AIRCRAFT CONNECTOR BONDING RESISTANCE TESTS AND MATERIALS ANALYSIS

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ABSTRACT

This paper discusses aircraft electrical connector bonding resistance tests conducted by the Electronics Failure Analysis Laboratory, Materials Integrity Branch, Air Force Research Laboratory (AFRL/MLSA) at Wright-Patterson Air Force Base, Dayton, Ohio. The electrical bonding resistance between a MIL-C-38999 cadmium and nickel-plated aluminum connector and mating surface has been found to increase over time. Indications suggest the growth of an oxide film on the faying surfaces being responsible for the increase in resistance. The initial evaluation attempted to determine the causes of this phenomenon by conducting connector bonding resistance tests and materials analyses using conventional cadmium-plated connectors. Time-based bonding resistance tests were then conducted using connectors plated with nickel-boron (Nybron®) and Ion Vapor Deposited (IVD) aluminum. Results were compared to the data obtained using conventional cadmium-plated connectors. At a later date, additional bonding resistance tests were conducted. Connectors made of bronze-aluminum alloy, stainless steel alloy, and titanium alloy were compared with conventional aluminum alloy connectors plated with cadmium and nickel. Tests were conducted both at room ambient conditions and in a salt fog environment. IVD aluminum-plated and titanium alloy connectors show promise for providing effective corrosion control with sufficiently low bonding resistance. Two workshops were conducted at Wright-Patterson Air Force Base to address connector bonding issues. Also presented are resistance measurements obtained from actual F-16 and F-15 aircraft in storage at Davis-Monthan Air Force Base. These measurements were made between various connectors and the associated airframe components to which they were mated.

INTRODUCTION

Electrical connectors in aircraft come in a wide variety of shapes, sizes, configurations, and materials. There may be between 500 and 2000 of them on a modern aircraft. Connectors are typically constructed of aluminum, titanium, stainless steel, or composite materials. Cadmium plating is usually applied to connectors used in Air Force weapon systems because it is an excellent corrosion inhibitor and has relatively high electrical conductivity. A chromate conversion coating is applied to achieve additional corrosion protection. The MIL-C-38999 connector is a common type found on aircraft and consists of a chromate conversion coating over cadmium plating which, in turn, is plated over nickel. The substrate is typically aluminum.

To insure uniform electrical shielding, the whole perimeter of the connector shell must be electrically connected to the component or aircraft frame member. The connection path must be between the connected members and not the fasteners, and must maintain a low resistance value over an extended amount of time. Military Specification MIL-C-38999 requires a maximum shell-to-shell bond resistance of 2.5 milliohms for the cadmium-plated (Class W) connector. However, an Air Force laboratory study concluded that bonded cadmium and aluminum surfaces allow the formation of an insulating oxide layer that causes electrical bond deterioration. Bond deterioration is not acceptable in an electronic grounding path because it can lead to poor electromagnetic interference/electromagnetic pulse (EMI/EMP) protection and, therefore, poses flight safety risks.

DISCUSSION

Connector Bonding Measurements on Stored Aircraft

As part of an aging aircraft study, it was desired to measure the connector bonding resistance of connectors and their points of attachment that have been in place on aircraft over a long period of time. This was done to determine the effect of long-term usage and storage on the electrical bonding of connectors to components and aircraft structure members. Access was gained to two F-15s and one F-16 aircraft in storage at the Aerospace Maintenance and Regeneration Center (AMARC) at Davis-Monthan Air Force Base. The aircraft selected were largely intact and had been prepared for long-term storage in the desert. Figure 1 shows one of the aircraft selected, an F-15, with its armament bay cover unlatched.

Figure 1 F-15 at Davis-Monthan AFB

Tail numbers indicated the F-15 aircraft were manufactured in 1973 and 1976 and the F-16 was manufactured in 1982. The F-15s were stationed in Hawaii, and the F-16 was based in Florida. Access was gained to several areas of the interior of the aircraft through landing gear wells, access panels, etc. A variety of bulkhead connectors were accessed, as well as some connected to avionics. Most of the connectors were of circular configuration (figure 2).

