlled by materials selection and consideration of application requirements, in particular operating temperature. Stress relaxation is a straightforward process and easily predicted as discussed by Bersett (10) and Horn (11). Selection of the contact spring material on the basis of the expected time/temperature profile of the connector application is sufficient to eliminate stress relaxation as a degradation mechanism.

Summary

Loss of normal force is a degradation mechanism in the sense that it reduces the mechanical stability of the contact interface making the connector more susceptible to corrosion. Loss of normal force through plastic deformation should be addressed in the design of the connector to ensure that spring deflections are not excessive and to minimize susceptibility to abuse, especially on mating. Stress relaxation is addressed through material selection to ensure that the spring has sufficient stress relaxation resistance for the operating environment. Operating temperature is the major factor in stress relaxation.

Degradation Mechanisms and Connector Design/Materials

It may be useful to restate some of the key issues of connector degradation in terms explicit to connector design/materials selection.

The Contact Finish

The contact interface, and, therefore, the contact finish are the key elements in connector degradation since all increases in contact resistance result from loss of contact area in some manner. The contact finish plays its primary role in influencing the corrosion behavior of the contact interface.

For precious metal finishes, gold - and to a lesser degree palladium and its alloys - is inert in typical connector operating environments. Connector design is directed

towards preventing corrosion from elsewhere in the connector from reaching the contact interface. Pore corrosion and corrosion from exposed base metal at stamped edges are of particular concern. Corrosion of precious metal finished connectors has been observed. Its effects depend on the operating environment, especially with respect to sulfur and chlorine. Shielding by the housing moderates the potential for corrosion.

For tin finishes, the major degradation mechanism is fretting corrosion which can occur in any operating environment. The major factor in fretting corrosion is the driving force for fretting motions. Differential thermal expansion is the most common driver. Connector design to minimize fretting susceptibility centers around high normal forces to provide sufficient friction force at the contact interface to prevent motion from occurring. Contact lubricants are also available to reduce oxidation susceptibility.

The Contact Spring

From a connector degradation viewpoint, the major spring material selection criterion is stress relaxation resistance. Loss of normal force through plastic deformation is predominantly a design exercise to ensure that spring stresses are not excessive. The variation in yield strength for the commonly use copper alloys is a secondary factor in this regard. Stress relaxation resistance, however, does vary significantly across the copper alloy range. Beryllium copper is the most commonly used alloy when stress relaxation is a major concern. Brasses should be avoided and phosphor bronzes are suitable for most applications.

The Connector Housing

The connector housing has received little attention in this discussion. This is primarily due to the emphasis on contact resistance degradation. Connector housing design, to shield the contact interface from the environment is the major contribution of the housing to connector reliability from a corrosion viewpoint.

A few comments on the connector housing in a context of other reliability issues is in order. The operating temperature, in use and in assembly, is a major factor in housing material selection. Surface mounting requirement and high temperature applications may dictate material selection. Chemical stability, primarily for assembly/cleaning operations may also be important. The range of materials available and suitable for connector housings is large and growing. Frequently some major characteristic, such as temperature capability or mold flow will dictate the material selection process.

This concludes the discussion of reliability in terms of connector structure, design and materials. Attention now returns to connector function and applications.

CONNECTOR APPLICATIONS/FUNCTIONS

Connector applications and functions are two ways to describe how connectors are used. Connector applications will be described in terms of the subsystems which are

being connected, a Levels of Packaging approach, following Granitz (12). Functionally connectors will be considered in terms of signal or power distribution. Consider applications first.

Connector Applications: Levels of Packaging

It is important to note that the Level of Packaging is defined by the points in the system which are being connected, not the connector itself. In fact, many connector types are used in more than one level of packaging. The six Levels of Packaging, and an associated connection/connector type, are:

1. Chip pad to package leads, eg. wire bonds
2. Component to circuit board, eg. DIP socket
3. Circuit board to circuit board, eg. card edge connector
4. Sub assembly to sub assembly, eg. ribbon cable assembly
5. Sub assembly to input/output, eg. D sub cable assembly
6. System to System eg. coax cable assembly.

Figure 15 schematically illustrates the six levels of packaging.

