

# REMAINING LIFE ASSESSMENT OF SHUTTLE REMOTE MANIPULATOR SYSTEM END EFFECTOR ELECTRONICS UNIT<sup>1</sup>

Vidyasagar Shetty, Keith Rogers, Diganta Das, and Michael Pecht  
CALCE Electronic Products and Systems Center  
University of Maryland, College Park, MD 20742

David Hiemstra and Stephen Martin  
MacDonald Dettwiler Space and Advanced Robotics Ltd.  
9445 Airport Rd, Brampton, Ontario L6S 4J3, Canada

## ABSTRACT

The Shuttle Remote Manipulator System End Effector Electronics Unit was designed in the 1970s with a target application life of ten years. They have performed without any failures for over 20 years. In 2001-2002, the manufacturer of the Shuttle Remote Manipulator System in collaboration with the CALCE Electronic Products and Systems Center of University of Maryland performed an analysis of the remaining life of the End Effector Electronics Unit. This article presents the portion of the remaining life assessment performed by CALCE. CALCE's portion of the remaining life assessment concluded that the printed wiring board assemblies of the EEEU could be extended until 2020 due to the robust design and lack of damage caused to the printed wiring board assemblies.

## INTRODUCTION

The Space Shuttle is currently the sole U.S. means for launching humans into orbit and providing cargo to the Space Station. The Space Shuttle has been the most reliable of various space launch vehicles. However, increasing costs to operate and maintain the Shuttle fleet, workforce reductions for Shuttle operations, a deteriorating launch infrastructure and budget cuts for safety and supportability upgrades, have led to questions about its continued viability past 2012. Safe operation of the Space Shuttle and developing a more reliable and lower-cost second-generation Reusable Launch Vehicle (RLV) are major NASA goals. However, these vehicles are not expected to be ready before 2020 and hence NASA hopes to extend the usage of the Space Shuttles into the year 2020. NASA has asked its major contractors to conduct remaining life assessment of the key components of the Space Shuttle. MacDonald Dettwiler Robotics (MD Robotics) of Canada, the prime contractor of the Space Shuttle robot arm (SRMS) is conducting a remaining life assessment of the End Effector Electronics Unit (EEEU).

The Shuttle Remote Manipulator System (SRMS) is a part of the Space Shuttle (see Figure 1). The first SRMS<sup>2</sup>, or Canadarm, was designed and developed by MacDonald Dettwiler Robotics (MD Robotics, formerly SPAR), under contract to the National Research Council of Canada. Canadarm has performed without failure for 20 years; placing payloads into their proper orbit, retrieving malfunctioning ones for repair, and is presently assisting in the assembly of the International Space Station.

## HARDWARE OF SRMS

A schematic of the SRMS showing the location of End Effector (EE) is shown in Figure 2. The End Effector (EE) allows the arm to capture stationary or free-floating payloads. The End Effector Electronics Unit (EEEU) is contained within the EE as shown in Figure 3. The electronic boards of EEEU drive the EE

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<sup>1</sup> This project was performed under contract by CALCE EPSC for MD Robotics, Brampton, Canada. Contact number 920508.

<sup>2</sup> The first SRMS flew on mission STS-2 in November 1981.

mechanisms and reads out the EE status. In addition to the EE, the SRMS contains other electronics, including the Servo Power Amplifier (SPA).

## **OBJECTIVE OF THE STUDY**

The objective of the study was to perform a remaining life assessment of the EEEU of the SRMS. The investigation provided technical justification for future courses of action on the EEEUs. The steps followed for achieving the objective included:

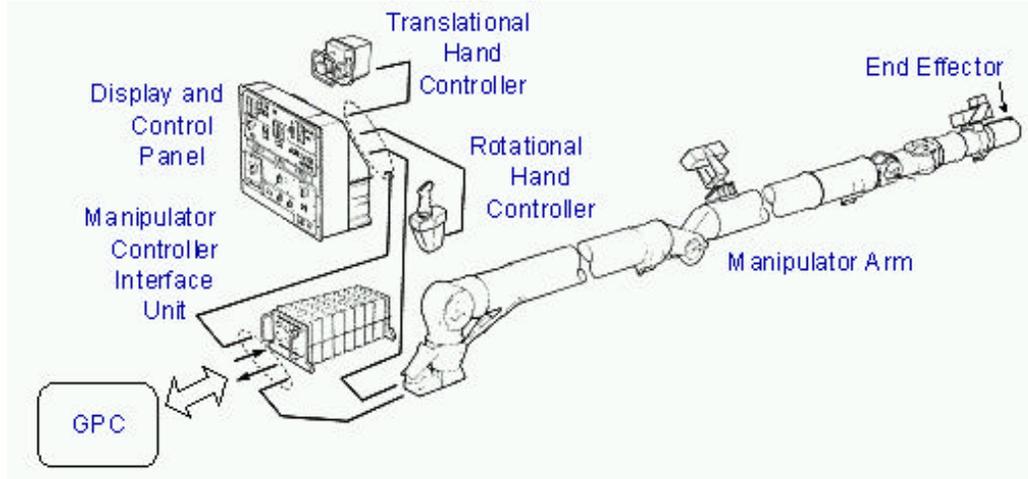
- Virtual remaining life assessment performed using calcePWA software to determine the mode, location, and approximate time of failure (interconnect failures) at the printed wiring board assembly level.
- Physical analysis of hardware representative of the EEEU build. The original analog Servo Power Amplifier (SPA) units were selected for physical analysis since no spare EEEU that had undertaken space flights was available. (The analog SPA units are similar to the EEEU in terms of the environments experienced, component types, design, manufacturing processes used, and date of manufacture).
- Destructive physical analysis of critical components<sup>3</sup> performed to check for quality problems or degradation.



