



# Component Repair Experiment-1: An Experiment Evaluating Electronic Component-Level Repair During Spaceflight

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## **Executive Summary**

The Component Repair Experiment-1 (CRE-1) examines the capability for astronauts to perform electronics repair tasks in space. The goal is to determine the current capabilities and limits for the crew, and to make recommendations to improve and expand the range of work that astronauts may perform. CRE-1 provided two-layer, functional circuit boards and replacement components, a small tool kit, written and video training materials, and 1 hr of hands on training for the crew slated to perform the experiment approximately 7 months prior to the mission. Astronauts Michael Fincke and Sandra Magnus performed the work aboard the International Space Station (ISS) in February and March 2009. The astronauts were able to remove and replace components successfully, demonstrating the feasibility of performing component-level electronics repairs within a spacecraft. Several unsuccessful tasks demonstrated areas in need of improvement. These include improved and longer training prior to a mission, an improved soldering iron with a higher operating temperature and steady power source, video training and practice boards for refresher work or practice before a repair, and improved and varied hand tools and containment system.

## **1.0 Introduction**

Future long-duration human exploration missions will be challenged by constraints on mass and volume allocations available for spare parts. Addressing this challenge will be critical to the success of these missions. As a result, it is necessary to consider new approaches to spacecraft maintenance and repair that reduce the need for large replacement components. On the ISS, the maintenance concept for avionics almost exclusively relies on the removal and replacement of entire Orbital Replacement Units (ORU's), with limited removal and replacement of circuit cards when possible. The next step to reducing the size of the items being replaced would be to implement component-level repair. This mode of repair has been implemented by the U.S. Navy in an operational environment and is now part of their standard approach for maintenance. It is appropriate to consider whether this approach can be adapted for application on future manned space missions. The Component-Level Electronic-Assembly Repair (CLEAR) project at NASA Glenn Research Center has begun to explore the logistics, training, and research and development required to provide this capability to future ISS operations as well as missions to the moon and Mars.

There are a number of benefits to in-situ electronics repair during a space mission. Providing a repair capability can help relieve the costs of launching and storing full-sized spares, a significant consideration for any space mission. The ability to perform repairs adds to the flexibility and range of activities available to the astronauts, increasing the ability to recover from faults or damage, or to take advantage of

opportunities such as scavenging used equipment or adapting equipment to a new, previously unforeseen opportunity. However, there are obvious differences between the repair capabilities of a ground-based versus a space vehicle or habitat. Technicians on Earth are well trained and have years of experience, while a crew member typically will not have this focused training and experience. A technician in a lab has access to a wide variety of tools, and is typically not limited in the power and volume or footprint available for these tools; space travel limits tools in both respects. While a consideration on Earth, containment and management of evolved fumes or debris are much more important in the contained, closed-loop environment of a vehicle or module. An in-situ electronics repair plan must account for all of these factors.

A necessary first step in evaluating an electronics repair capability is to determine the current capabilities to conduct electronics repairs. To do this, the CLEAR team developed CRE-1, a Station Development Test Objective (SDTO). CRE-1 has two main goals. The first goal is to demonstrate the feasibility of performing component-level electronics repair tasks during a space mission. This includes understanding which component types and sizes are amenable to manual repair by an astronaut. The second goal of this work is to determine ways to provide and improve an in-situ repair capability, with recommendations for crew training, tools, and ways to expand the types of repairs a crew member could perform during a mission. The next section describes the experiment including circuit cards, replaced components, tools, facilities, and astronaut training followed by the results from the experiment including a visual inspection, a review of the operations and downlinked video, and results from a crew debriefing. This document concludes with a discussion of the results and recommendations for future work and for enabling an electronics repair program for future space flight missions.

## **2.0 Experiment Description**

CRE-1 provided ISS astronauts a set of five realistic circuit boards, three sets of replacement parts, and a small selection of tools commonly used for electronics repair and manufacturing on Earth. These tools supplemented some existing equipment already aboard the ISS as described below. CRE-1, as flown to the ISS, was a scaled-back version of the experiment initially proposed. This initial experiment, described in Appendix A, was reduced in scope to reduce the package volume to allow for manifesting within the tight launch constraints available for SDTOs aboard the Space Shuttle.

### **2.1 Overall Design of Experiment**

The astronauts performed five of the following six tasks normally conducted to complete a component-level electronic repair<sup>1</sup>:

1. Removal of conformal coating
2. Removal of defective component (both destructive and non-destructive)
3. Preparation of board surface for component replacement
4. Placement of new component
5. Soldering of new component
6. Replacement of conformal coating of repaired area

The last step, replacement of conformal coating, was not attempted during CRE-1 as is discussed later in this section.

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<sup>1</sup> In general, the first step to component-level repair is fault diagnostics. This is required to understand what component, if any, must be replaced. Fault diagnostics were not part of the CRE-1 scope; astronauts removed and replaced pre-determined components using hands-on training, written procedures, and video training. The CLEAR project does provide a detailed concept (Ref. 1) for conducting fault diagnostics within the confines of a spacecraft environment.

### **2.1.1 Removal of Conformal Coating**

First, the crew removed conformal coating from the joint area of the circuit board and component legs. A conformal coating is a material applied in thin layers to a circuit board during the manufacturing process. This layer protects the circuit and components from foreign object damage, moisture and humidity, and can help slow flame spread during a fire. This coating must be removed to provide direct access to the soldered joint area. The method for removing the conformal coating varies based on the type of material and can include mechanical methods, such as rubbing, scraping, or sanding with a hand or motorized tool; heating, to melt or decompose the coating material; or using a chemical solvent to dissolve the conformal coating. For CRE-1, the crew used a hand tool (a fiber-glass stick<sup>2</sup>) with a rub and scrape technique to remove conformal coating from the board.

### **2.1.2 Removal of Defective Component (Both Destructive and Non-Destructive)**

The next step is to remove the original, faulty component. There are two general methods for performing this task and both were attempted by the astronauts during CRE-1. First, one may cut the component legs and remove the component, leaving the remaining leg debris in the solder joint for removal during the next step in the process. While simple, this process can cause damage to the circuit board if a leg is not cut completely, and can be difficult when component legs are spaced close together. This process can also make future diagnostic studies of the removed part difficult, as the diagnostic equipment must attach to shortened or removed component legs. Alternatively, a crew member may heat a solder joint or multiple solder joints along one side of the component, and once the solder is liquefied lift the component leg away from the joint area. In CRE-1, all heating is performed using a resistively heated soldering iron, described later. This process is more complicated than simply cutting the component legs, and may damage a circuit board by attempting to remove a leg before the solder completely liquefies, but it keeps the component legs intact for future analysis and may be easier for multi-legged components with closely spaced legs.

### **2.1.3 Preparation of Board Surface for Component Replacement**

The third step is to prepare or clean the circuit board joint area of any leg debris and remaining solder and conformal coating from the original joints. The leg debris may be removed by heating the joint and removing the debris with tweezers or, for surface mount components, wiped with the remaining solder into solder wick. The solder wick is also necessary for through-hole components, to remove the original solder from the through-hole. The crew member must also remove remaining conformal coating, so it does not contaminate the new solder joint or prevent the new component from resting flat on the circuit board surface. Stray particles of conformal coating must also be removed; tweezers or pressing a loop of adhesive tape<sup>3</sup> to the circuit board is typically sufficient for this task.

### **2.1.4 Placement of New Component**

The placement of components in reduced gravity was accomplished differently for through-hole and surface mount device (SMD) components. There were two types of through-hole components: a resistor and a multi-leaded integrated circuit (IC). To reduce crew time needed for conducting the repair, the resistors were pre-bent so that they would fit into the through-holes on the circuit card. For through-hole components, the astronaut first aligns the proper component leg with the correct through-hole, and then inserts all legs fully into the through holes. Sometimes this required slight bending of the component legs. Once inserted, one or two legs (depending on the component type) are bent flush to the circuit board, clinching the component in place. The excess lead length is then trimmed, if necessary, particularly for through-hole resistors.

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<sup>2</sup>Also called a spudger.

<sup>3</sup>When using adhesives, care must be taken to avoid generating electro static discharge (ESD) which can damage components. Special ESD safe tapes were used during CRE-1 which helped minimize this effect.