Figure 2 Connectors inside F-15 aircraft

Resistance measurements were made between the connector shells and the bulkheads or avionics using the four-point probe system connected to a Keithley digital multimeter. Nine connector/bulkhead assemblies were measured on one F-15 aircraft, and four from another F-15. It was attempted to take measurements from connectors in approximately the same location on both aircraft. Eight connector/bulkhead assemblies and three connector/avionics assemblies were measured on an F-16 aircraft. Resistance measurements varied widely, and ranged from 3.0 milliohms on a connector mated to a bulkhead located inside a wheel well of an F-15 aircraft to 8400 milliohms (8.4 ohms) on a connector attached to a bulkhead located inside an F-15 aircraft underneath the cockpit. There appeared to be no correlation between bonding resistance measurements and the age or location of the connector on the aircraft.

Cadmium-Plated Connector Bonding Resistance Tests and Materials Analysis

A project was initiated at AFRL/MLSA to determine the cause of increasing bonding resistance between cadmium-plated electrical connectors and their mating surfaces over time. Military qualified bulkhead-style connectors and chromated aluminum mating plates machined to accept them were obtained for this evaluation (Figure 3).

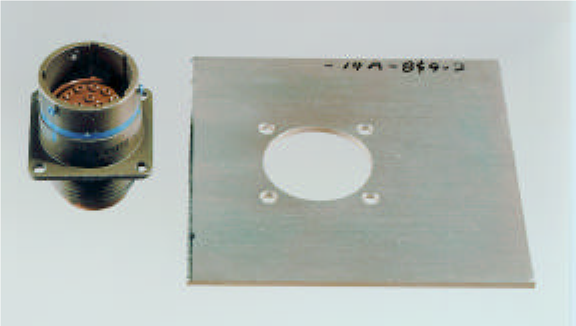

Figure 3 Test connector and mounting plate

Cross sections of the connector plating system were examined in the scanning electron microscope (SEM) using energy dispersive spectroscopy (EDS). This was done to determine the thickness and elemental composition of the platings and base metal for both the connectors and mounting plates. A polished cross-section of the connector flange was prepared to show the disposition and thickness of the various platings and base metal (figure 4).

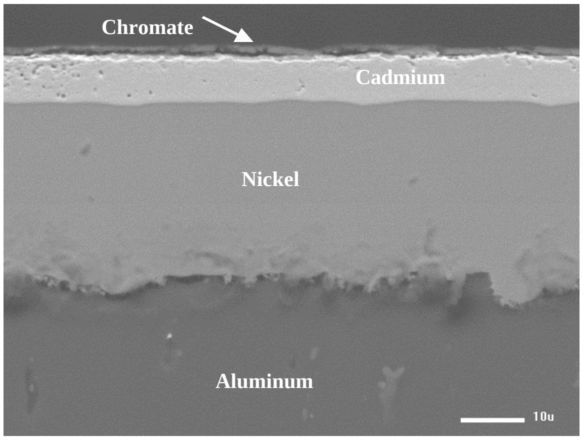

Figure 4 SEM micrograph of polished cross section of cadmium-plated aluminum showing plating layers and thicknesses

Secondary ion mass spectrometry (SIMS), a surface analysis technique, was used to determine the elemental composition of the surface of the connectors and mating plates. This is a much more sensitive analytical technique than EDS.

Three sets of connector and test panel assemblies were prepared. The connectors were bonded to the panels with screws and nuts electrically insulated from the rest of the assembly with Teflon tape and Nylon washers. Two assemblies were prepared with their screws tightened to 18 inch-ounces and the other assembly tightened to 96 inch-ounces of torque (field value). One assembly from each torque value was tested under room ambient conditions. The other assembly prepared at the lower torque value was tested under a pure oxygen atmosphere in a glass jar (figure 5).

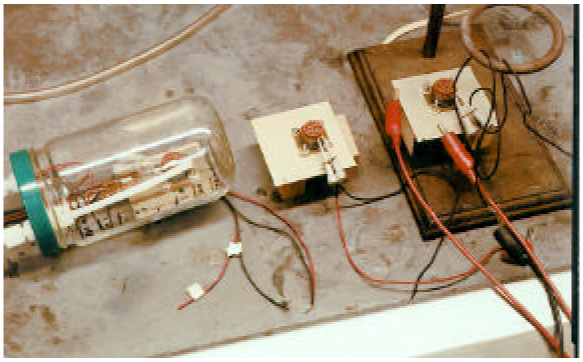

Figure 5 Three assemblies under test

The assemblies were bonded together for 55 days. Electrical resistance was measured daily using the four-point probe test method (figure 6).