**Figure 1: Shuttle Remote Manipulator System (SRMS)**

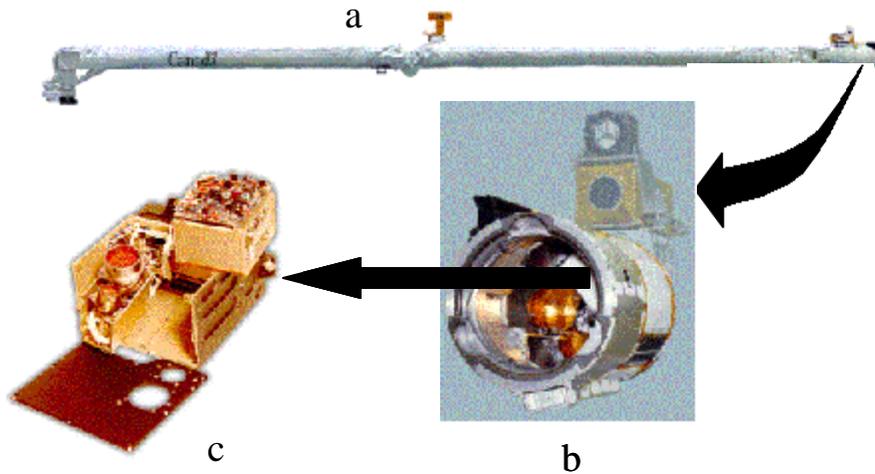
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<sup>3</sup> CALCE and MD Robotics identified polarized tantalum capacitors and transformers to be critical components



**Figure 2: Schematic of the SRMS**

## VIRTUAL REMAINING LIFE ASSESSMENT



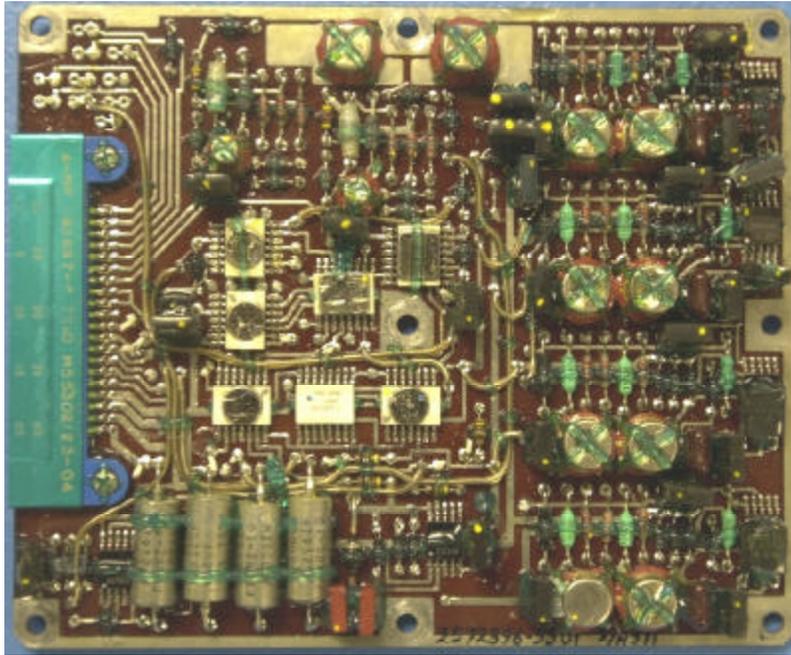
**Figure 3: Physical hierarchy of the SRMS (a-SRMS, b-EE, C-EEEU)**

Virtual remaining life assessment is a methodology for assessing electronics through the use of validated failure models and simulation tools. The methodology involves the application of simulation software to model physical hardware and to determine the probability of the system meeting the desired life goals. The virtual remaining life assessment was performed using calcePWA software. Virtual remaining life assessment using calcePWA (ref. [1]-[10]) was conducted on two SPA boards (Power Switch Driver Off and Electronics Interface (Figure 4)) and on two EEEU boards (Logic & Commutation and Power Conditioner). The steps in virtual remaining life assessment are described below:

### Design Capture

Design capture is the process of identifying and documenting geometrical, material, and mounting information to generate a model of the physical hardware. Design capture involves evaluating the electronic

system at all hierarchies (e.g., enclosure, circuit cards, parts, physical interfaces) based on the objectives of the assessment. Each individual component of the circuit card assembly is characterized by a set of geometrical and material parameters by the hardware capture and material identification and properties.