SMD components were tacked (via soldering) into position using a small amount of solder placed on one of the leads. Again orientation was very important in placing the component properly. The astronaut aligned the proper component legs and circuit board pads, holding the component with tweezers while reheating and flowing the previously placed solder over the component leg, tacking the component in place.

### **2.1.5 Soldering of New Component**

After cleaning the circuit board to place the new component, the astronaut soldered the new component into place. The astronaut added heat and solder to each joint, making a heat bridge, from one side of the circuit board, filling the through-hole and forming a fillet on both sides of the circuit board. For SMD components, the astronaut added a small amount of solder to each of the circuit board pads and legs, soldering each joint one at a time.

### **2.1.6 Cleaning the Joint Area and Replacement of Conformal Coating of Repaired Area**

The final step to performing an electronic repair is to clean the new joint areas and apply a new layer of conformal coating. Cleaning the joint area removes residue from the solder flux used during soldering. Some types of flux, such as rosin active (RA) or rosin mildly active (RMA), are acidic and can, over time, damage the solder joints. The flux residue can, with many conformal coating materials, interfere with the adhesion between the circuit board and coating material. The CRE-1 experiment, however, did not require cleaning the joint area. This was because the solder provided for CRE-1 used a no-clean type of flux; flux residue from this material would not damage the circuit boards or joints, reducing or eliminating the need to clean the joint areas. Furthermore, the manufacturer indicates that conformal coating can be reapplied without any cleaning of the circuit board.

Typically, the cleaning of circuit boards after soldering usually requires large (~100 mL) amounts of solvent, usually alcohol. Managing such a large, free amount of liquid would be very difficult in reduced gravity. In addition, the air handling systems of the ISS can also be damaged by vaporized alcohols. For the ISS, only 1 mL of alcohol can be evaporated daily into the cabin. Nonetheless, the lack of cleaning did not interfere with the validity of the CRE-1 tests, despite these factors.

To complete the repair, conformal coating typically would be reapplied over the new solder joints, legs, and component body, restoring the integrity of the coating and the protections it provided. The coating material selected, and specified in a later section, is thick and viscous, similar to petroleum jelly. Unfortunately, reapplication of conformal coating was not performed during CRE-1 operations. Although part of the original experiment, the conformal coating was eliminated to reduce the mass and volume of the CRE-1 payload. This was an acceptable compromise since the CRE-1 team believed that applying the conformal coating material in reduced gravity would be no different than performing the same process in normal gravity.

## **2.2 Circuit Board Description**

The CRE-1 team provided the crew members five functional circuit boards, such as the one shown in Figure 1. The circuit boards are 3.1 in. long and 1.8 in. wide. Each circuit board has four sections. The first section, in the upper left quadrant of the circuit board, is used to accept and distribute power to the other three, independent sections. The astronauts did not work on this section of the circuit board, and did not power and use the circuit during the mission; it is only used by the CRE-1 team to determine proper function of the circuit board before turning the hardware over before launch, and after receiving the hardware at the end of the mission. The other three quadrants are independent circuits which, when powered and properly constructed, blink a LED at 1 Hz. The first circuit, in the upper right quadrant, is



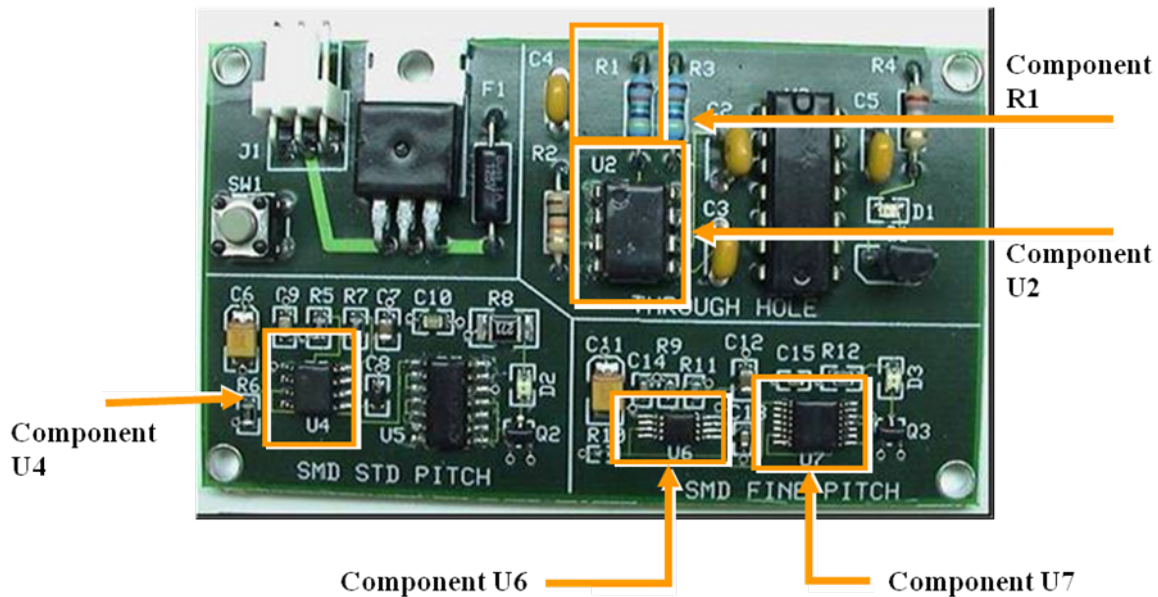


Figure 1.—The CRE-1 circuit board highlighting the five components crew members removed and replaced.

populated with through-hole components. The crew worked on two components in this quadrant: R1, a resistor, and U2, an eight-lead dual in-line package (DIP). The second quadrant used “standard pitch” surface mount devices which had a lead/pad spacing of 0.050 in. between adjacent component legs. The astronauts removed and replaced U4, an eight lead small outline integrated circuit (SOIC) from this section of the circuit board. The third quadrant is populated with “fine pitch” surface mount components, where the pad spacing is 0.025 in. Initially, the CRE-1 team did not plan any crew work with these components. During the course of CRE-1 operations, additional crew time became available and the astronauts attempted to remove components U6 and U7 as this would further the objectives of the CRE-1. Table 1 lists the components worked by the crew, the type of component, and the section of the circuit board where the component resides.

TABLE 1.—COMPONENTS WORKED DURING CRE-1 OPERATIONS.

Component	Type	Location on board
R1	Plated through hole resistor	Through hole
U2	8-pin Dual Inline Package (DIP)	Through hole
U4	8-pin Small Outline Integrated Circuit (SOIC)	SMD Standard Pitch
U6	8-pin Thin Small Outline Package (TSOP)	SMD Fine Pitch
U7	16-pin TSOP	SMD Fine Pitch

The CRE-1 circuit boards are generally typical of those used in other NASA applications, particularly in ISS science payloads. Three of the circuit boards (serial number 1, 2, and 3) have a conformal coating, Dow 3140, with a thickness of 0.004 in. Two of the circuit boards (serial numbers 9 and 10) do not have conformal coating. These uncoated boards were added as “contingency” boards, for use by the astronauts as practice or if they encountered problems removing or working with the conformally coated circuit boards. Ultimately, the CRE-1 team was given enough crew time to add these uncoated circuit boards into the test matrix, providing additional opportunities for the crew to work these tasks. The circuit boards are a two-layer design, meaning the traces connecting the components run along the top and bottom surfaces of the circuit board. This is not typical of circuit boards; most boards have additional interconnecting layers within the circuit board. The original CRE-1 circuit board design used four layers, but the team

learned during ground testing that the 600 °F soldering iron tip available on the ISS did not provide enough heat to reliably reflow solder in the through-holes for removal. Changing to a two-layer circuit board did not present this heat loss issue, at the cost of some fidelity between standard flight circuit boards and the CRE-1 circuit boards.

## 2.3 Tools

The CRE-1 team provided a small tool kit for the crew to use during CRE-1 operations. The tools provided are standard tools used for working with electronics components, and are typically small, with fine points suitable for manipulating the small parts and working areas found in electronics repair. The provided tools expand the capabilities of the ISS Tool Kit, which does not have the small tool sizes needed for this work. A white fabric pouch, shown in Figure 2, stores the tools when not in use. The tool kit includes two sizes of cutters, standard and fine, shown in Figure 3. The cutters were used to cut component legs, solder wick (described later), and solder wire, if necessary. The standard sized cutter was used for through-hole components, solder wick, and solder wire. The fine cutters were used on the standard and fine pitch surface mount devices.