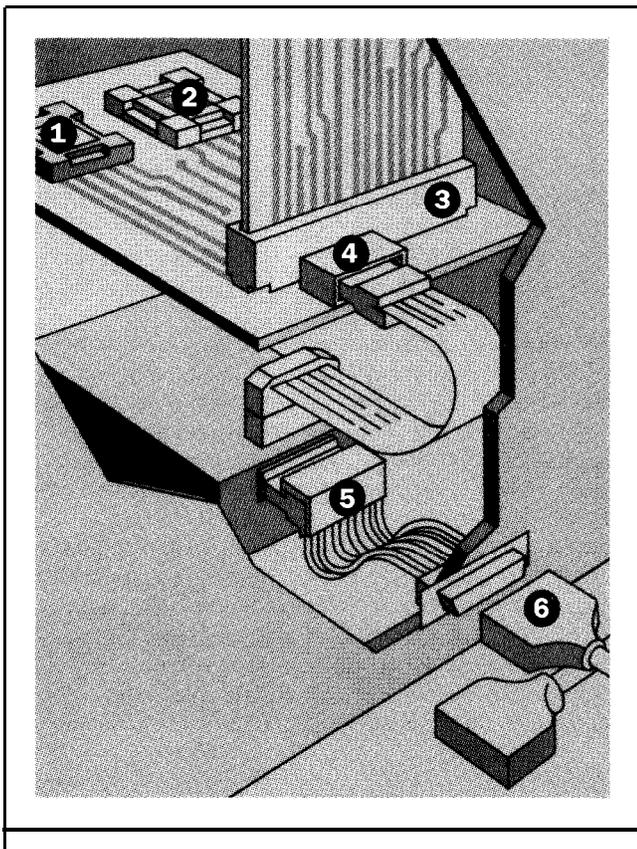


Figure 15. Schematic representation of an electronic system indicating the Levels of Packaging.

Some general comments on the individual levels are in order.

Level 1

The characteristics of Level 1 interconnections are:

- Most often made by highly automated methods.
- Are very specialized.
- Are usually not separable or repairable.
- Are enclosed by the device package.
- Must be extremely reliable.

Level 2

Interconnections at this level:

- Usually must withstand soldering environments.
- Are relatively small in size and usually do not need mounting hardware.
- Have contacts that are not individually repairable.
- Have low mating cycle requirements.
- Are serviced by trained personnel.

Level 3

Level 3 interconnections are the first level at which separable connectors appear. Advances in microelectronics technology have led to high performance, high I/O printed circuit boards which lead to the following requirements on level 3 connectors:

- High pin counts, over 1000, and high density connectors, 0.100 inch centerlines with 0.050 rapidly coming on.
- Mating forces become important due to high pinouts, with guiding hardware and keying also being needed.
- Mating cycle requirements are in the tens to hundreds.
- High speed capability to support board processing speeds, nanosecond switching and controlled impedance are becoming important.
- Repairability is required.
- Trained assembly personnel are used on the system level, but application by users is increasing so robustness becomes a consideration also.

Level 4

Level 4 interconnections are characterized by a large variety of connector types and often include cables. Requirements for level 4 connectors include:

- Special features to facilitate cable applications.
- Mating cycles in the hundreds.
- Robustness due to exposure to untrained users.
- Locking and latching features are common.
- Requirements for shielding are increasing.

Level

Level 5 interconnections are the connections to the outside world, I/O connectors. They share many of the requirements of level 4 with a few additional.

- Because one half of the connector is outside the system, standardization is important for intermatability.
- For the same reason, robustness, ease of use and cosmetics are important.
- Shielding, filtering and interference considerations become important.

Level

The variety of level 6 interconnections is also large and includes cabling. Many of the level 4 and 5 requirements remain important.

- Robustness increases in importance.
- Mating cycle requirements may be high, several hundred.
- Shielding and filtering may be more important due to longer exposed lengths.
- Standardization is a major consideration.

These comments are sufficient to provide a context for connector applications and indicate the variety of requirements connectors must meet. Attention now turns to connector function.

Connector Function: Signal and Power Distribution

Connector requirements for signal and power distribution are different in fundamental respects. In some cases, however, the same connector will be used for both applications. Such applications require a basic understanding of the difference between signal and power contact requirements.

Signal Requirements

Signal distribution requirements center around maintaining the integrity of the signal waveform. For high data rate systems this may involve controlled impedance connector designs and careful attention to signal to ground ratios. In general, however, this level of sophistication is not necessary and consideration of the connector resistance alone is sufficient.

The magnitude of the required connector resistance is strongly dependent on the devices in the circuitry the connector must interconnect. For many devices high connector resistance, hundreds of milliohms, can be tolerated. This "relaxation" of connector requirements does not simplify connector design. Contact resistances of this magnitude are inherently unstable due to the fact that they represent a very small contact interface area and are, therefore, very sensitive to degradation through corrosion or mechanical disturbances. The ability of a system to tolerate higher connector resistance, however, does impact on connector reliability as will be discussed in a later section.

