AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF CHARGING ON THE INTERNATIONAL SPACE STATION

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ABSTRACT

An experimental investigation has been undertaken to determine the effects associated with operating the International Space Station (ISS) without a Plasma Contactor Unit (PCU). The role of the PCU is to maintain the potential of the ISS to within 40 volts of the ambient plasma potential. In the event of a PCU failure, ISS structure may charge to –160 volts with respect to the Low Earth Orbit (LEO) plasma, due to the use of high voltage photovoltaic solar arrays. Operation without a PCU will result in the charging of the oxide layers on anodized aluminum components facing into the RAM direction. In this investigation, arcs were observed as a result of anodized materials charging in a plasma environment. Actual ISS materials were used in the investigation. The materials included meteoroid and debris shield samples, as well as components from the Extra-vehicular Mobility Unit (EMU). Results show that the occurrence of arcs was dependent on several factors including material composition and applied voltage. Damage resulting from an arc is shown, as well as the effect of arc damage on thermal properties.

INTRODUCTION

The International Space Station's (ISS) main power source is the 160-volt (V) solar arrays. In the past, satellites and spacecraft have used much lower voltage solar arrays, generally 40 V. The increase in solar array voltage and the negative ground design means that it is possible for the ISS to float at –140 V relative to the surrounding plasma. Earlier work by Carruth and Vaughn (refs. 1, 2) indicated that the breakdown voltage of the ISS structural anodized aluminum was much less than –140 V. Because of the damage to the structural aluminum and the impact on thermal properties due to arcing, two plasma contactors were included in the ISS design. They are attached to the Z1 truss with one operational and one on standby. They are designed to maintain ISS's potential to ± 20 V with respect to the surrounding plasma.

Concerns over the plasma contactor's operational capabilities led to further testing in 2000. These tests addressed the issues of PCU failure, arcing damage and its effect on thermal properties, synergism between plasma and atomic oxygen, and any hazards to an astronaut on extravehicular activity (EVA) in the event of PCU failure. Extensive testing has been performed at the Marshall Space Flight Center (MSFC) and Glenn Research Center (GRC) to address these issues.

ARCING

Chromic acid anodized aluminum was selected for ISS's meteoroid/debris shielding, pressure walls, and trusses because of its specific thermal properties. To meet the required passive thermal control, the anodized aluminum has a very thin oxide layer, approximately 0.05 - 0.08 mils (1.3 - 2 μm) thick. As a dielectric, the aluminum oxide can charge when in contact with LEO plasma and acts as a 1-8 millifarad (mF) capacitor.

To calculate the capacitance of the anodized sections of the ISS, the formula for a parallel plate capacitor can be used. For a parallel plate capacitor with a dielectric, the formula is:

$$C=k\varepsilon_o A/d.$$

For charging on the ISS, k is the dielectric constant for the oxide layer, ε_o is the permittivity of free space, A is the area of anodized aluminum, and d is the thickness of the anodized (oxide) layer. The capacitance is therefore proportional to the surface area of the ISS modules and inversely proportional to the thickness of the oxide layer. Given the large area of anodized material and the very thin oxide layer associated with the anodized sections, the ISS capacitance is quite large. The capacitance for different builds of the ISS was calculated by Carruth (ref. 3). The capacitance for the ISS 5A stage, for example, was found to be 6.9×10^{-3} farads. For the test conducted in this investigation, large electrolytic capacitors were chosen to simulate the capacitance of the ISS early build stages.

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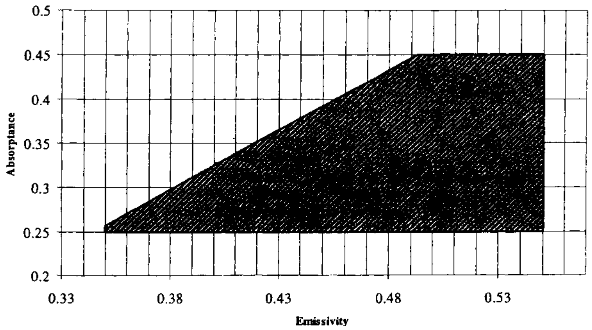

Figure 1. BOL Specification for Chromic Acid Anodized Aluminum (Figure courtesy of Boeing)

Witness samples of ISS manufactured debris shields and other surfaces were provided for laboratory test. These samples were anodized according to Boeing process specification D683-29365, which has very tight tolerances for optical properties. The anodized aluminum samples were characterized for solar absorptance and infrared emittance before and after plasma exposure. The specification calls for beginning-of-life (BOL) solar absorptance and infrared emittance within the boundaries shown in figure 1.