The tool kit also contains three types of tweezers (Figure 4). One type is a standard tweezers, with rounded tips. The second type is curved tweezers with fine tips, and the third is a reverse tweezers with rounded tips. The reverse tweezers open rather than close when the arms are squeezed, and act similarly to a hand-held clamp. Providing different tweezers gave the crew a variety of options, depending on the task at hand and personal preference. All the tweezers had smaller tips than those provided in the ISS Tool Kit, with the curved tweezers tip having fine points.



Figure 2.—CRE-1 Tool Kit, unfolded.



Figure 3.—Standard (left) and fine (right) tipped cutters, part of the CRE-1 Tool Kit.

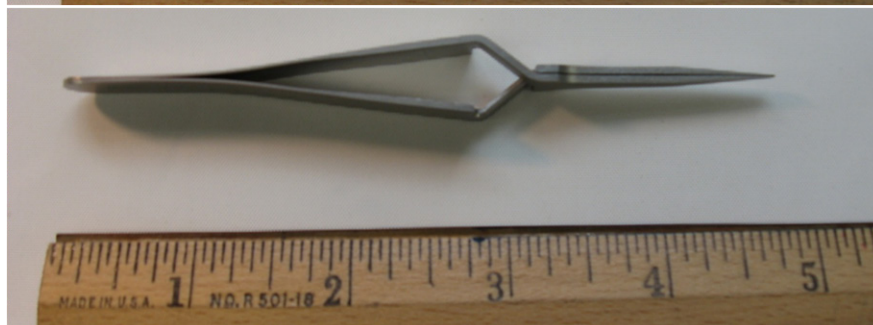


Figure 4.—Straight (top), curved (middle), and reverse (bottom) tweezers included in the CRE-1 Tool Kit.



The tool kit contains a fiberglass stick (Figure 5) which is used to rub the conformal coating off the circuit board and bend or clinch component leads. The dental pick (Figure 6) also cleans conformal coating in tight areas of the circuit board and can be used to help position a component lead on a circuit board pad. The tool kit also contained a spool of standard solder wick, a copper braid used to absorb liquid solder when cleaning the joint area; a small spool of solder wire, a eutectic (63% tin, 37% lead) alloy with Kester 245 no-clean flux core, which has a diameter of 0.015 in.; and a syringe with Kester 958 liquid flux, which is added to a joint area to help remove and clean the original solder.

The final items in the CRE-1 tool kit were two tips (Figure 7) for the U.S. Soldering Kit soldering iron, a Weller PTA6, a 1/8 in. screwdriver tip, and Weller PTP6, a 1/32 in. screwdriver tip. The CRE-1 team provided the larger soldering iron tip to replace a similarly sized tip in the U.S. Soldering Kit. These tips were required for work with the small standard pitch and fine pitch SMD components. Additionally, the existing tips in the U.S. Soldering Kit had shown damage in previous work (Ref. 2).



Figure 5.—Fiberglass stick, used for removing conformal coating, from the CRE-1 Tool Kit.

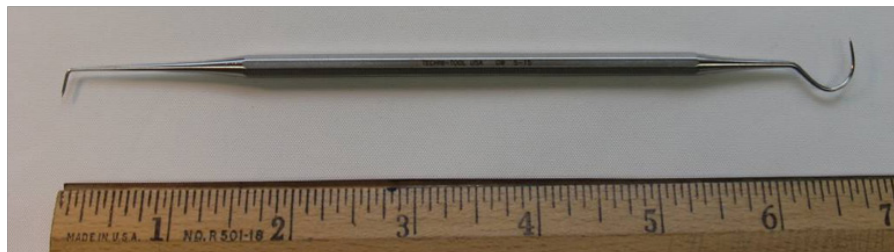


Figure 6.—Dental pick from the CRE-1 Tool Kit.



Figure 7.—Soldering iron tips provided in CRE-1 Tool Kit: 1/32 in. (left) and 1/8 in. (right).

The CRE-1 experiment also used equipment available on the ISS for general repair work and other tasks. This includes the Maintenance Work Area (MWA), a flat table which attaches to wall racks and provides a work space for the crew. Mounting to the MWA is the containment area, a tent-like structure used to contain vapors and debris generated during soldering or other work. The U.S. Soldering Kit contains a soldering wand similar to a Weller TCP12P soldering iron, modified to accept rechargeable batteries as a power source, as well as soldering iron tips, solder, solder wick, and heat sinks not used in CRE-1. CRE-1 also used the circuit board clamp provided with the MWA, but provided a longer vertical rod to improve crew visibility. CRE-1 operations also required use of a vacuum line to remove vapors and debris generated during the soldering process, a 15X magnifying visor to improve visibility for the crew, and a still camera and lab video camera to record the work in progress and provide real-time images and video to the CRE-1 team on the ground, which is discussed below. Figure 8 shows the setup of the MWA and containment area during CRE-1 operations.

During ground testing, the CRE-1 team observed that the clamp holding the circuit board could not be positioned close enough to the viewing port of the MWA containment area. The shaft, along which the clamp can be fastened, was too short. Adequate visibility of the circuit card is important for soldering operations conducted while the containment area is sealed. Therefore, a 12.75 in. aluminum shaft (also shown in Figure 8) was provided with the CRE-1 hardware to allow the board clamp to be brought closer to the viewing port.

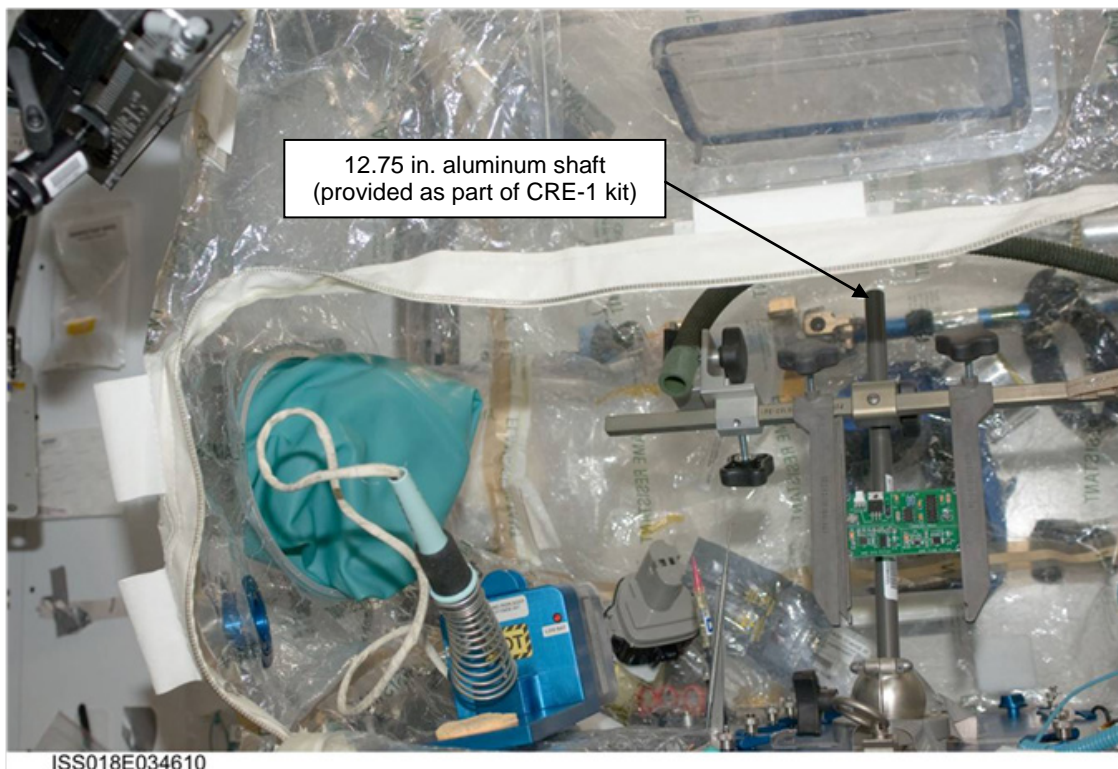


Figure 8.—MWA setup with containment area, soldering iron, and CRE-1 circuit board.