Power Distribution Requirements

Resistance requirements for a contact or connector intended for power distribution are much more sensitive to resistance. This is a result of the Joule heating which accompanies current flow. Joule heating, which is proportional to the connector resistance, can result in increases in the connector operating temperature, a major factor in connector degradation, and create conditions for thermal runaway. In many cases the current rating of a contact is determined by a 30 degree Centigrade temperature rise, T -rise, criterion so minimizing resistance maximizes current rating. Both magnitude and stability of contact resistance are critical for power applications. In addition to T -rise, there are fundamental limits to allowable current through a contact based on interface melting considerations. This subject is beyond the scope of this paper, see Corman and Mroczkowski (13) for additional discussion.

Power distribution in connectors can be carried out in two different modes, dedicated power contacts and signal contacts in parallel. Design and circuit considerations differ in the two cases (13).

Summary

Connector requirements are dependent on the application in which the connector is used. Two approaches, Levels of Packaging and Signal/Power have been discussed. The level of packaging impacts connector design with respect to durability and resistance requirements as well as the necessity for accounting for the potential for abuse of the connector by the user. Signal/power considerations highlight the criteria for contact resistance, both magnitude and stability.

CONNECTOR RELIABILITY: FIELD AND LABORATORY

In the Introduction it was stated that connector reliability depends on the requirements the connector must meet and on the degradation mechanisms to which the connector is exposed. The previous discussion has provided a context for the following discussion of connector reliability in the field, and a proposal for methods to estimate connector reliability through laboratory testing.

A simplistic definition of reliability for a connector is:

The probability of maintaining a specified range of connector resistance under specified operating conditions, for which designed, for a specified time.

As discussed, the connector application determines the resistance requirements, and the operating conditions, which in turn determine the degradation mechanisms which may be active.

It is useful to consider degradation mechanisms in the context of whether they are intrinsic or extrinsic. Intrinsic mechanisms are related to the design and materials of

construction of the connector. Extrinsic mechanisms are those which are related to the application.

Examples of intrinsic degradation are corrosion, loss of normal force through stress relaxation, and Joule heating leading to temperature related degradation.

Examples of extrinsic degradation are contamination and fretting corrosion. Each of these conditions is dependent on the application of the connector, both in manufacturing and usage in the final system. Such degradation mechanisms can be qualitatively assessed, but, in general, are difficult, if not impossible, to quantify for use in a determination of connector reliability.

Examples of other degradation mechanisms, which are outside the scope of connector reliability, include using the connector outside its rated temperature range (both ambient and enclosure related), applying currents in excess of the product specification (in both single and distributed modes), and improper mating practices (mating at excessive angles, pulling on cables, etc.) leading to contact abuse. Such degradation is outside the scope of connector reliability in that the connector is being used outside the “specified operating conditions for which designed” section of the reliability definition and, therefore, is misuse of the connector.

Connector manufacturers have control over intrinsic degradation, but not over extrinsic factors. Extrinsic degradation can be controlled only by proper specification of product performance by connector manufacturers and proper use of the available information by the user. This joint responsibility ensures that the “under specific conditions for which designed” section of the definition is met. In this case, “user” is intended to include connector and electrical equipment manufacturers as well as the ultimate user of the equipment.

Two field studies on connector reliability will be reviewed in this context.

Field Reliability Studies

The first study was conducted by Grau (14) in the late 70s. It included nine connector types as used in telephone central offices. Four central office sites with different severities in environmental categories were studied. The sample size was very large, over 50,000 contact pairs were measured or examined.

Some of the key conclusions from the study include:

- . No circuit failures due to connectors were experienced during the study.
- . Resistance values higher than expected were found, 100 ohms was the “max” recorded.
- . Factory contamination was a major contributor to the high resistance values.
- . No evidence of pore corrosion was found.

These conclusions are interesting in that they indicate that high values of connector resistance do not necessarily lead to circuit failures, at least in the telecommunications equipment studied. Extrinsic degradation, factory contamination, was a major contributor to high resistance. Pore corrosion, felt by many to be a major source of degradation, was not found. This supports the previous comment that the environment plays a key role in whether corrosion migration will occur.