**Figure 4: Electronics Interface board**

### **Life-Cycle Environmental Profiles**

A life-cycle environment profile is a forecast of events and associated environmental conditions that equipment will experience from manufacturing to end of life. Life-cycle environment profile information is necessary for both the simulation of life through virtual remaining life assessment, and for understanding and interpreting the physical analysis observations. The product's life-cycle environment describes the storage, handling and application scenario of the product, as well as the expected severity and duration of the load conditions for each scenario. Load conditions include temperature, humidity, pressure levels, vibration or shock loads, chemically aggressive or inert environments, sand, dust, electromagnetic radiation levels, and loads caused by operational parameters such as current, voltage and power (ref. [11]). The virtual remaining life assessment using calcePWA takes into account temperature, vibration and shock as the input load conditions because reliability of interconnects<sup>4</sup> primarily depends on these three load conditions.

The life-cycle loading for the calcePWA simulation included the environmental conditions that the electronics are exposed during their complete life (e.g., test, transportation, operation). Two profiles were used for the simulation: twenty years of life and forty years of life (which includes the predicted environment for the next twenty years of operation assuming an increased frequency of Shuttle launches). The number of missions undertaken by an individual unit in the first twenty and next twenty years was approximated at fifteen and twenty-five respectively.

As conventional with space hardware, one unit was built as a “qualification unit” and that unit that is not used for actual missions. The remaining units are acceptance tested and shipped to the launch site at Florida, where they are stored in a clean room. The arm is functionally tested in Florida before each launch (this testing does not involve thermal cycling or vibration and hence it is not modeled). The SRMS is loaded in the Shuttle, which typically stays on the launch area for two months. Between launch and landing, the Shuttle experiences the operational profile. Usually the Shuttle lands in Florida. If it lands in

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<sup>4</sup> Only second level interconnect (solder joints) failure can be detected using calcePWA.

California due to inclement weather conditions in Florida the Shuttle gets ferried back to Florida on top of a large aircraft. If no rework or testing is required, the SRMS goes into controlled storage. If rework or testing is needed in the SRMS, it is shipped by controlled ground transport to Canada. Acceptance testing in Canada occurs if any rework is performed and then the SRMS is shipped back to Florida for continued controlled storage up to the next launch. The environmental profile chosen for the simulation using calcePWA is the worst case profile that matches the two EEUs which are used on missions, despite having undergone qualification testing due to major changes in EE design. The ground transportation profile was not modeled since the temperature levels were similar to storage and the vibration levels were negligible when compared to the test and launch levels.

### *Thermal profile*

The thermal cycle segments were used as a part of life-cycle environment profile. They consist of:

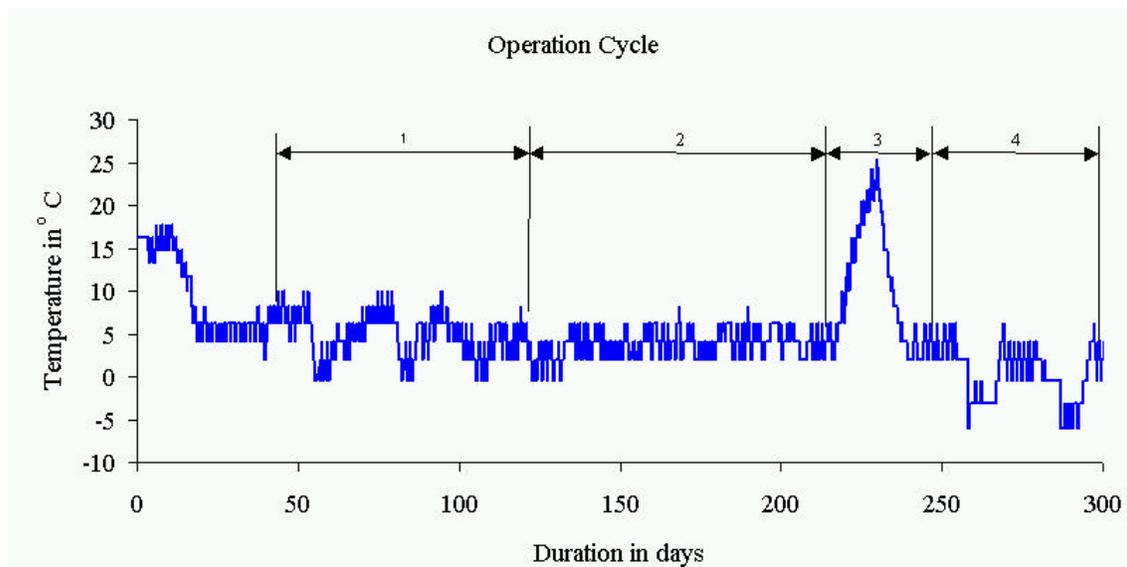
Qualification testing was performed to determine whether the unit can survive for the expected life. The units that undergo qualification testing are typically not used for missions. The profile consists of 27 cycles and the temperature profile experienced is between  $-36$  to  $81^{\circ}\text{C}$ .