## **2.4 Training**

The CRE-1 team provided a number of training materials for the crew, who did not have prior experience performing electronics repairs. The team prepared a detailed procedure outlining each step in the removal, cleaning, and replacement process for component R1, U2, and U4. The team also made a training video, demonstrating each step for each component. These materials were uploaded to the ISS prior to operations and available to the crew during operations.

Prior to flight, the astronauts received 1 hr of hands-on training in July 2009 (about 7 months prior to conducting the experiment aboard the ISS). The training was based on the written procedures and training video, and led by a NASA electronics technician and instructor. During this training, the crew members practiced all of the necessary tasks for component repair. This includes soldering all of the joint types, though not necessarily completing all the solder joints for a particular component (i.e., soldering four of the eight leads on U4). This limit on practicing the electronics repair skills was dictated by the amount of time available with the astronauts. The astronauts were not shown how to identify flaws in the work and methods to remedy these flaws. These aspects were not covered because rework was discouraged by the team and the limited amount of time available for training preventing lessons on what to look for and how to find the flaws (magnification and still photos, where on the component to look, etc.).

Additionally, the CRE-1 team was able to provide some assistance during crew operations on the ISS. Live downlinked video allowed the team to watch the crew member work, and note their progress and some of the successes and difficulties the crew encountered. This view was limited by the field of view of the camera system, which was too wide to discern fine details of the work. The team could also ask and answer questions to and from the crew, and provide some updated procedures or questions at the end of each day. The crew members also took still photos of the work, both to document the work as it progressed and as a source of magnified views of their work, beyond what the magnifier visor could provide.

## **2.5 Post-Flight Analysis**

One of the key areas of post-flight analysis is identifying areas to improve crew training and tools, and finding the current limits for electronics repair. First, the team inspected the downlinked videos and still photos to determine any problems or successes from the available information. Another key aspect of the post-flight analysis was the inspection of circuit boards returned from operations on ISS. The inspection was carried out by a NASA electronics technician who is qualified for this type of work. The boards were inspected using a bench microscope (20-100 X magnification), typically used for populating and inspecting circuit boards. The technician determined if the work passed the NASA Standard 8739.3, Soldered Electrical Connections (Ref. 3). For joints that did not pass the standard, the technician also noted if rework would be required to make the solder joint functional, or if the joint is functional as-is. In addition, the CRE-1 team debriefed the ISS crew members, asking both general and specific questions based on observations during the flight operations as well as those based on results of ground inspections of returned circuit boards. Finally, select solder joints were analyzed for void defects (Ref. 4).

## **3.0 Results**

Component Repair Exp-1 (CRE-1) experiment was launched to the ISS on November 14, 2008, aboard the Space Shuttle Endeavor as part of STS-126. Operations took place during Increment 18 from February 19 to March 2, 2009. The five circuit boards were returned to Earth on March 28, 2009, aboard the Shuttle Discovery after completing mission STS-119.



Figure 9.—Astronauts Michael Fincke (left) and Sandra Magnus (right) work on CRE-1 during Expedition 18.

### 3.1 Operations Summary

The following section describes the activities of Astronauts Michael Fincke and Sandra Magnus while performing CRE-1 operations on-board the ISS from February 19 to March 2, 2009. Figure 9 shows a photo of each crew member working on CRE-1 aboard the ISS. The following sections list, day by day, the operations conducted on that day, with some notes on the amount of time required for various tasks and comments made by the crew or noticed by the ground team during the video downlink. Each section ends with a table listing, for that session, the component worked on, the type of work done, and an estimate based on downlinked video of how much time those tasks required. The durations of the tasks are important to future mission planners. More detailed descriptions of each day's activities may be found in the Appendix B.

#### 3.1.1 Day 1, February 19, 2009

Michael Fincke began operations by installing and configuring the ISS and CRE-1 equipment needed for the work, including the Containment Area, Soldering Kit, and other tools. After completing these tasks, he began work on CRE-1 Board 1. Table 2 shows a summary of the tasks completed and estimates of the time required to perform the work. The CRE-1 team took the time estimates from the video downlink of the activities. Loss of Signal (LOS) periods required several activities to be grouped together for these time estimates.

Astronaut Fincke completed the removal and replacement of R1 and the removal and cleaning of U2 during the allotted time. He also commented after the work that soldering in reduced gravity took longer than in normal gravity training, and he worked on various techniques for positioning the soldering iron tip and solder on the circuit board.

TABLE 2.—TASKS COMPLETED ON BOARD 1, DAY 1

Component under work	Tasks completed	Time to complete, min
R1	Conformal coating removal; Component removal; Solder removal	35
R1	New component placement and soldering	10
U2	Conformal coating removal; Component removal; Solder and conformal coating removal begun	35
U2	Solder and conformal coating removal completed	25

### 3.1.2 Day 2, February 20, 2009

Michael Fincke continued working on Board 1 during this session. Prior to beginning work, he commented that the batteries used with the Soldering Kit were not charging properly. He also commented on molten solder flowing differently in reduced gravity, with the solder not flowing as freely as in normal gravity training, requiring him to develop his own techniques in reduced gravity.

During this session, Fincke completed the replacement of U2, and removed and replaced U4. He also found a charged battery for use with the soldering kit. Table 3 shows the time required to complete these tasks.

TABLE 3.—TASKS COMPLETED ON BOARD 1, DAY 2

Component under work	Tasks completed	Time to complete, min
U2	Insert new component; Solder 3-4 joints	15
U2, U4 (other tasks)	Solder remaining U2 joints; Remove U4 conformal coating; Remove U4; Begin cleaning U4 pads (find good battery, take still photos of U2)	30
U4	Clean U4 pads; Solder new U4 on board 1; Take photos, resolder a U4 joint	25

### 3.1.3 Day 3, February 23, 2009

Prior to beginning the session's work, Michael Fincke commented that using a good battery helped in the soldering process, and that he was using the ISS still camera to both document his work and as a magnification and joint inspection aid. During this session, he removed and replaced components R1, U2, and U4 from Board 2. Fincke changed the order of operations, working task by task (removing conformal coating from all three components, for example) rather than working one component at a time. With extra session time, the CRE-1 team recommended that Fincke attempt removing U6 and U7, tasks which are outside the original scope of CRE-1 but would provide information on small components with closely spaced component leads. The ground support team recommended using the same technique for removing U4—cutting the leads then cleaning the solder and leg debris—for U6 and U7. Fincke attempted this, and commented that it was difficult to cut one lead at a time, and must cut two or three leads at a time due to the size of the fine cutters. This led to damage to one of the lands on U7, and Fincke commented that components U6 and U7 were at the limit of his capabilities. Table 4 lists these tasks and the time required to complete them. With still more time remaining, Fincke then worked on Board 9, removing and replacing components R1 and U2; Table 5 lists the time required to complete these tasks.

TABLE 4.—TASKS COMPLETED ON BOARD 2, DAY 3

Component under work	Tasks completed	Time to complete, min
R1 and U2	Remove conformal coating; Remove components; Clean solder and remaining conformal coating	110
U4	Remove conformal coating; Remove components; Clean solder and remaining conformal coating	25
R1	Solder new component	9
U2	Place and solder component	22
U4	Place and solder component	14
U6	Remove conformal coating; Remove component; Clean pads	34
U7	Remove conformal coating; Remove component; Clean pads	43



TABLE 5.—TASKS COMPLETED ON BOARD 9, DAY 3

Component under work	Tasks completed	Time to complete, min
R1, U2	Remove component; Clean solder and leg debris; Replace component	39

### 3.1.4 Day 4, February 24, 2009

Astronaut Sandra Magnus worked on Board 3 during this session and this was her first session of CRE-1. She removed and replaced R1, U2, and U4. While removing the original U4 component, the astronaut pulled three pads from the circuit board. During operations, the team speculated that the pads were pulled during removal of the component. This was later confirmed by ground inspection (see App. C.3). Subsequently, Astronaut Magnus soldered the new U4 in place with the circuit board as-is, using only the five remaining circuit board pads. Table 6 lists these tasks and the time needed to complete them. During the process, Astronaut Magnus commented that the molten solder tended to wet and stay near the iron tip, rather than flow onto the pad area on the circuit board.