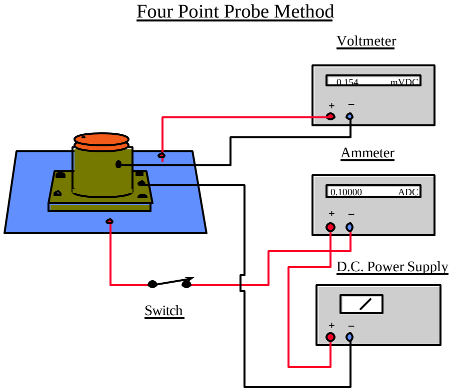

Figure 6 Four point probe resistance test

Resistance values climbed steadily over time on all three samples, exceeding 7 milliohms and 3.5 milliohms for the lower and higher torqued samples in air, respectively. The assembly in pure oxygen exceeded 250 milliohms at the end of the 55 day period. The addition of oxygen increased the rate and final bonding resistance value. Application of additional pressure and maintaining a constant pressure at the faying surfaces reduced the rate of bond resistance increase and final value.

Surface analysis of connector and aluminum plate surfaces before and after exposure tests revealed the presence of a large number of elements that readily form oxides. The examination of bonding surfaces also shows that only a small area is actually in intimate contact. This appears to be a function of the surface disparities and distortion that can occur by fastening the connector at the corners or edges. The increase in bonding resistance is most likely due to the small area physically making contact between the connector and aluminum plate surfaces and the presence of various oxides at these contact points. AFRL/MLSA report WL/MLS 97-069 discusses this project in detail.

Electrical bond deterioration is a driving force behind the decision to replace cadmium in connector manufacture. Another reason for replacing cadmium deals with the cadmium plating process. It uses hazardous chemicals and generates hazardous waste. The Environmental Protection Agency (EPA) has targeted 17 hazardous substances for reduction or elimination because of the quantities used, toxicity, persistence, and mobility. Cadmium is one of the chemicals on this list. The Air Force is currently eliminating the use of these EPA-17 chemicals to reduce exposure of workers to these materials, reduce maintenance costs, and to meet increasingly stringent pollution control requirements.

Nybronâ Plating

Other coating systems were examined that may be less susceptible to oxide formation while maintaining a stable and acceptable bond resistance level between faying surfaces. AFRL/MLSA suggested plating the connector surfaces with a nickel-boron material, trade-named “Nybron®.” AFRL/MLSA had found this plating to be effective in several structural applications and believed its low electrical resistance would also make it an effective connector plating. An investigation was initiated to compare changes in bonding resistance between Nybron®-plated and cadmium-plated connectors and their mating surfaces over time.

Several connectors were plated with a nickel-boron (0.42 percent boron), or Nybron®, plating. A fracture face cross section of a Nybron®-plated connector was examined in the SEM (figure 7).

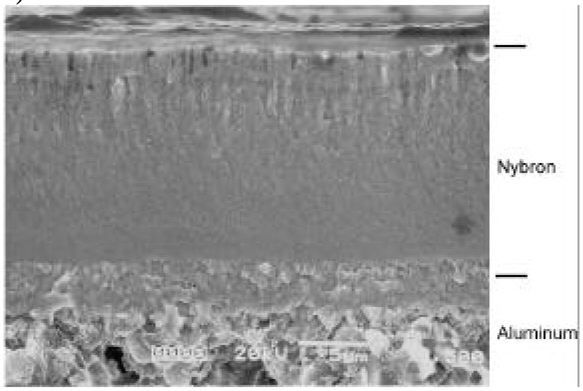

Figure 7 Nybron® plating fracture face

A Nybron®-plated connector and a conventional cadmium-plated connector were mated to chromate-coated aluminum plates. Care was taken to isolate the mounting screws from the assembly, as in the previous experiments. The screws were tightened to 96 inch-ounces torque.