Elsewhere on ISS, sulfuric acid anodize is used, mainly on truss structures. This is a thicker anodize and thus less likely to arc than the chromic acid anodize, but several samples were included in this study for completeness. The samples were anodized according to the McDonnell Douglas (now Boeing) specification STP-0554. The specification calls for BOL solar absorptance of 0.49 ± 0.09 and infrared emittance of 0.86 ± 0.04 for aluminum alloy 2219-T851 plate.

The MSFC PCU Plasma Interaction Chamber is a 3' dia. x 4' long (0.91 x 1.22 m) vacuum chamber capable of a base pressure in the low 10^{-7} Torr (1.33×10^{-5} Pa) range (fig. 2). A hollow cathode plasma source uses argon gas to produce a low density (10^6/cm^3), low temperature (1 eV) plasma to simulate the low Earth orbit plasma environment. The chamber also contains a Langmuir probe to measure the plasma properties during testing. Measurements of the plasma indicated electron temperature, T_e in the range of 0.95 to 1.6 eV and plasma density, n_e in the range of 0.76 – 1.3 x 10^7/cm^3.

Sample size was 4 in. x 6 in. (10.2 x 15.2 cm). One side was completely covered with Kapton tape, as were the edges. The Kapton tape insulates one side from arcing and eliminates edge effects.

A typical sample plate of chromic acid anodized aluminum with arc events is shown in figure 3. The set-up for the arcing threshold tests is shown in figure 4. The circuit consists of a large electrolytic capacitor to simulate the capacitance of ISS. The capacitor is charged to a negative potential with a power supply. A charging resistor is placed between the power supply and the capacitor. The high impedance of the resistor effectively removes the power supply from the circuit during an arc event. The voltage on the capacitor is measured as well as the current flow in the circuit. Typical voltage and current traces during an arc event are shown in figures 5 and 6. The voltage and current shown in figures 5 and 6 correspond to an arc initiating on a chromic acid anodized plate connected to a 1.1×10^{-3} farad capacitor.

For the early tests of the chromic acid anodized aluminum, the voltage was set to zero then slowly increased until arcing occurred. To study the effects of arcs at different energies, the capacitance was varied between 1.2 mF, 2.4 mF, and 6.6 mF. The breakdown voltage for this thin anodization was found to be approximately 80 V. Later tests of the chromic acid anodized aluminum involved setting the voltage at –140 V and letting the plate arc for a predetermined amount of time (e.g. 1 hour, 12 hours) or until arcing stopped (64 hours).