TABLE 6.—TASKS COMPLETED ON BOARD 3, DAY 4

Component under work	Tasks completed	Time to complete, min
R1	Conformal coating removal	25
R1	Component removal; Solder removal, further cleaning	29
R1	Insert, solder new component	14
U2	Remove component; Remove conformal coating	20
U2	Remove leg debris; Remove solder; Remove remaining conformal coating	55
U2	Insert, solder new component	14
U4	Remove component; Remove conformal coating	13
U4	Remove solder and leg debris	12
U4	Solder new component	21

### 3.1.5 Day 5, February 26, 2009

Michael Fincke complete work on Board 9 during this session, removing and replacing U4. With additional time remaining, he then removed U6 and U7, trying different techniques to remove the components compared to his previous work. The astronaut heated each original solder joint and lifted the leg out of the molten solder, using the dental pick. This process led to a damaged circuit board lead on U6. This process was repeated on one side of U7, but on the other side, all leads were heated and lifted at once, with some success. Again, the lead spacing on U6 and U7 were difficult to work with using the tools and methods provided. Table 7 list the time used to complete each task.

TABLE 7.—TASKS COMPLETED ON BOARD 9, DAY 5

Component under work	Tasks completed	Time to complete, min
U4	Remove component	5
U4	Clean leg debris and solder	5
U4	Attach new component (including still photo inspection and resoldering one joint)	18
U6	Remove component	10
U7	Remove component	20

### 3.1.6 Day 6, March 7, 2009

During this final session for CRE-1, Sandra Magnus worked on removing and replacing R1, U2, and U4 on circuit board 10. Table 8 lists each task completed and the time required for the task. The session was successful in attempting and completing this work, with the use of still camera images to check and retouch new solder joints on U2. During voice communications Astronaut Magnus mentioned that forming new solder joints for U4 required positioning the soldering iron tip at the far end of the circuit board pad, and positioning the solder wire near the component leg, which worked with some success.

TABLE 8—TASKS COMPLETED ON BOARD 10, DAY 6

Component under work	Tasks completed	Time to complete, min
R1	Remove component; Clear solder; Insert new component	18
R1	Solder joints	18
U2	Remove component	4
U2	Remove leg debris	4
U2	Remove solder	15
U2	Solder joints	13
U4	Remove component	6
U4	Clean pads	6
U4	Solder new component	19

## 3.2 Inspection results

On April 30, 2009, CRE-1 team members, including the team electronics technician, inspected the CRE-1 circuit boards used during ISS operations by Astronauts Michael Fincke and Sandra Magnus. This inspection followed an inspection of the still photos taken by the crew and the down linked video of ISS operations by the electronics technician. Inspecting the circuit boards required the use of a standard bench inspection microscope, with magnifications varying from 7X for general inspection to 20X for close inspection of specific joint features. The visual inspection focused on the requirements of NASA Standard 8739.3, though the notes also indicate if the solder joint would be functional, if not meeting the specification. In addition, a power supply set for 9 VDC, 100 mA output provided power to the circuit boards to test the circuit operation; the integrated ammeter in the power supply provided an estimate of the peak current used in the circuit.

Table 9 summarizes the results of a visual inspection and functional test of circuit boards 01, 02, and 03 (boards with conformal coating) and Table 10 summarizes the visual inspection and functional test results for boards 09 and 10 (boards without conformal coating). Each table lists the components worked for each board, and if the component is functional, if it passes inspection based on NASA Standard 8739.3, and if further rework is necessary. Components are judged to be functional if the LED for that section of the circuit blinked in the correct pattern. Examining components to the NASA Standard 8739.3 indicates that the work is of the same quality that technicians and engineers must meet for flight hardware, and is judged based on the geometry and surface finish of the new solder joints. The rework comment indicates if, after failing the NASA Standard 8739.3 visual inspection, further work is necessary for the component to be functional. For example, component R1 on Board 03 failed the visual inspection due to excessive solder on the bottom of the solder joint. This failure of the visual inspection, however, does not lead to functional failure, and no further work is needed. For components U6 and U7, NASA Standard 8739.3 does not apply, because those criteria focus on the characteristics of an installed component. Since U6 and U7 were only removed and not replaced, a “N/A” has been used in Table 9 and Table 10.

TABLE 9.—SUMMARY RESULTS OF CRE-1 ISS BOARDS 01, 02, AND 03

	Board 01			Board 02					Board 03		
	R1	U2	U4	R1	U2	U4	U6	U7	R1	U2	U4
Functional?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
Pass 8739.3?	Yes	No	No	Yes	Yes	No	N/A	N/A	No	No	No
Rework?	No	Yes	No	No	No	No	No	Yes	No	Yes	Yes

TABLE 10.—SUMMARY RESULTS OF CRE-1 ISS BOARDS 09 AND 10

	Board 09					Board 10		
	R1	U2	U4	U6	U7	R1	U2	U4
Functional?	Yes	Yes	No	No	No	Yes	Yes	No
Pass 8739.3?	No	No	No	N/A	N/A	No	No	No
Rework?	No	Yes	Yes	Yes	Yes	No	Yes	Yes

Figure 10 shows some of the soldering issues found in the initial inspection. This figure shows both a good solder joint, and a solder joint that failed inspection and would require rework. The good solder joint shows a fillet on the top side of the circuit board, wetting the leg of the component. The second solder joint does not have sufficient solder filling the plated through hole; in practice, this solder joint would require rework to ensure proper wetting of the solder and a functional circuit. Figure 10 also shows some yellow residue on the circuit board near the soldering joints. This residue is believed to be from the flux used in the soldering wick which was not a no-clean type flux. The flux used in the solder and provided in the syringe was no-clean type and did not leaving significant residue during ground bench testing.

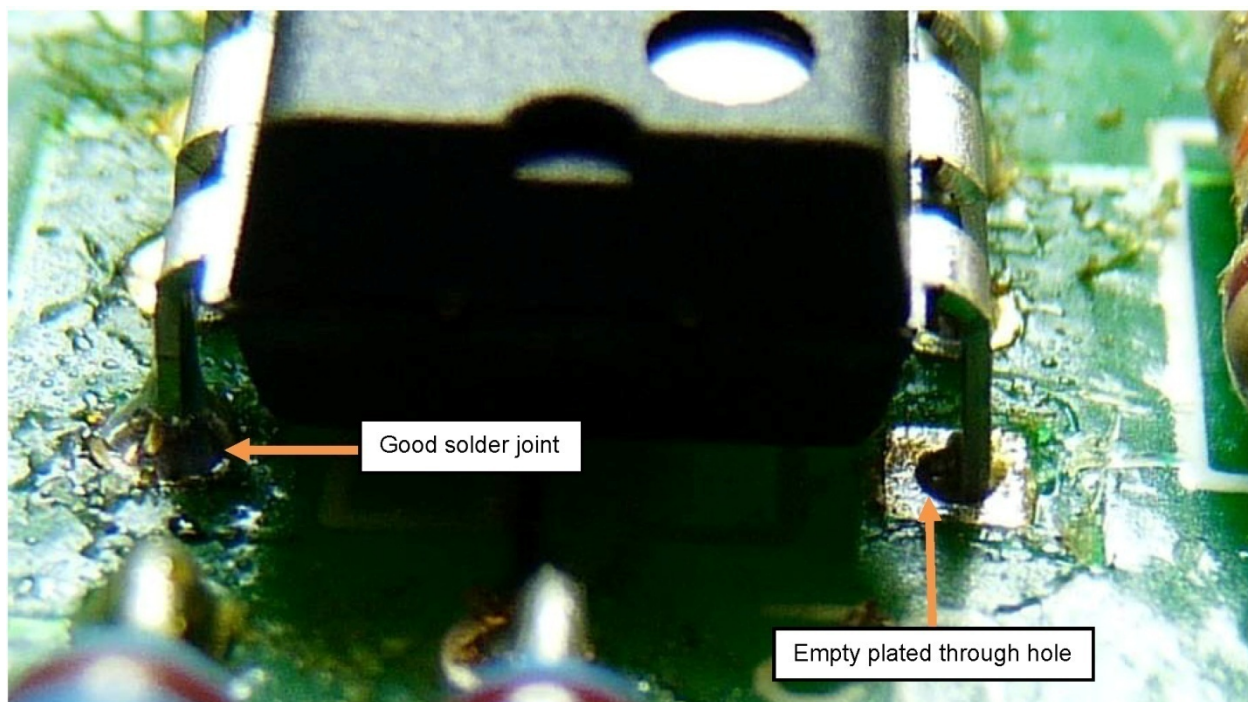


Figure 10.—A good solder joint (left) and solder joint where solder did not fill the plated through hole (right) from Board 01, component U2.