A second study, after Yager and Nixon (15), covered a broader range of applications, test instrumentation and computer equipment, and environments. In this study the “samples” consisted of printed wiring board assemblies which had been returned for repair. The study was one of failure analysis rather than reliability as such. Since, in general, the source of the failure was not identified, the authors refer to “defects” rather than “degradation mechanisms”. The terms are related but not identical. The sample included 90 assemblies incorporating 12 different connector types.

Some of the conclusions from this study include:

- An organic film was the predominant defect on the PWB fingers.
- A variety of defects were identified, both intrinsic and extrinsic, representing the variety of application environments sampled.
- Intrinsic defects observed included pore corrosion, edge corrosion and corrosion creep.
- Extrinsic defects observed included an organic film, dust and debris and scratches.
- The study also noted the effect of shielding of the connector from the environment by the housing.

The authors categorized the defects in terms of the percentage of samples exhibiting the defect and the severity, on a scale of one to five, five being the most severe. The most common defect, observed on 97 percent of the samples with almost 50 percent at a severity level of 4, was an organic film, a contaminant. Corrosion effects were non uniform. Pore corrosion was commonly observed at low to moderate severity. Edge corrosion and corrosion creep were infrequent and at low severity. Once again, extrinsic defects were found to predominate.

While limited, the data from these two studies suggest that extrinsic degradation mechanism are more common than intrinsic. If true, this fact has significant implications for connector reliability, in particular for estimating connector reliability.

Avoiding extrinsic degradation is a joint task of connector manufacturer and user. Connectors can be designed to be resistant to contamination and abuse, but only attention to product instruction sheets on the use of connectors can minimize such degradation.

With respect to estimating connector reliability, a predominance of extrinsic degradation complicates the issue

considerably in that it is difficult to model or simulate such degradation mechanisms. The significance of this limitation will be more apparent after a laboratory approach to connector reliability is discussed.

Laboratory Estimation of Reliability

There are two approaches to estimating connector reliability through laboratory exposures, comparative and statistical. Each has advantages and limitations.

A comparative program would involve using a connector of known reliability as a reference through a series of laboratory exposures intended to simulate application conditions of interest. Comparative data, say contact resistance, for the reference and test connector after exposure could be used to assess the relative reliability of the test connector. The relevance of the data would be dependent on the confidence with which the reference connector reliability was determined and the confidence level that the laboratory exposures appropriately simulate application conditions of interest.

To determine connector reliability using a statistical approach we must address at least the following issues:

- The active degradation mechanisms must be identified and categorized with respect to their importance in the application of interest.
- Appropriate tests, acceleration factors and exposures must be known, defined, or determined, for these degradation mechanisms.
- Failure criteria appropriate to the application of interest must be established.
- The statistical approach to determining, or calculating, reliability values must be agreed upon.

The following comments on each of these issues will suffice for the purposes of this paper. For additional discussion see Mroczkowski and Maynard (16).

Degradation Mechanism

Degradation mechanisms have been discussed in previous sections. The subject here is categorizing them with respect to their importance. This is not necessarily a trivial task and depends on both the operating environment and the system operating requirements. As mentioned, connector design/materials determine the potential degradation mechanisms, and application conditions determine which mechanisms are active.

Test Factors.

There are two major issues here. The first is ensuring that the test exposure simulates the application conditions. A related, but even more complex issue is determining an acceleration factor. Since the definition of reliability includes performance for a specified time and acceleration factor for the test exposure is required. In simple terms, the objective is to be able to document that A days exposure to test B is equivalent to X years of operation in environment Y. There are few tests for which such an objective is met.

Failure Criteria:

What is the appropriate value of contact resistance to use in establishing contact reliability? There are two possibilities, the product specification value, which is somewhat generic, and an application related value.

Fundamentally, 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 with respect to ensuring that the specified contact resistance maximum will be maintained in its intended RANGE OF APPLICATIONS. In this respect, the product specification value includes a "safety factor" to account for the range of possible applications for the connector.

In a particular application, on the other hand, a user will have established a value of contact resistance at which the system of interest will cease to function. The value may be 100 milliohms, or more, in a signal application or 0.5 milliohm, or less, for a power contact. The "failure" criterion for contact resistance should be based on this application specific value and not the product specification contact resistance. The desired requirements on confidence limit and reliability should then be applied with this resistance value as the upper limit of acceptability.

Statistical Methods:

Many of the issues concerning statistical treatment of the data obtained from individual contacts are straightforward. Relating contact data to connector performance does, however, raise some issues. For example, the contact data are obtained on contacts in a particular connector. The data, therefore, are influenced by the connector. How this influence is to be quantified or included in the connector reliability calculation merits attention.