Acceptance testing was performed after assembly of the unit and after each rework, to validate the workmanship of the unit before undertaking the next mission. On average, EEUs are acceptance tested once every 3 missions, so acceptance testing was performed five times. The profile has a total of 20 cycles and the temperature profile experienced is between  $-25$  to  $70^{\circ}\text{C}$ .

Storage is used to depict the 356 days a year (on average) that a SRMS spends in climate controlled storage. There were 7120 cycles and the temperature profile is between  $17$  and  $27^{\circ}\text{C}$ .

Ferry flight is done when there is a possibility that inclement weather may endanger the safety of the Shuttle crew, the Shuttle is diverted to an alternate landing site at Edwards Air Force Base in California. However, all storage, maintenance, testing, overhaul and pre-launch work is performed in Florida (or at other specialized test facilities) and the Shuttle needs to be brought back using a ferry flight. The ferry flight profile refers to one flight from California to Florida atop a jumbo jet. Total number of ferry flights was 5 for the unit considered for simulation and the temperature profile was assumed to be between  $-40$  and  $35^{\circ}\text{C}$ .

Operation cycle consists of four different cycles based on the environmental profile experienced by the SRMS. Data for the operation temperature cycle simulation was based on the data from mission STS-092. MD Robotics and NASA maintain data on all Shuttle launches. STS-092 was chosen as representative of the environment because it was the closest to the median operating environment. The SRMS uses thermal blankets and heaters (with thermistors) to moderate, control, and monitor temperatures. The profile of operation cycle is shown in Figure 5. The profiles for qualification, acceptance, ferry flight and storage cycle are shown in Figure 6