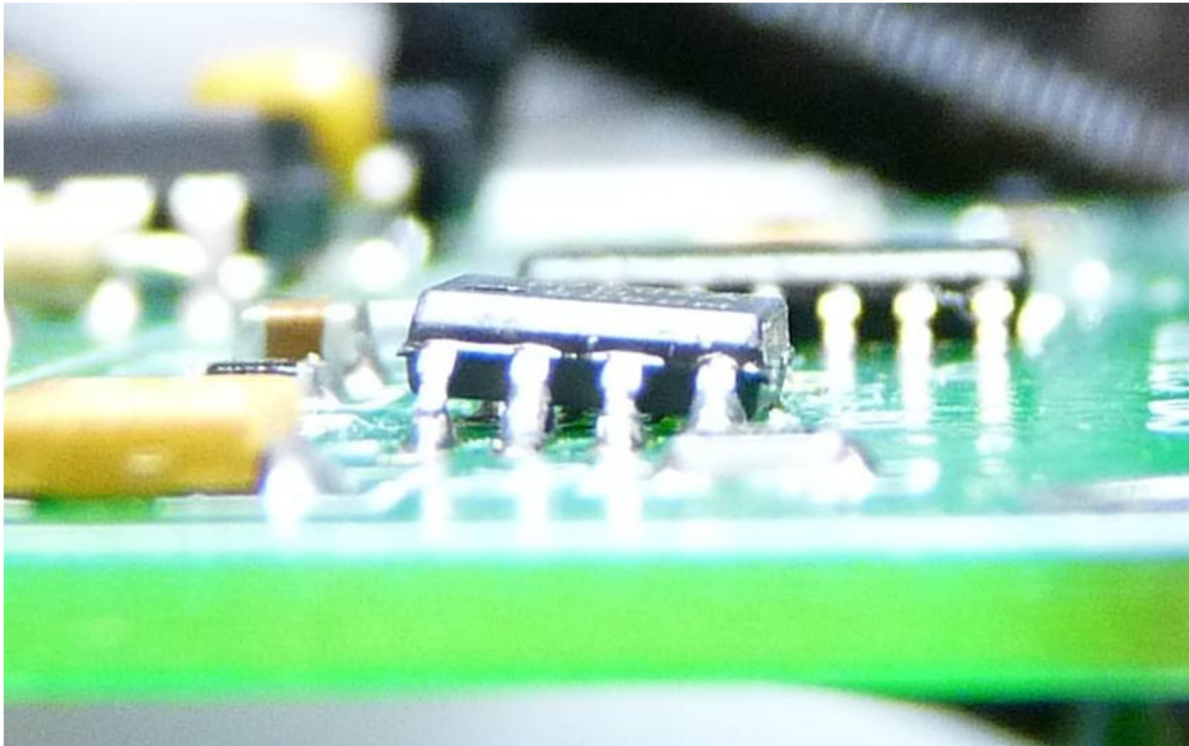


Figure 11.—Component U4, Board 02 where the component legs are not flat on the circuit board pads, but the solder joints bridge from the legs to the pads.

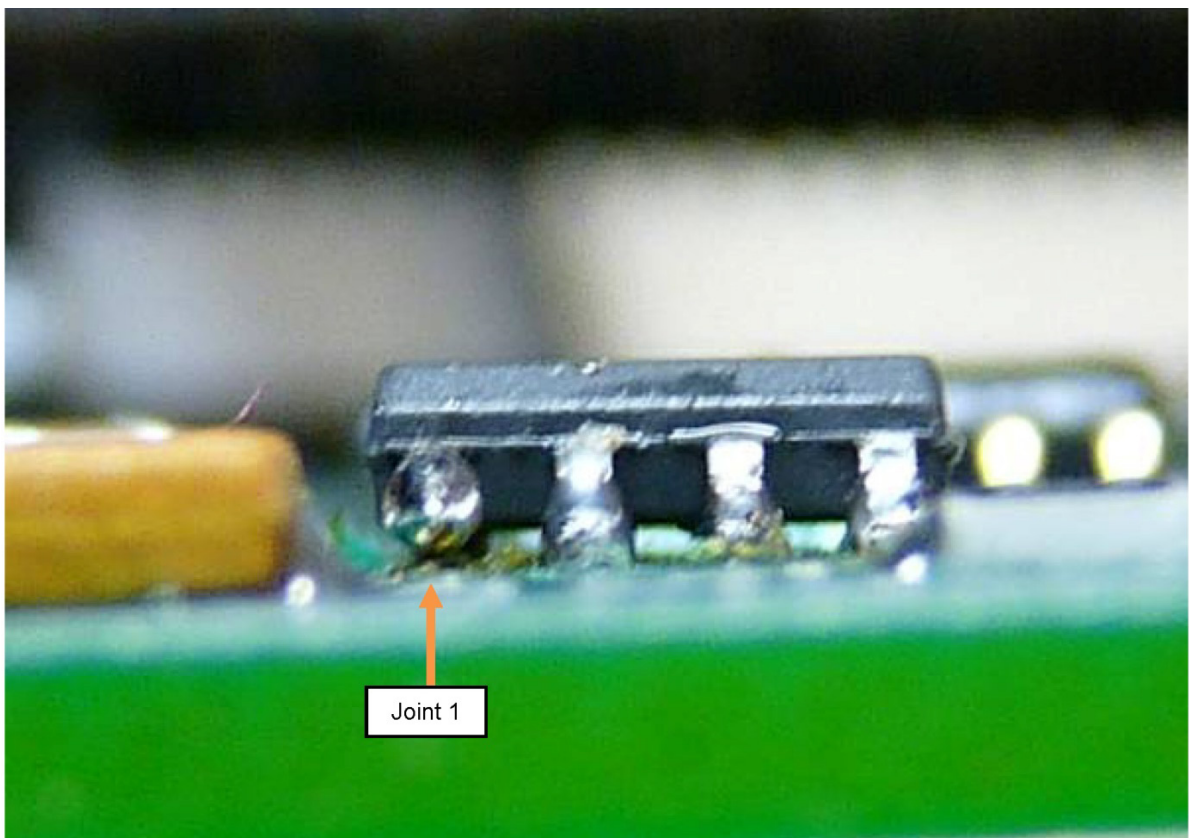


Figure 12.—Component U4, Board 10, again without all the component legs flat on the circuit board pads. In this case, a solder bridge between Leg 1 and pad 1 did not form.



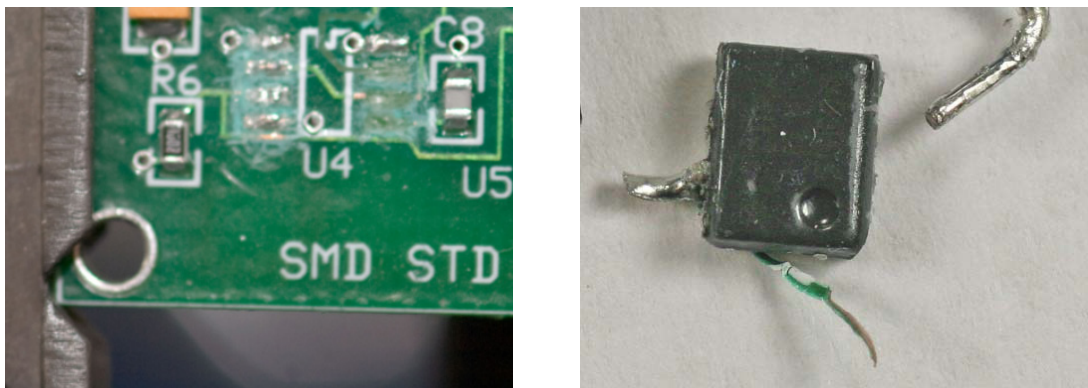


Figure 13.—The area surrounding component U4, Board 03 (left) after removing the original component. There is damage to pads 5, 6, and 7. The pulled leg and circuit board pad, attached to the original component, are seen on the right.