Both assemblies were tested at room ambient conditions for 55 days. Bonding resistance of the assembly using the cadmium- plated connector increased steadily over time. In contrast, the bonding resistance of the Nybron®-plated connector assembly remained less than 0.5 milliohm. AFRL/MLSA report WL/MLS 97-095 discusses this project in detail. Nickel-boron plating may be considered when there is a long-term, low electrical bond resistance requirement. Environmental concerns must be taken into account, however, due to the presence of the element boron in the plating.

Ion Vapor Deposited Aluminum Plating

In view of this, AFRL/MLSA proposed the use of connectors plated with ion vapor deposited aluminum (AIVD). This material has distinct advantages over cadmium and nickel plating on aluminum alloy connectors. AIVD plating provides the necessary conductivity and corrosion protection, while at the same time being environmentally friendly. Both the AIVD plating and the application process are nonpolluting. The plating is pure aluminum and is applied electrically; no chemical baths are used.

It was decided to compare bonding resistance changes of cadmium-plated and Nybron®-plated connectors to AIVD-plated connectors and their mating surfaces over time. Several rectangular connectors and machined aluminum plates were AIVD-plated and conversion coated. A polished cross section of a connector so treated was examined in the SEM (figure 8).

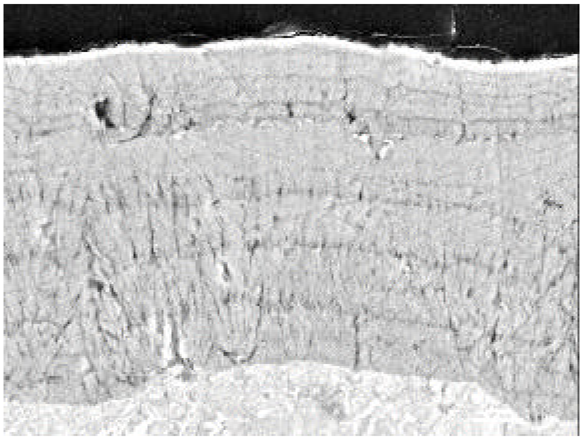

Figure 8 AIVD connector plating cross section

The one-to-two micron thick chromate conversion coating can be seen at the top of the cross section. Below this was a striated layer about 12 microns thick. It is assumed this is the area that had been compressed from the shot peening procedure. This seals the AIVD coating and is generally done by the plating specialist as a corrosion prevention measure. A cross-sectional fracture face of this connector was also prepared (figure 9). Note the top seven microns of plating has a somewhat different appearance than the remainder. Also note the columnar grain structure, which is typical of the AIVD plating process.

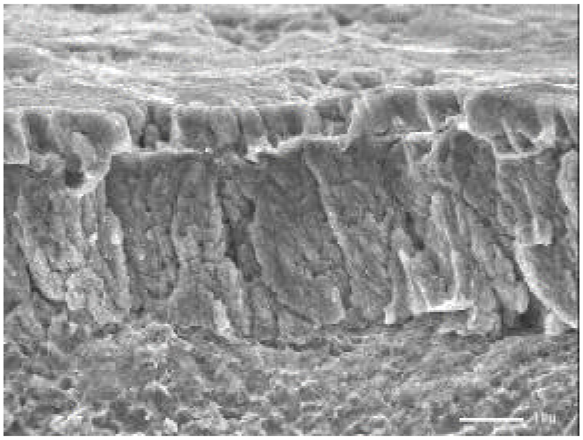

Figure 9 AIVD plating fracture face

Several sets of connector and test panel assemblies were prepared using the same bonding procedures as with the Nybron® plating testing. Two AIVD assemblies were tested at room ambient conditions for a period of 60 days. Another AIVD assembly was subjected to a salt fog exposure in a chamber adjusted according to ASTM B-117. The chamber utilized a continuous salt fog spray. The exposure time was 500 hours. Also included in the salt spray test were cadmium-plated and Nybron®-plated connector assemblies for comparison.

Resistance values for the AIVD assemblies tested in room ambient conditions were very low initially, and did not increase significantly during the test period. They remained well within the acceptable limit of 2.5 milliohms. Bonding resistance of the IVD aluminum and cadmium-plated samples in the salt fog rose gradually, exceeding 20 and 30 milliohms, respectively, by the end of the test. Bonding resistance of the Nybron®-plated connector assembly climbed very rapidly in the salt fog chamber, exceeding 140 milliohms after 500 hours. The amount of corrosion and deposits increased dramatically on the Nybron® test article. In contrast, the other two assemblies did not show nearly as much of an increase in corrosion products over time (figures 10, 11, and 12).