**Figure 5: Operation temperature cycle**

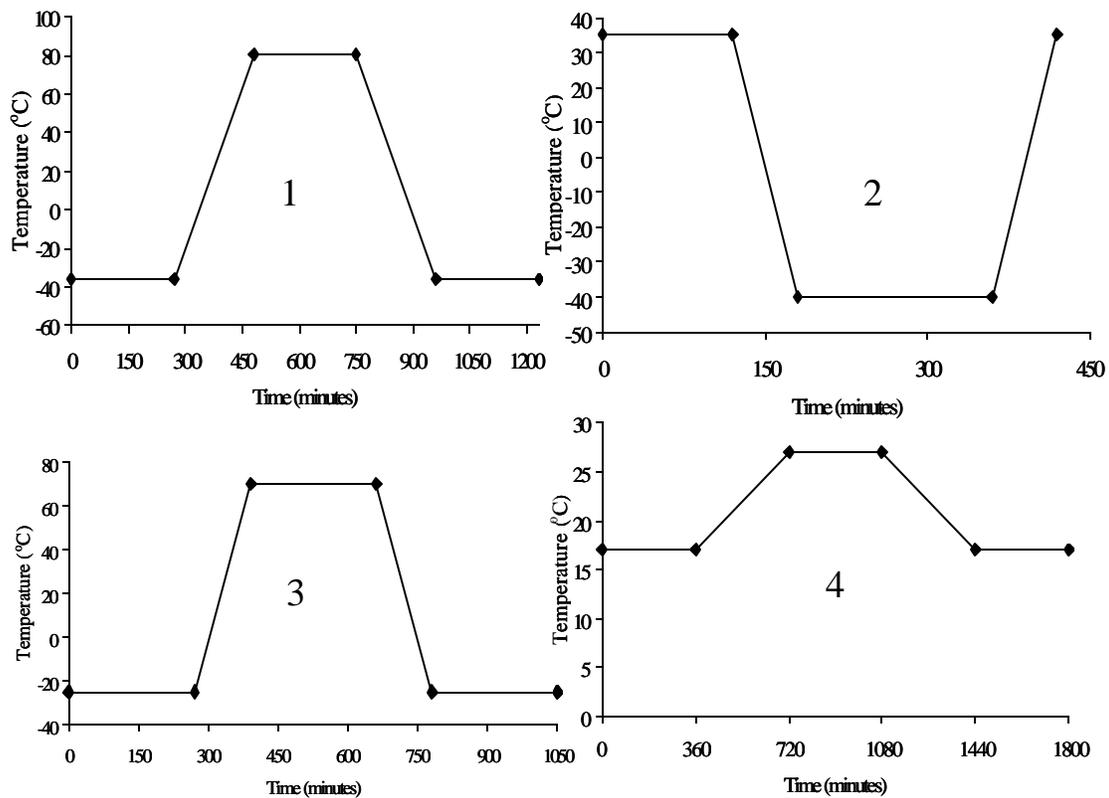


Figure 6: Life-cycle environment profiles [ 1-Qualification, 2-Ferry flight, 3-Acceptance, 4-Storage]

### Vibration Profile

The 20-year vibration profile sees 4 acceptance vibration tests and the qualification vibration tests for the End Effector. The acceptance vibration is performed 5 times for the End Effector Electronics Unit. Each vibration profile is explained below.

EEEU acceptance vibration tests (EEEU AVT) are conducted on the EEEU after construction or rework and are conducted 5 times for a period of 1 minute per axis. Table 1 shows the power spectral density (PSD) values for the cycle at different frequencies.

Table 1: EEEU AVT

Frequency (Hz)	Power Spectral Density ( $g^2/Hz$ )
20	0.030
80	0.480
100	0.480
180	0.083
2000	0.008

EE acceptance vibration test (EE AVT) is conducted for the whole EE assembly to confirm workmanship (quality of the work) of the unit after construction or rework. This test is conducted 4 times for 15 missions; and takes one minute per axis. Table 2 shows the power spectral density (PSD) values for the cycle at different frequencies.

**Table 2: EE AVT**

<b>Frequency (Hz)</b>	<b>Power Spectral Density (<math>g^2/Hz</math>)</b>
20	0.010
80	0.040
350	0.040
2000	0.007

EE quality and acceptance vibration test (EE QAVT) is performed during qualification of the unit. The purpose of QAVT is to validate that the qualification unit is designed well enough to survive all AVTs that a flight unit will see and is conducted 3 times for 15 minutes each. Table 3 shows the power spectral density (PSD) values for the cycle at different frequencies.

**Table 3: EE QAVT**

<b>Frequency (Hz)</b>	<b>Power Spectral Density (<math>g^2/Hz</math>)</b>
20	0.017
80	0.067
350	0.067
2000	0.012

EE qualification vibration test (EE QVT) is performed during qualification of the unit. The purpose of QVT is to validate that the qualification unit is designed well enough to survive all life vibrations that a flight unit will experience and is conducted once for 50 minutes. Table 4 shows the power spectral density (PSD) values for the cycle at different frequencies.

**Table 4: EE QVT**

<b>Frequency (Hz)</b>	<b>Power Spectral Density (<math>g^2/Hz</math>)</b>
20	0.032
80	0.500
350	0.500
2000	0.005

Operation vibration refers to the vibration that the boards are exposed to in a normal mission. The operation vibration lasts for 5 seconds, and since there are total of 15 missions the total time taken is 75 seconds. The PSD profile of the End Effector Electronics Unit qualification vibration test (EEUU QVT) is used for operation profile because it is considered as an indicator of operation vibration. Table 5 shows the power spectral density (PSD) values at different frequencies.

**Table 5: Operation vibration**

<b>Frequency (Hz)</b>	<b>Power Spectral Density (<math>g^2/Hz</math>)</b>
20	0.051
80	0.800
100	0.800
190	0.117
2000	0.011

## **Virtual Reliability Assessment**

Life-cycle assessment is used to identify potential failure sites, damage mechanisms and failure modes, based on the product architecture and life-cycle loads. This step includes a stress, damage, and life assessment.

### Stress assessment

Environmental and operational loads are applied to captured hardware design to determine if there are any high stress areas that might require evaluation. During the stress assessment global loads (loads on whole Circuit Card Assembly) are transformed into local loads (loads on components), which are then used to evaluate the stress condition for each component and determine the potential failure sites. Thermomechanical stresses and deformations are the major contributors to interconnect failures. Thermal stresses are usually associated with mechanical (structural) failures (e.g., ductile rupture, brittle fracture, creep, stress relaxation, thermal shock, stress or corrosion). The load transformation as performed in calcePWA takes environment, architecture (board and components), power and heat dissipation (components) as input and produces the stress fields

Thermal - Thermal analysis in calcePWA is based on the control volume theory and uses a finite difference approach. The thermal analysis program automatically discretizes the board, based on the number of layers through the thickness and grid size specified on the planar surface of the board. The discretization process creates a three dimensional matrix of the nodes representing the cubic sections of each layer. Thermal resistances for each node are based on the layer material and the material inserts within the region defined by individual nodes. When the thermal analysis is performed, the program calculates the node temperatures for each layer. The temperatures for which boards are modeled were assumed to be uniform boundary conditions along all the edges.