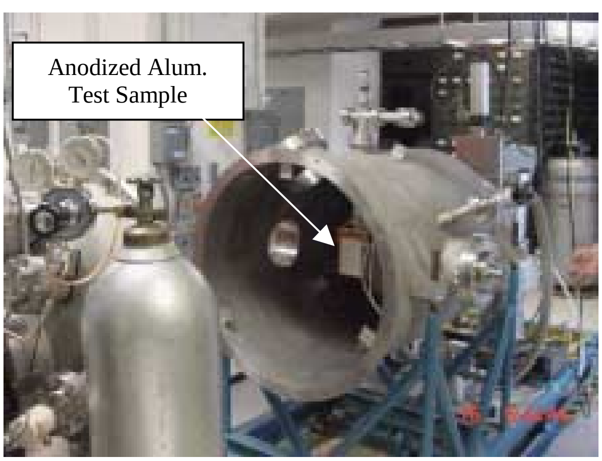

Figure 2. MSFC PCU Plasma Interaction Chamber

Figure 3. Post-Test Sample with Arcing Damage

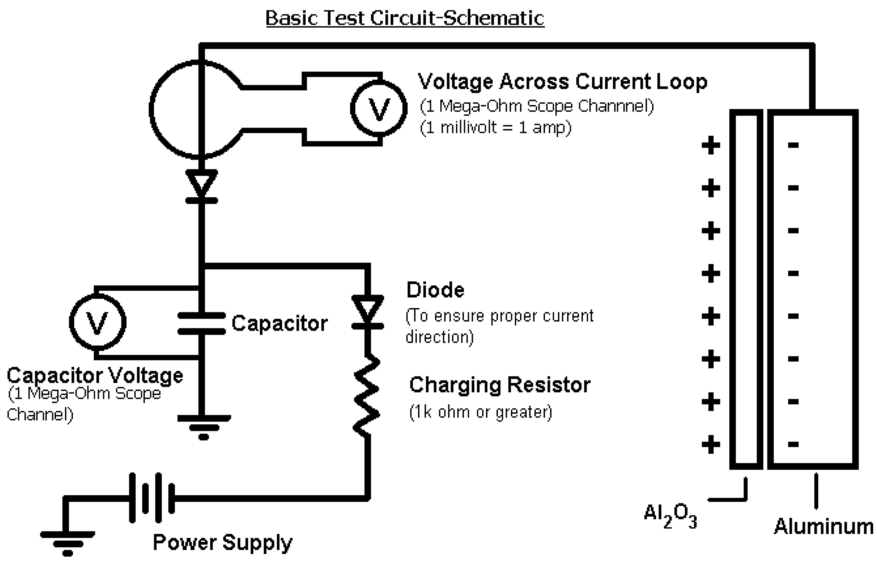

Figure 4. Circuit Diagram for PCU Plasma Interaction Tests

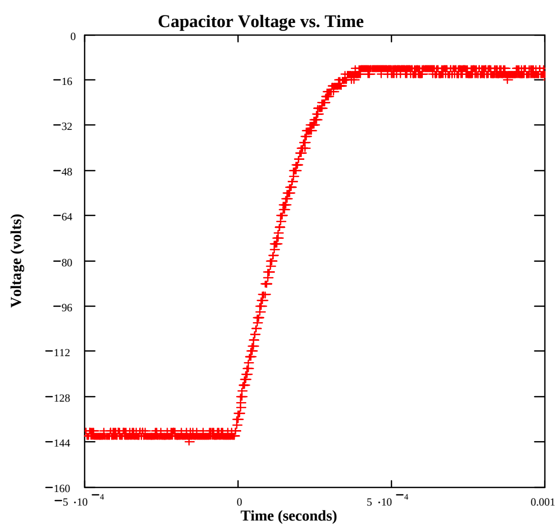

Figure 5. Typical Capacitor Voltage Curve During Arcing

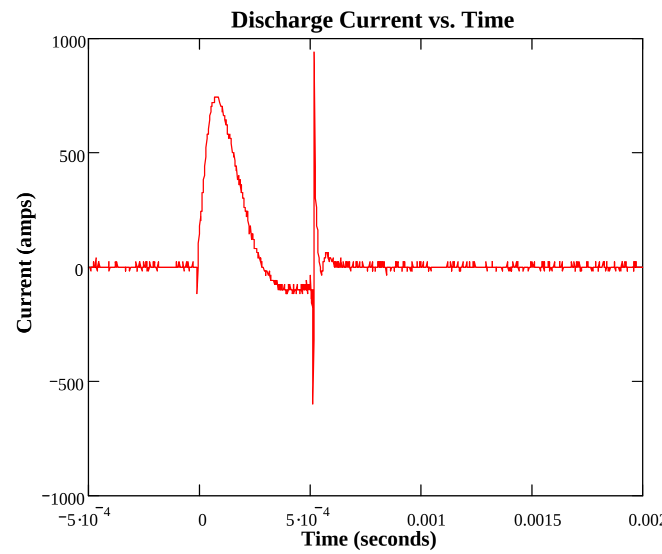

Figure 6. Typical Discharge Current During Arcing

Sulfuric acid anodized aluminum is used on the ISS truss structure and other components. This is a much thicker anodize, on the order of 0.6 mils (15 µm) thick. Samples of sulfuric acid anodized aluminum were tested for breakdown threshold in the PCU Plasma Interaction Chamber. Voltage was set to zero, then slowly increased until arcing occurred. As would be expected, the breakdown voltage for the sulfuric acid anodize was higher than that of the thinner chromic acid anodize. Breakdown voltage at 1.1 mF capacitance was 200 V.