Summary

The purpose of this discussion was to present some of the issues and considerations which are pertinent to determining and calculating connector reliability via a laboratory testing program. A reliability evaluation program consists of the following steps:

1. Determine an application specific contact resistance acceptance criterion. A criterion will also be required for any other failure mode which is to be included in the evaluation program.
2. Develop a test program to address the expected degradation mechanisms operative in the application. Ranking of failure modes may be considered in this process.
3. Derive acceleration factors, when possible, for the tests to be specified. When this cannot be done no reliability prediction can be made. In such cases only comparative performance capabilities can be provided.
4. Decide on the statistical treatment appropriate to the data generated in the evaluation program.
5. Calculate the component reliability.

It must be emphasized that both the connector manufacturer and the user should agree on the content, approaches and values to be specified in these steps individually, and in the evaluation program in general. In particular, mutual engineering judgements must be made to select appropriate "acceptance/failure" criteria and acceleration factors. A reliability evaluation program according to these procedures will allow estimation of the intrinsic reliability of a connector. It is important to note, however, that such a program does not, and cannot, address extrinsic degradation modes.

CONCLUSION

This paper has reviewed some of the interactions between connector materials/design and application environments and requirements as they impact connector reliability. Approaches to evaluating or estimating connector reliability have been discussed. Reliability estimation for intrinsic degradation mechanisms is feasible, within limits, but extrinsic degradation mechanisms cannot be accounted for in a laboratory environment.

To achieve the highest reliability in a connector, the intrinsic connector reliability, determined by connector design/materials selection, must be preserved by conscientious attention to connector specifications, to ensure operation of the connector within its designed area of application, and avoidance of extrinsic degradation processes such as contamination in assembly and application. Connectors can be designed to resist, but not totally eliminate susceptibility to, such degradation.

REFERENCES

1. Williamson, J.B.P., "The Microworld of the Contact Spot", Proc. 27th Ann. Holm Conference on Electric Contacts, 1981.
2. Mroczkowski, R.S., "Connector Contact Surfaces: Where the Action Is", Presented at Indicon, 1983.
3. Abbott, W.H., "The Corrosion of Porous Gold Platings in Field and Laboratory Environments", Proc. 13th International Conference on Electric Contact Phenomena, 1986.
4. Mroczkowski, R.S., "Corrosion and Electrical Contact Interfaces", Paper #328, NACE, Corrosion 85, 1985.
5. Mroczkowski, R.S., "Materials Considerations in Connector Design", Proc. 1st Electronic Materials and Processing Conf., American Society for Materials, 1988.
6. Rabinowitz, E., Friction and Wear of Materials, John Wiley and Sons, Inc., New York, 1965.
7. Antler, M., and Drozdowicz, M.H., "Wear of Gold Electrodeposits: Effect of Substrate and of Nickel Underplate", Proc. 9th International Conference on Electric Contact Phenomena, 1978.
8. Antler, M., "Wear of Contact Finishes: Mechanisms, Modelling, and Recent Studies of the Importance of Topography, Underplate and Lubricants", Proc. 11th **AM**. Connections and Interconnection Technology Symposium, 1978.
9. Whitley, J.H., and Mroczkowski, R.S., "Concerning Normal Force Requirements for Precious Metal Plated Contacts", Proc. 20th. **Ann.** Connections and Interconnection Technology Symposium, 1987.
10. Bersett, T.E., "Back to Basics: Properties of Copper Alloy Strip for Contacts and Terminals", Proc. 14th Am. Connections and Interconnection Technology Symposium, 1982.
11. Horn, K. W., and Zarlingo, S.P., "Understanding Stress Relaxation in copper Alloys", Proc 15th Ann. Connections and Interconnection Technology Symposium, 1983.
12. Granitz, R.G., "Levels of Packaging", Instruments and Control Systems, August, 1992.
13. Corman, N.E. and Mroczkowski, R.S., "Fundamentals of Power Contacts/Connectors", Proc. 23d Ann. Connections and Interconnection Technology Symposium, 1990.
14. Grau, T.G., "A Field Study of the Electrical Performance of Separable Connectors", Proc. 28th. Elec. Comp. Conf. 1978.
15. Yager, T.A., and Nixon, K., "A Field Study of Connector Reliability", IEEE Trans. CHMT, Vol. 7, No. 4, 1984.
16. Mroczkowski, R.S. and Maynard, J.M., "Estimating Connector Reliability", IEEE Trans. on Reliability, 1991.