Vibration - In calcePWA vibration analysis tool, the PWB is divided into a number of Kirchoff plate elements (elements with three degrees of freedom, out of plane displacement, and rotation about both in-plane axes). The stiffness matrix and the consistent mass matrix of each material are determined using material properties information and variational methods. Once the global stiffness and the mass matrices are calculated, the natural frequencies and the mode shapes are determined using eigenvalue and eigenvector extraction techniques. The boundary conditions are based on how the boards are fastened to the whole unit. The Electronics Interface board was fastened at 8 points by screws to the unit; those 8 points were taken in calcePWA as simply supported boundary conditions. Any connector present on the board was modeled as simply supported section across the complete connector length. The components near locations of maximum curvature have the maximum vibration induced stress.

### Damage and Life Assessment

The damage assessment utilizes the stress conditions determined in the stress assessment and calculates the reliability of the failure site based on the failure mechanisms. The calcePWA simulation results give the degradation in terms of damage ratio (DR). DR is ratio of applied cycles ( $N_{\text{applied}}$ ) to the estimated number of survivable cycles at the current exposure level ( $N_{\text{life}}$ ).

When the damage ratio reaches one, failure occurs. Hence  $(1 - DR)$  gives the fraction of life remaining assuming the presence of similar life-cycle loading conditions. Parts having highest DR for each of the four boards are shown in Table 6.

**Table 6: Interconnects of parts having highest Damage Ratio for each of the four boards**

Unit - Board	DR for 1 <sup>st</sup> 20 years (with qualification)	DR for subsequent 20 years	DR for 40 years
SPA - Power Switch Driver Off board	0.017	0.009	0.026
SPA - Electronics Interface board	0.038	0.003	0.041
EEEU - Logic & Commutation board	0.089	0.014	0.103
EEEU - Power Conditioner board	0.016	0.008	0.024

### PHYSICAL ANALYSIS OF ASSEMBLIES

Physical analysis gives an opportunity to evaluate other damages and deteriorations that may be caused by the environmental effects not accounted for in the virtual remaining life assessment. Physical analysis of assemblies was conducted through visual and optical inspection of the boards and interconnects.

Visual Inspection was performed in accordance with military and space requirements at the time of manufacture and current industry standards (ref. [12]-[15]). Boards (Electronics Interface and Power Switch Driver Off) along with their components from analog SPA underwent visual and optical inspections. Emphasis was placed on board edges, base material, solder joints, connector pins, plated through holes, solder resist, dimensional characteristics, coatings, component damage, bow and twist, and component mounting/securing.

## **Teardown**

Teardown was performed to disassemble the SPA unit and access the boards for inspection. During this process the feasibility of assembling the unit together was analyzed, to identify the constraints that exist if the units were to be upgraded by replacing some items or performing some rework. It was observed that conformal coating was covering the boards and components, wires were bundled together and attached to the board with adhesive, physical working dimensions were limited and adhesive was used to secure the parts to the boards. The spacing between the boards and from the edge of the boards to the sides of the unit was limited. Parts were bent due to lack of spacing between individual boards and there was an instance of the board being drilled through to accommodate a part. The disassembled SPA unit after teardown is shown in Figure 7.

A NATO study had found that life extension is sometimes possible through “replacements” and rebuilds” (ref. [16]). However, in this case, any life extension methodology that requires repair and upgrade is not recommended for several reasons including the difficulty of possible repairs due to limited physical working dimensions. Replacement of failed or degraded parts with original parts is also not feasible due to the obsolescence of a large number of parts in the last twenty years.

## **Board Inspection**

During the board inspection process the hardware was checked for surface imperfections, conformal coating coverage, solder mask quality, subsurface imperfections, imperfections in the conductive circuitry, visible discoloration and board warpage. No defects were detected during board inspection for specific areas that the board was examined.