Microscopic inspection of the arcing site shows a central pit and Lichtenberg patterns radiating from the pit (fig. 7). The size of the pit and the extent of the radial pattern depend on the arc energy. This arcing produces ejecta in the form of vapor and fine particulate. Samples of other ISS and EMU materials were placed in the plasma chamber as contamination witness samples. Teflon with silver/Inconel backing, aluminized beta cloth, Z-93 white thermal control coating, fused silica windows, and Orlon fabric were characterized before and after testing, with special attention to any particulate fall-out from the anodized aluminum plate. After a test in which an anodized aluminum plate was subjected to a total of 180 arcs, small (<1 mm) metal pieces were found on the Orlon fabric sample. Closer examination showed

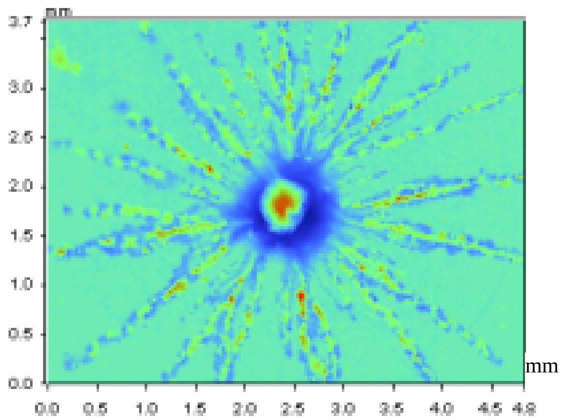

Figure 7. Arc pit in anodized aluminum

that no melting or other damage to the fabric occurred. The probability of metal particles leaving an arc site and striking an EMU was determined to be very low, since arcs occurring on ISS will be spread out over many meters, and the experiment constraints forced close proximity between the aluminum plate and the suit material.

EFFECTS ON OPTICAL PROPERTIES

Passive thermal control on ISS requires tight tolerances of solar absorptance and infrared emittance to maintain acceptable heat levels. Increases in the ratio of solar absorptance to infrared emittance may require early replacement of the meteoroid/debris shields or danger to the astronaut on EVA if touch temperature limits are exceeded. By measuring the optical properties of the aluminum before and after testing, we can calculate the change based on percent area damaged by arcing. Figures 8 and 9 show this change for chromic acid anodized aluminum. One series of tests involved repeated arcing of the anodized aluminum until the entire surface was covered with arc pits and other arcing scars. Solar absorptance and infrared emittance measurements of these samples indicated an increase in the a/e ratio from 0.66 to approximately 1.5.

Thermal models were used to predict temperature changes on ISS surfaces. Variables included the orientation of ISS and the surface area that may arc (ref. 3), as well as the recharge time. The arc density per unit area can then be calculated for time in orbit, with accompanying changes in solar absorptance and infrared emittance. The endcones of the US Laboratory module (*Destiny*) and Node 1 (*Unity*) are in the ram direction in Local Vertical Local Horizontal (LVLH) orientation and thus would receive the most damage due to arcing in the event of a PCU failure for early ISS builds. ISS may also fly with the X-axis perpendicular to the orbit plane (XPOP). In that case, the sides of the Laboratory and Node 1 cylinders would have more damage due to arcing. Both LVLH and XPOP conditions were considered in thermal modeling. The thermal analysis showed that touch temperatures can be exceeded, but only after months without an operating PCU and no other actions taken to mitigate charging effects (ref. 4).

SYNERGISM WITH ATOMIC OXYGEN

Atomic oxygen (AO) is produced by the interaction of molecular oxygen and ultraviolet (UV) radiation. At LEO, AO impacts the surface of a spacecraft with energies of 5 – 7 eV, causing erosion and oxidation damage to exposed materials. After an arc occurs, bare aluminum is exposed. AO reaction to the aluminum will produce a thin oxide layer. This may lead to continued arcing and subsequent loss of aluminum material.

The MSFC Atomic Oxygen Drift Tube System (AODTS) was used to study any synergisms between AO and plasma arcing. The AODTS produces a thermal atomic oxygen plasma on the order of 0.1 eV energy. Samples are exposed outside the RF field to eliminate exposure to any plasma charged particles and unwanted sample heating.