Photos of the original U4 component from circuit board 3 show the cause of the difficulties encountered during that removal and replacement (Figure 13). The returned chip shows circuit board pad and circuit board traces still attached to the original component leads. This indicates that the original leads were not completely cut, and the pads and trace were pulled off the circuit board with the original chip, under the assumption that the leads had been cut. This type of error can occur on the ground, and indicates a lack of experience working with these components and tools, which can only be remedied with practice.

A summary of results for each circuit board may be found in Appendix C.

### 3.3 Crew Debrief Notes

These notes are from the crew debriefing held on May 6, 2009, at Johnson Space Center. Astronauts Michael Fincke and Sandra Magnus were present, as well as John Easton, Peter Struk, and Gary Gorecki from the CRE-1 team at NASA Glenn Research Center, and Blake McCracken, an Operational Support Officer (OSO) at the NASA Johnson Space Center. The crew made general comments about the CRE-1 work, and then answered specific questions, adding comments along the way.

The session began with John Easton briefing the crew on the method of analysis and the inspections conducted to date, and described the results of those inspections. The crew was interested in the results, and generally happy with the results.

When asked about the usefulness of the training, they felt that the hands on training were critical to the experiment's success. They also noted that the general soldering class conducted by OSO was also very useful as a foundation, with the CRE-1 training building on that foundation (author's interpretation of their words).

#### 3.3.1 Question 1

***What components (through hole resistor R1, through hole chip U2, and surface mount chip U4) were easier to remove or replace, and which were more difficult? What made the components easier or more difficult than the others?***

Sandra Magnus felt that the through hole components were easier, as she didn't have to worry about damaging the circuit board pads. They were also bigger than the SMD components, which helped as well. Michael Fincke also commented that U4 was difficult because it was small; if there was a SMD the size of U2—with corresponding pad sizes—then that would be easier to work on. Both crew members said the size issue was the biggest difficulty. Additionally, Magnus felt she was scratching the circuit board during

conformal coating removal, and that was another concern. The visual inspection showed that she did not damage the board during this process, alleviating that concern.

### **3.3.2 Question 2**

*Which tasks (removing conformal coating, or removing solder from a through hole, for example) were easier for you, and which were more difficult? What made these tasks easier or more difficult?*

Both crew members agreed that removing the conformal coating was the most difficult process, and the most time consuming. Fincke felt that removing solder from the plated through hole after removing the component was fairly easy. He also commented that the ESD Safe Tape was not sticky enough to use as a trash collection strip during flight; he simply used the vacuum hose to remove debris.

### **3.3.3 Question 3**

*Can you describe some of the techniques for the various steps in removing, cleaning, and replacing a component you developed while performing the work? We would especially like to hear about the soldering process; both Magnus and Fincke made comments about adapting a technique for forming solder joints.*

Fincke commented that in general the process for soldering in microgravity is similar to the process in normal gravity. The solder flowed a little differently, but it still flowed as expected over pads and through plated through holes. Magnus noted that the solder flow seemed to be a function of how hot she got the joint area. She found she needed to heat the area for a while with the iron—reminding herself to do this at times—or else the solder would ball onto the tip of the iron. She tended to keep the iron tip further away from the solder wire, similar to but exaggerated compared to her process on the ground. She also noted that just as the solder melted, she would remove the soldering iron. Fincke noted that small changes in technique were the difference; using good batteries for the soldering iron helped him (this problem was resolved before Magnus began work on her boards).

### **3.3.4 Question 4**

*How would you compare performing repairs aboard the ISS versus on the ground?*

Fincke commented that operating in space was not a big factor; all he needed was small technique changes. Magnus noted that she would work faster on the ground than in space, and it was easier to get a good fillet shape on the ground. Both agreed that stabilizing their bodies was not an issue.

### **3.3.5 Question 5**

*Do you have any recommendations to possibly improve any of the procedure steps?*

Magnus used the video exclusively during operations based on Fincke's recommendation, and commented that it would be hard to describe the work in words, that video was much better. Fincke commented earlier that he read the procedures before beginning the CRE-1 work, but did not use them during the work. Both relied on the video, going back and forth from it to the work for refresher frequently during the work. Fincke felt that following step by step procedures would take a long time to do the work. He also commented that the video was broken up in chunks that were a little awkward in practice (talking about putting board away at the end of each component)—he understood why, but suggested that such steps weren't necessary. Both crew members agree that if something broke and they needed to replace a component, the practice should be to make the best training video possible showing tools and operations, and have a section on inspecting the work. Then the crew could take photos, send to Earth, and use ground team evaluations for further work if necessary.

### **3.3.6 Question 6**

***Do you have any recommendations for adding or changing tools? Were there any tools you didn't think helped in the work, and didn't use?***

Magnus would have liked more fine point tools, including a finer tipped solder iron tip. Fincke commented that a better kit was needed so tools didn't float away. More magnification is also necessary, and lighting is very critical (the use of the work light was important). Both crew members used the laptop to zoom in on photos taken during work. This was difficult to do during operations because it interrupted the work flow too much.

### **3.3.7 Question 7**

***Were the written procedures and video helpful? Do you feel that both were essential to successful repairs? Was one better than the other?***

This question was answered earlier in the debriefing, and not asked.

### **3.3.8 Question 8**

***We noticed that the repairs were performed with the MWA opened. Do you feel that the repairs could have been accomplished with the MWA closed?***

Neither crew member wanted the MWA Containment closed; they felt that would be too difficult to work with. Both had the vacuum on continuously. Fincke commented that the only time he saw solder balls was when wiping the solder off the iron tip; he kept the vacuum near the sponge for this reason. He did not see solder balls while soldering. Fincke also commented that he worked with the containment area open during another project, In-Space Soldering Investigation (ISSI) (Ref. 6).

### **3.3.9 Question 9**

***Would you be comfortable performing similar repairs on a critical piece of hardware?***

Both astronauts indicated they would be comfortable performing critical repairs, given a good training video to prepare them for the work and observation by a ground support team watching the work they do live, offering suggestions and critiquing the work. A practice board would be a good idea, using it to figure out techniques. This, coupled with a good training video, would help build skills and perform a dress rehearsal of the repair. The video should explain what can and can't "break" or be damaged, what the crew can and can't do or attempt—let them know where the danger zone is in terms of the work. An example was Magnus pulling a pad on U4—she didn't initially realize that was a possibility. The video should also show what good, effective work and bad work that needs to be reworked should look like.

### **3.3.10 Question 10**

***How helpful was the visor magnifier?***

The crew noted that the visor magnifier was required, and that a better one (with higher magnification) is needed.

### **3.3.11 Question 11**

***Do you have any additional comments, observations, suggestions, or questions for the PIs?***

The crew added comments and observations throughout the debriefing, and are captured in the responses.

### **3.3.12 Question 12 (for Magnus)**

*Regarding component U4, it appeared that the pads were lifted during one of the repairs. Do you think this happened while cutting away the component, or when wicking solder from the joint?*

Magnus believes the pad was lifted off the circuit board while lifting the old component off; she didn't know lifting the pads was a problem. She noted that she used both tweezers and solder wick to remove legs on U4; frequently she could see the leg debris and could pick it off with the tweezers. Magnus commented on the need for finer cutters, and Fincke commented that towards the end of his work he used the fine cutters exclusively. They commented on a need for the right tools, after discussing the limitations of the cutter sizes and solder tip limitations, and on the need for better magnification and better soldering iron tips.

### **3.3.13 Question 13 and 14 (for Fincke)**

*For the fine pitch components that were only removed and not replaced (U6 and U7), please describe your technique. Did you attempt to heat and lift all the legs on one side of the component?*

*What improvements, including tools and training, do you think are necessary to make the removal and replacement of small components such as U6 and U7 feasible?*

Fincke used tweezers and the solder iron to remove the legs of U7. He tried the cutters to cut a couple of legs at once, and may have loosened a pad this way. He commented that direct conversation with the ground would be good, especially for critical work, after discussing the removal method originally proposed at the time of the work (laying the soldering iron tip along all joints on one side of the component). Fincke also commented on the need for proper tools, training, magnification, and lighting. He also commented on not closing the work volume.

### **3.3.14 General Comment**

Generally, the crew found the experiment useful, challenging, and fun.