Figure 10 Nybron-plated assembly after salt fog exposure

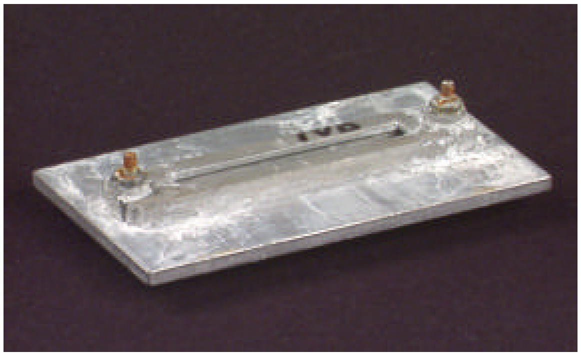

Figure 11 AIVD-plated connector assembly after salt fog exposure

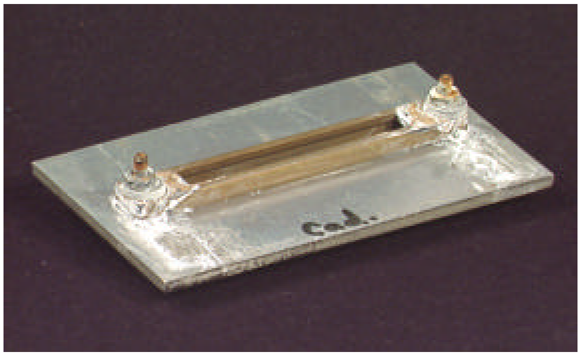

Figure 12 Cadmium-plated connector assembly after salt fog exposure

These experiments indicated the IVD aluminum-plated connectors show promise to provide effective corrosion control, as well as sufficiently low bonding resistance. They also indicated the need to develop methods for measuring and controlling conversion coating thickness and composition. This is because electrical bonding appears to be highly dependent on coating thickness, especially the conversion coating. Ion vapor deposited aluminum was evaluated in AFRL/MLSA report 98-75.

Bronze-Aluminum, Stainless Steel, and Titanium Alloys

An effort was made to find connector materials which would give good electrical characteristics without the need for platings. Flange-mounted circular connectors made of bronze-aluminum alloy and stainless steel were obtained from the Royal Air Force and J-Tech (Tustin, California), respectively. A jam-nut mounted titanium alloy circular connector was obtained from Allesandro Automatic (Los Angeles, California). Bonding resistance tests were conducted comparing these with conventional cadmium and nickel-plated aluminum alloy connectors. Tests were conducted at room ambient conditions and in a salt-fog environment. Resistance measurements during room ambient tests were acquired with an in-house devised data acquisition system that provided continuous 24-hour sampling and storage without the assistance of an operator (figure 13). This apparatus is shown schematically in figure 14.

Figure 13 Data acquisition and control interface

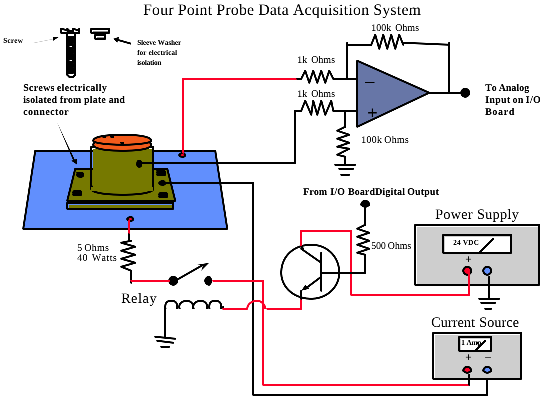

Figure 14 Schematic representation of test fixture

Room Ambient Tests

After cleaning, the connectors were mated to aluminum mounting plates which had been conversion coated with alodine chromate conversion coating. The flanged connectors were fastened with stainless steel screws and nuts to the mounting plate (figure 15). The titanium connector was fastened with a jam nut (Figure 16). To prevent the fasteners from contributing to the conductivity of the assemblies, the screws were wrapped with Teflon® tape and fiber washers were used under the nuts. A fiber washer was also used under the jam nut for the titanium connector. The outside surface of the connector was wrapped in Teflon® tape to isolate it from the mounting plate. The screws for the three flanged connectors were torqued to 96 inch-ounces with a torque wrench. The jam nut on the titanium connector was tightened to 30-36 inch-pounds. This is the recommended torque value for a size 9 connector shell. Initial resistance readings were made using a four-point probe measurement system (AEMC Micro-ohmmeter, Model 5600). This test was conducted at room ambient conditions. The temperature and humidity was respectively 72°F and the 38% RH. Resistance measurements during room ambient tests were acquired with an in-house data acquisition system that provided continuous 24-hour sampling and storage without the intervention of an operator (figure 13).