One of the chromic acid anodized aluminum samples was repeatedly arced for 72 hours for a total of 4437 arcs. This sample was later placed in the AODTS and exposed to the equivalent of 3 months in LEO. After the AO

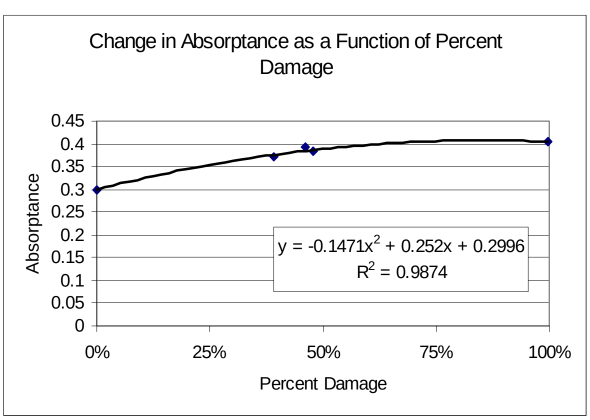

Figure 8

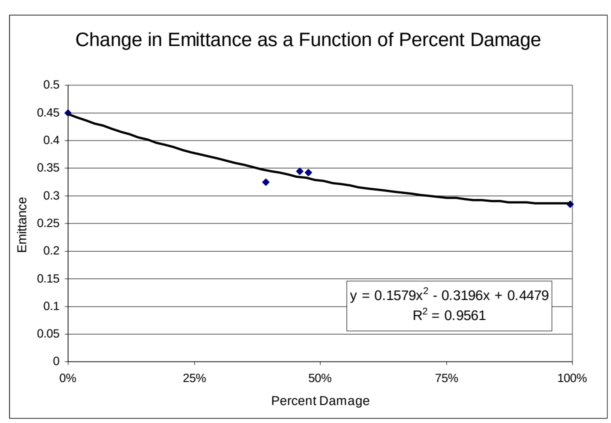

Figure 9

exposure, it was returned to the PCU Plasma Interaction Chamber and subjected to further arcing. After 19 hours at 140 V, the sample sustained only 30 more arcs. This demonstrates the synergistic effect of AO and plasma but was not cause for concern.

EMU CONCERNS

Astronauts on EVA are attached to the ISS by a safety tether made of stainless steel wire. Contact between this tether and exposed metal on the EMU could move the EMU and astronaut ground negative of the local plasma the same as the ISS structure voltage. EMU hardware was tested for breakdown voltage in a plasma environment. The Display and Control Module (DCM), a Body Restraint Tether (BRT), and a Mini-Work Station (MWS) were biased at a negative voltage via a capacitor test circuit. Testing began with the voltage set at 60 V, increasing in 5 V increments until an arc was observed. The voltage was held at each increment for a minimum of one minute. Several of the metallic parts sustained arcing at 70 V. Results from these tests are given in Table 1.

Table 1. Arcing Test Results for EMU Components

EMU Component	Breakdown Voltage Range	Average Breakdown Voltage	Capacitance
Display and Control Module	-68 to -80 V	-76 V	4.2 mF
Body Restraint Tether	-152 to -162 V	-158 V	4.2 mF
Mini Work Station	-68 to -70 V	-69.5 V	4.2 mF