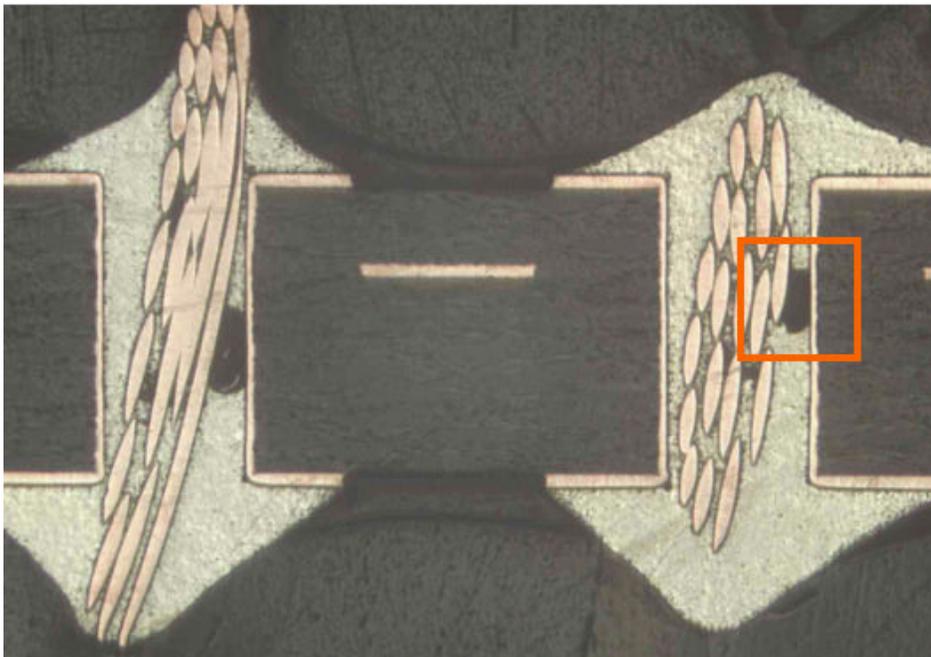
## **Board Cross-Sections**

Cross-sectioning was performed on the two SPA boards (Power Switch Driver Off and Electronics Interface). The defects that were observed in the cross-sectioned areas of the board were attributed to manufacturing errors, and not to wearout failure mechanisms. It can be concluded that the presence of these manufacturing defects did not adversely affect the operation of the boards because this SPA performed without failures for all the missions it undertook. Some of the manufacturing defects that were observed using optical microscope are:

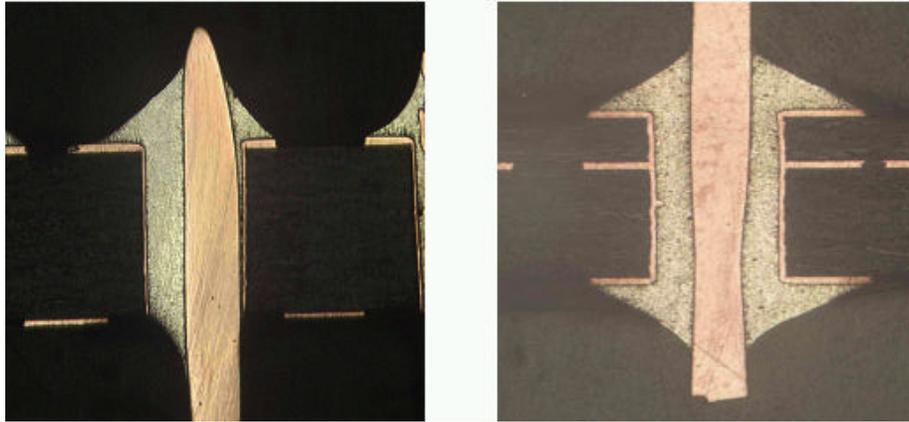
- voids in solder joints (Figure 8)
- pin misalignment (Figure 9)
- nodules (small lump of copper) in the plated through hole (PTH) walls (Figure 10)
- copper foil thinning
- separation between PTH wall and fiber/resin matrix interface
- poor solder joint fillets
- cracks at solder/PTH interface