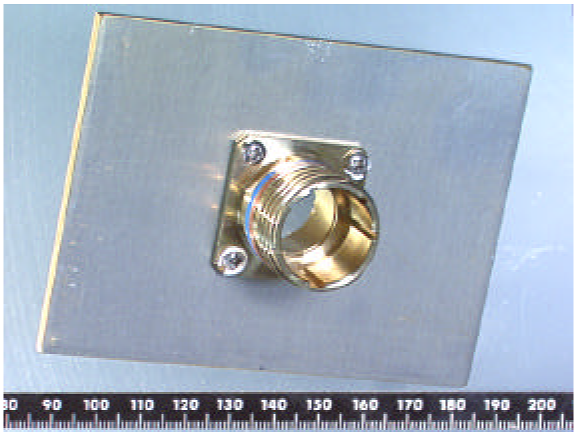

Figure 15 Bronze-aluminum connector mounted

Figure 16 Titanium alloy connector mounted

Initial measurements were made by sampling every hour for the first 24 hours. Subsequent measurements were taken every four hours thereafter. Previous experience has shown the bonding resistance changes rapidly in the first 24 hours. Data were acquired continuously for a period of two months. Of the four connector materials tested, only the cadmium-plated aluminum type exceeded the specified resistance limit of 2.5 milliohms during the test (Charts 1 and 2). It failed in the first 24 hours of testing. The remaining three connector assemblies increased slightly in the first 24 hours and then remained nearly constant throughout the test (Chart 3).

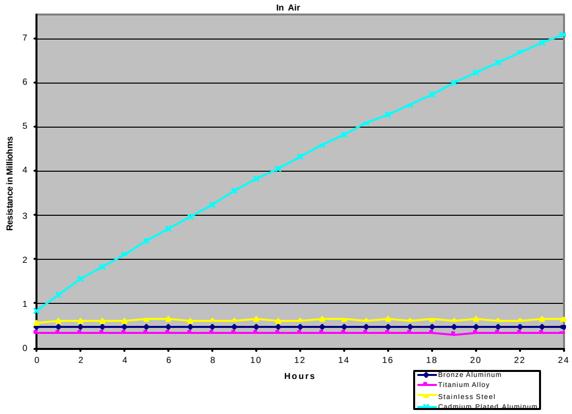

Chart 1 Bonding resistance at room ambient conditions of the four connector materials (first 24 hours)

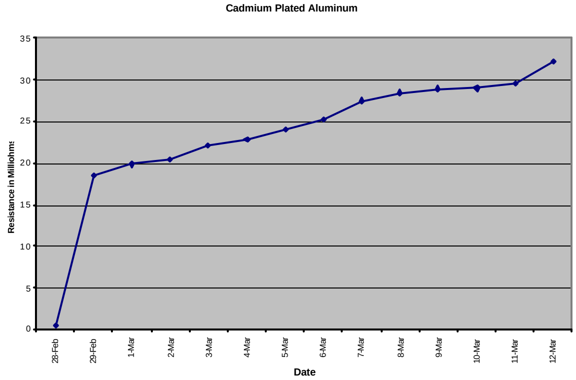

Chart 2 Bonding resistance of the cadmium-plated aluminum connector at room ambient conditions