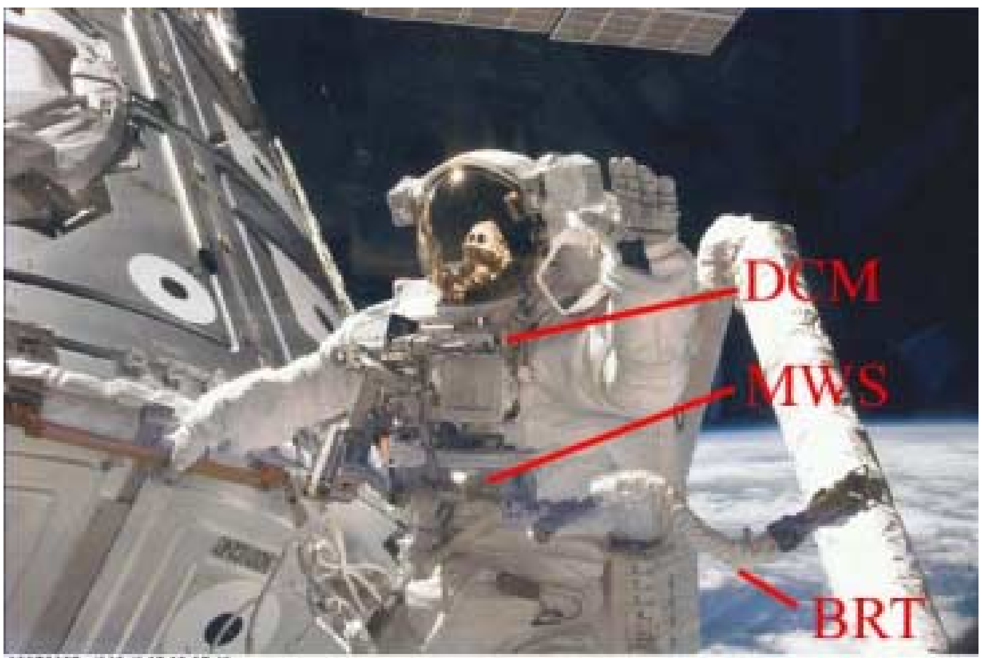

Figure 10. Astronaut on EVA. Display and Control Module (DCM), Body Restraint Tether (BRT), and Mini-Work Station (MWS) are indicated.

Several types of cloth used in the EMU suit were later tested as covers to protect the EMU components from arcing. A DCM cover, single and double ply Ortho fabric, clear Teflon film, and a section of Thermal Micrometeoroid Garment (TMG) with 5 layers of Mylar were tested as covers over chromic acid anodized aluminum. The range of bias voltages was –60V to –200 V. The voltage was changed in 5 V increments, with a minimum hold time of 1 minute. When the aluminum plate was completely covered, no arcing occurred. When gaps up to 5 mm were introduced, arcing was observed in the range of –130 V to –155 V.

Very little energy can be stored in the anodized EMU surfaces, given their small area, but plasma contacting ISS outer surfaces could provide a low impedance path through the structure and tether. In this case, an arc on the EMU could in fact discharge the station capacitance (via the arc plasma), resulting in a high energy and high current discharge through the EMU. Circuit analysis has been performed for the case of a high current discharge through the EMU. The analysis shows that potential shock hazards exist for the crew member in the EMU (ref. 5). Safety for the astronauts must be assured to a two-fault tolerant level. This has led to EVA operational changes, where both PCUs must be operating before an EVA takes place. If the PCUs are not operating at an optimum level, the solar arrays may be vectored or shunted to lower the voltage.

CONCLUSIONS

Tests on ISS materials in a plasma environment have been conducted. The tests have shown that anodized ISS surfaces are subject to dielectric failure in the event that the structure potential falls to $\leq$ -70 volts with respect to the LEO plasma. The effects of arcing have been shown to alter the thermo-optical properties of debris shield and represent a potential hazard to EVA astronauts. To protect an astronaut on EVA, several designs for covering exposed anodized sections on the EMU were tested. While different materials were shown to reduce charging effects, the allowable gaps in the covers were found to be prohibitively small ($\leq$ 5 mm).

Further investigations into the problems associated with charging of thin anodized materials are ongoing. Investigations focusing on low voltage (< 70 V) arcing has begun. Mechanisms capable of discharging remote areas away from an arc, via the arc plasma, are also being investigated.

ACKNOWLEDGMENTS

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REFERENCES

1. Carruth, Jr., M. R., et al, "Plasma Effects on the Passive Thermal Control Coating for Space Station Freedom", AIAA Paper No. 92-1685, AIAA Space Programs and Technologies Conference, Huntsville, AL, March 1992.
2. Vaughn, J. A., et al, "Electrical Breakdown Currents on Large Spacecraft in Low Earth Orbit," Journal of Spacecraft and Rockets, Vol. 31, No. 1, Jan.-Feb. 1994.
3. Carruth, Jr., M. R. et al, "ISS and Space Environment Interactions Without Operating Plasma Contactor", AIAA Paper No. 2001-0401, AIAA Aerospace Sciences Meeting, Reno, NV, January 2001.
4. Alred, John et al, "External Contamination Support to PCU Team 1 Special Assessment – TIM #3", presentation at third Technical Interchange Meeting, NASA Johnson Space Center, Houston, TX, August 9, 2000.
5. Harold Hansen, "EMU Sneak Circuit Analysis", memorandum #ED-945, Hamilton Sundstrand, Windsor Locks, CT, November 3, 2000.