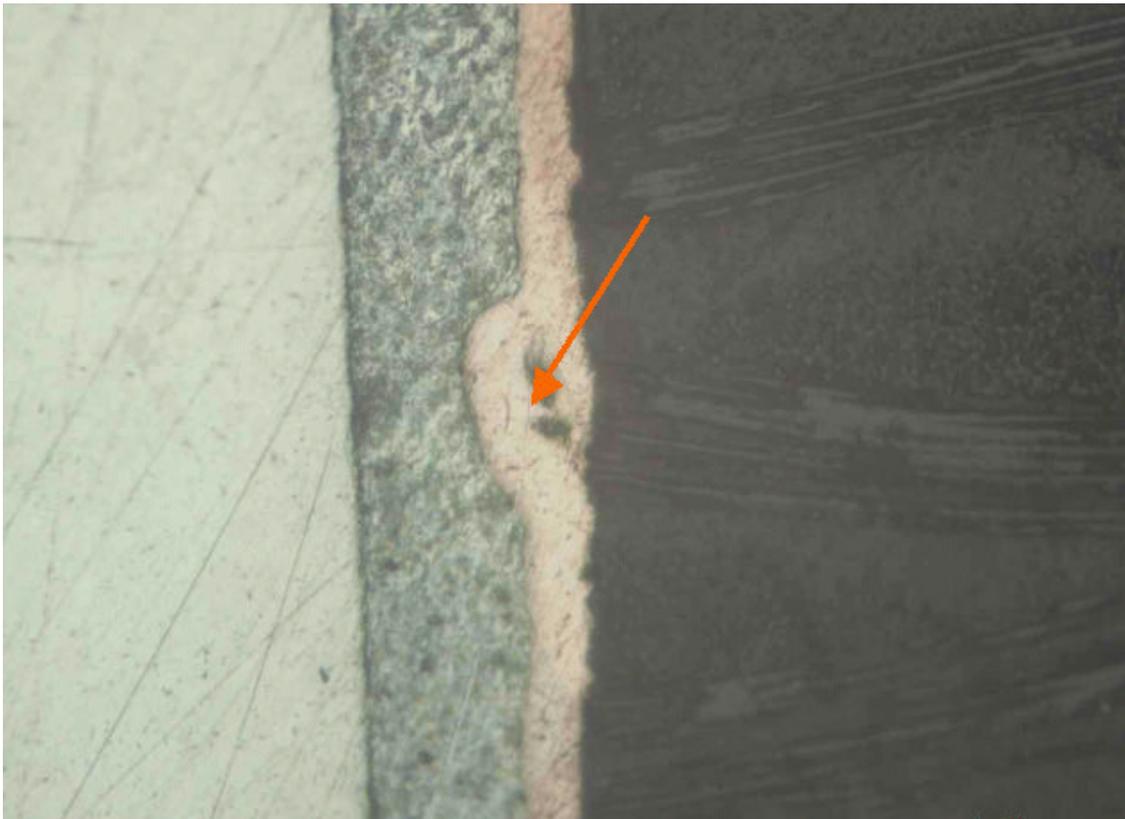
**Figure 7: Disassembled SPA unit after teardown was performed**



**Figure 8: Location of voids as seen in the highlighted portion of the solder of the PTHs**



**Figure 9: The cross-sectional photo on the right shows good pin alignment in the PTH. The PTH on the left shows the example of bad pin alignment. It is closer to the right side, causing a large difference in the size of the solder fillets.**



**Figure 10: Nodules in the plated copper walls of the PTHs**

### **Component Inspection**

Component inspections were conducted in the areas of solder paste application, part alignment, part appearance and soldered interconnections. No defects were observed in the areas for which the components were examined.

## **Destructive Physical Analysis of Critical Components**

Destructive physical analysis was conducted by cross-sectioning two tantalum capacitors and two transformers. Each component was visually inspected using a low magnification microscope (10 - 50 X) and electrically tested. Since the transformers could not be removed from the board without damage, they were inspected on the board while the capacitors were inspected after removal from the board. The components were then potted in a room-temperature cure epoxy resin to prevent chipping or edge rounding during cutting, grinding, and polishing. After curing the epoxy resin, sections of interest were cut out with a liquid cooled diamond edge-sectioning saw and then ground and polished. Micrographs of the polished cross-sections were taken using optical (15 to 1000X) and/or environmental scanning electron microscopy (ESEM) (used when larger magnifications or higher resolutions were required). The results of destructive physical analysis did not reveal any degradation problems for the capacitors and transformers.

## **CONCLUSIONS**

Based on the visual inspection, the PWB assemblies have not suffered from failure mechanisms normally incurred during storage, such as electrostatic discharge (relatively large metallization lines and conductor spacing), corrosion due to moisture ingress (no defects in conformal coatings of board and components), fatigue or cracking due to thermal excursions (no cracks, chips or nicks on board, parts or interconnections), or damage from shock and vibration (due to how the parts and boards are secured).

The printed wiring boards are robust due to conservative design rules, however the quality of boards' manufacturing is significantly below that of current processes. No failures occurred during the operation of the SPA, hence it can be concluded that presence of manufacturing process indicators did not affect the reliability of the boards. When viewed by the naked eye or low magnification (up to 25X), no defects were observed in any of the boards or components during the external visual inspection, therefore the assemblies meet their manufacturing standards (ref. [12]).

The assessment of the environmental and operational profile reveals that a large majority (>90%) of the unit's time is spent in storage. Simulation using calcePWA found that remaining life of the interconnects is greater than forty years because the damage accumulated at interconnects of the EEEU after twenty years and forty years of use is low – with damage ratio below 0.05 for all parts except one (connector of Logic and commutation board of EEEU unit). Qualification thermal cycling was predicted to be causing the maximum damage for all components in all the four boards for the first 20 years of operation and damage caused by vibration was negligible. CALCE's portion of the remaining life assessment concluded that the printed wiring board assemblies of the EEEU could be extended until 2020 due to the robust design and lack of damage caused to the printed wiring board assemblies.

MD Robotics performed further analyses of the EEEU's reliability for NASA under Change Request 1365, delivering report MDR-RMS-R.2778 Rev A.

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