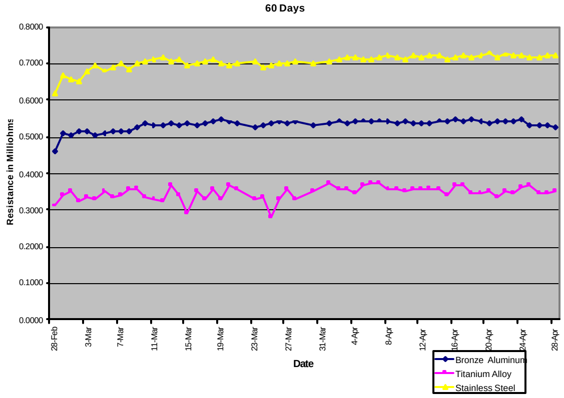

Chart 3 Bonding resistance of bronze-aluminum, titanium alloy, and stainless steel at room ambient conditions for 60 days

Salt Fog Tests

A second set of four connectors were tested in a salt fog environment, according to ASTM B-117-97, (Standard Practice for Operating Salt Spray (Fog) Apparatus). Upon removal from the salt fog environment, the connector assemblies were gently rinsed in warm water and a soft acid brush was used to clean the salt deposits from the surface. The assemblies were then allowed to dry at room ambient for one hour. The assemblies bonding resistance was measured with the data acquisition system described previously.

Initially, the connector assemblies were removed from the salt fog environment and tested every 24 hours for the first 4 days. Thereafter, the assemblies were removed from test every two days for measurements. This process was continued for four weeks or until the connector reached a resistance above the failure limit of 2.5 milliohms. Noted during this test was the heavy buildup of white colored deposits around the mating areas between the connector and mounting plate for each of the connector assemblies. Of the four connectors tested, only the titanium alloy connector was able to maintain a resistance value below the 2.5 milliohms failure limit for the four-week period. The cadmium-plated aluminum connector failed in just one day; the bronze-aluminum connector lasted two days, while the stainless steel connector failed after five days (Chart 4).

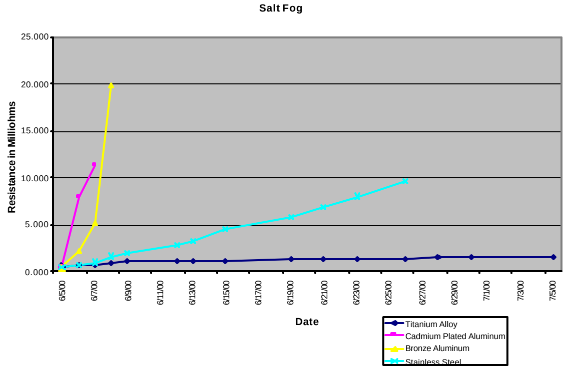

Chart 4 Bonding resistance of the four connector materials in a salt fog environment

All connector assemblies tested in the salt fog environment were found to have a heavy buildup of white colored deposits between the faying or mating areas of the connector and mounting plate. Elemental analysis determined these deposits to be sodium and chloride ions as expected from the salt fog spray. Deposits were more pronounced on the faying areas of the cadmium-plated aluminum and bronze-aluminum connector assemblies (figures 17). The titanium alloy, as well as the stainless steel connector assemblies, exhibited less salt fog deposits on these faying areas than the other connectors (figure 18).

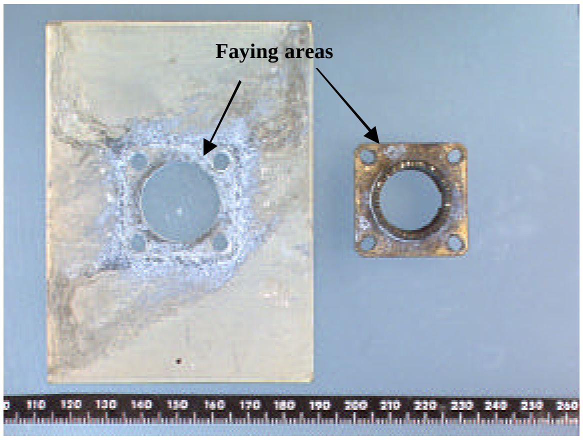

Figure 17 Heavy deposits from salt fog on faying areas of bronze-aluminum connector and mounting plate

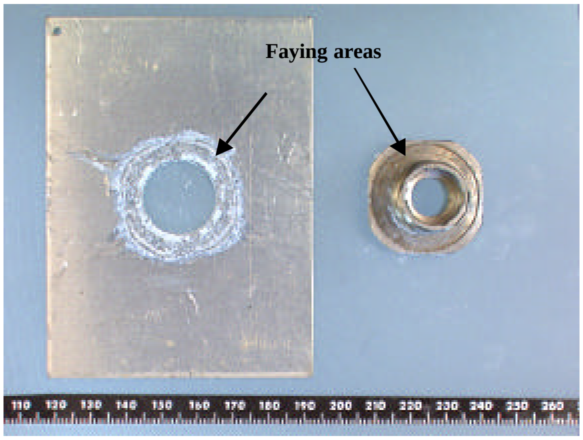

Figure 18 Titanium alloy connector and mounting plate with lighter deposits on faying areas from salt fog

Workshops

Two workshops were conducted at Wright-Patterson Air Force Base in 1996 and 1997 to address the issues of connector bonding. Representatives from various U.S. government agencies, manufacturers, and universities were in attendance. The Royal Air Force and the Defense Evaluation and Research Agency of the United Kingdom were also represented.

Both workshops featured presentations by a number of the attendees. Topics included bonding resistance tests and materials analyses of connectors utilizing cadmium plating and possible replacement plating materials. These included AIVD, nickel-boron, thermal sprays, and other novel plating systems. Other issues were discussed, including surface treatments, conductive gels and gaskets, and connector fastening procedures.

A number of candidate solutions were proposed. These included mechanically removing the plating from the mating surfaces, followed by the immediate application of a conversion coating and assembly. A non-conductive sealant would then be applied. Also suggested was the use of conductive grease to be applied in a controlled factory environment, and conductive sealants, particles, and gaskets. Alternative finishes and materials were proposed, such as Ion vapor deposited (IVD) aluminum, nickel-boron alloys (Nybron®), titanium, and nickel-plated composite connectors. Methods to increase faying surface contact were also suggested, along with using the fasteners as part of the conductor path.

As a result of the discussions by those in attendance and the topics presented it was agreed chromate conversion coatings are fraught with problems and need to be replaced, if for no other reason, for environmental concerns. It was recognized conductivity is presently obtained primarily through the fasteners and that the faying surfaces are, in reality, very small. It is desirable to have increased intimate contact area. This can be accomplished by roughening the mating surfaces to break through the oxide layer. Sealers should be used to reduce oxygen exposure at the bond interface.

Conclusions

Cadmium-plated aluminum connectors mounted to aluminum plates exceeded 2.5 milliohms bonding resistance on their faying surfaces both in the room ambient and salt fog tests in approximately 24 hours. The bronze-aluminum, titanium alloy, and stainless steel assemblies, after showing a minor increase in bonding resistance initially, were able to maintain a steady resistance value far below the 2.5 milliohms maximum limit during the room ambient test. The bronze-aluminum and stainless steel connector assemblies bonding resistance exceeded 2.5 milliohms during the salt fog test in two and five days respectively. Only the titanium alloy connector maintained a bonding resistance below the 2.5 milliohms limit. The titanium alloy may have maintained a low bonding resistance due to a better metal to metal seal between connector and plate. This may be due to the jam nut fastening to the mounting plate.

Elemental examination of surfaces show the increase in bonding resistance is likely due to the small area physically making contact between the cadmium-plated aluminum connector and aluminum mounting plate. Increased resistance during the salt fog test was due to the salt fog penetrating the poor metal-to-metal seal between the connector and mounting plate for the bronze-aluminum, cadmium-plated aluminum and stainless steel connector assemblies.

System requirements appear to be the motivating force for resolving connector bonding issues. Designs and analyses are based on the 2.5 milliohm maximum connector bonding resistance requirement, for example. Bond measurements are not regularly or periodically verified; when measurements are made, however, bonds often fail the test. There is universal concern for meeting EMI requirements and for replacing platings and coatings that may not be available in the future. Environmental requirements are becoming more stringent, resulting in fewer acceptable materials. It was mutually agreed a team concept was needed to solve problems. This team would include the customers, suppliers, scientists, and engineers.

Consideration should be given to redesigning the connectors and their method of fastening and bonding. The use of additional fasteners and/or increasing the torque on the present fasteners may improve the opportunity for “gas-tight” seals between the connector and mounting plate. Bonding tests should be conducted using jam nuts for fastening and bonding connectors made of materials other than titanium. The jam nut method of fastening appeared to effect a better electrical bond than the screws in the corners.

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