## **4.0 Discussion**

One of the goals of CRE-1 is to test the limits of current capabilities and to find the improvements required to make in-situ electronics repair a viable capability for future missions. The results of the CRE-1 operations show a great deal of potential for future astronauts to perform low-level electronics repair during a mission. Each crew member was able to remove and replace components successfully, demonstrating that with limited training and tools these low-level repairs are a realistic option for future missions. However, each crew member experienced difficulties with some of the tasks. These problems range from forming solder joints that are functional but do not pass current standards, to failed solder joints and damage to the component or circuit board. The difficulties encountered by the crew point to areas requiring improvement. Further, the crew members were not trained to identify and correct mistakes or flaws in their work, which contributed to the number of components which did not pass a visual inspection to NASA Standards. The results of the CRE-1 work show two main areas for improving an electronics repair capability: improving crew training and improving the tools provided. These areas along with recommended future work are discussed below.

### **4.1 Crew Training**

The CRE-1 team provided the crew with limited training. This included 1 hr of hands-on instruction, a training video showing all steps in the repair process, and detailed written procedures. The training video and procedures were available to the crew during CRE-1 operations, and the crew commented on viewing the video before work as well as reviewing relevant segments of the video immediately before



performing a specific task. While these activities and materials were helpful and key to the successes of CRE-1, they were also too limited and point to a greater need for training to make in-situ electronics repair a viable option for future missions. Ways to improve the training of crew members include: (1) emphasizing the fundamentals of soldering rather than specific tasks, (2) increasing the amount of hands on training, (3) providing reinforcing and task-specific training videos, and (4) ensuring that future crews have at least one person with a background in electronics repairs. These recommended improvements are further described below.

#### **4.1.1 Fundamentals of Soldering**

One area of improvement is in the emphasis of the training itself. The training for CRE-1 was specific for the components used and tasks required. The written procedures and training video presented a step by step process for performing the tasks necessary to remove and replace the specific components, describing how to remove conformal coating from each component or how to cut component U2 from the circuit board and remove the leg debris, for example. While this method contributed to the overall success of the experiment, it did present some limitations to the current work and to future work if this paradigm were used for future operations and repair capabilities. By emphasizing specific tasks and processes, the crew was limited in their ability to anticipate difficulties and required more time to work around those difficulties. Using this training regime would limit future crews to working with a select list of components, or approaching unfamiliar components only by analogy to known tasks and processes. It would also limit future crews abilities to evaluate and correct when necessary their own work (inspection and correction of work are not aspects of the repair process explored in CRE-1).

A different training paradigm focuses on the fundamentals of repair work and soldering; the training would focus on why specific tasks are performed and how the outcome should look and perform, while allowing the crew to practice the specific tasks and methods leading to those outcomes. For example, the training would discuss how a solder joint should look and what this indicates for the mechanical and electrical connection, while training how to achieve this goal. Understanding this basic aspect of soldering, for example, can then be applied to virtually any solder joint a crew member may encounter during a repair. Once the fundamentals of repair are taught, the training can then include more specific techniques, demonstrating how the fundamentals apply to the more specific example. Understanding the fundamentals also prepares the crew for working with unfamiliar components and tasks by providing them a basic set of fundamentals applicable to virtually any situation. For these reasons, the focus of training should change from that used in CRE-1.

#### **4.1.2 Increased Hands-On Training**

A second improvement is to increase the amount of hands-on training the crew receives. While the single hour of time used by the CRE-1 team was sufficient for the specific tasks, it will not be sufficient for a robust in-situ electronics repair program. A longer course, ranging from 4 to 16 hr, would provide a number of benefits. The CLEAR project, working jointly with the US Navy, has made a recommendation (Ref. 4) for an astronaut training course for manual component-level electronics repair including syllabus topics and approximate course durations. The most important aspect of a longer training period is more opportunity for hands-on practice with an instructor present to offer guidance for various soldering techniques. The increased time will also allow for instruction in the fundamentals of electronics repair as discussed, forming a solid foundation for future work in the class and during a mission. The increased time also allows the crew to put these fundamentals into practice by working with a wide range of components, well beyond the components used in CRE-1. The training may also include additional aspects of electronics repair beyond the removal and replacement of components. This includes repairing damage to the circuit board, such as land and trace repair, repair of connectors or jumpers, and other repairs to damage or faults that may occur during a mission.

### **4.1.3 Reinforcing and Task-Specific Training Videos**

An additional aid to in-situ repairs is to provide training materials and practice boards and components for the crew. The crew should have a library of videos documenting the training they have received, as well as videos documenting repair procedures they may not have specific training with, but are within their capabilities and are repairs that may occur. In cases where the crew do not have a training video prior to a repair, ground support teams should produce one and send it electronically to the crew prior to a repair. These practice materials and videos will help the crew maintain proficiency at the repairs, and practice specific tasks prior to conducting the repair. One result from the CRE-1 tests is the crew preference for video training over written procedures.

### **4.1.4 Crew Member With Background in Electronics Repairs**

Future crews should include someone with previous experience in electronics repair tasks. This person's experience could include experience as an electrical or electronics engineer, laboratory or practical experience in another field, and personal work as a hobby or side-interest, but does not require this person to be an experienced, certified electronics technician. Further, the entire crew should be trained as described, with the "experienced" person receiving further training. Training the entire crew can prevent the "experienced" member facing a backlog of repairs, and will increase the flexibility of the crew for scheduling and/or conducting repair activities.

## **4.2 Improved Tools**

The results of CRE-1 point out three broad areas for improving the tools provided to crew members for in-situ electronics repairs. The first area discussed is the soldering iron, and some of the requirements for a new instrument. The next area is in magnification of the work, a containment area, and crew comfort. Finally, additional tools to the ones already provided by the ISS and CRE-1 are proposed.

### **4.2.1 Improved Soldering Tool Set**

The CRE-1 experiment illustrated a number of improvements to the soldering tool set which would make in-situ electronics repair a viable option. The first improvement is providing a soldering iron with higher temperature tips than the 600 °F currently available with the U.S. Soldering Kit soldering iron. Typically, 700 °F is a suitable soldering temperature for most applications. The higher temperature will improve function by providing more heat to the joint area, a critical improvement for a number of reasons. First, modern circuit boards use multiple internal conductive layers. These internal connections allow for simpler design of circuit boards and denser component layouts, but draw heat away from the work area when soldering. The CRE-1 team learned of this problem when designing the circuit boards. The original design of the CRE-1 circuit boards used four internal layers; the relatively cool temperature of the U.S. Soldering Kit did not provide enough heat to overcome loss through the internal layers, leading to the redesign of the circuit boards. Second, higher temperatures will melt the solder faster and reduce the dwell time of the soldering iron on the joint, which improves the joint formation and makes the soldering task easier on the operator. Third, the higher temperature also compensates for the presence of heat sinks or other heat loss paths on a circuit component or board.

In addition to the higher tip temperature, the soldering iron should have a fast recovery time, returning the tip to operating temperature after contact with cold components and joint areas. This will improve the quality of the joints and ease the work of the crew. The soldering iron should also have accurate temperature control, to provide flexibility to the crew for task-specific temperatures and helping to ensure rapid tip temperature recovery time.

Another improvement is to provide the crew a wider range of available tip shapes. A variety of shapes allows the crew to work with a variety of component types and sizes, from wide, flat tips (or channel or box shaped tips) for surface mount devices such as U4 on the CRE-1 board to large, rounded tips for the

through-hole type components such as U2 on the CRE-1 board. Soldering tips of different sizes and shapes would also make the removal of components U6 and U7 easier for the crew.

Another improvement for the soldering iron is to address the power source for the soldering iron. As discussed, the crew encountered difficulties when using the soldering iron in the U.S. Soldering Kit when the rechargeable battery voltage dropped. This is also seen in the tip temperature testing the CRE-1 team performed after the flight. A future soldering iron should be powered from a constant power source (i.e. from the vehicle power system), or operate with improved batteries which hold charge for a longer work time than currently available. Finally, mission outfitters and planners may consider additional, task specific soldering tools. One example is a soldering iron with a vacuum line attached, which rapidly removes solder from a repair site. Additional tools such as this are not required, but could ease the repair task if provided.

Another soldering tool that should be provided is a back plane heater. This heater is placed below a circuit board and radiantly heats the entire board prior to work. Heating the entire board provides a number of benefits. Heating the entire board to a temperature near, but not over, the solder flow temperature requires less heat from the soldering iron, resulting in shorter dwell times with the soldering iron. Heating the entire board also reduces the temperature gradient between the joint under work and the rest of the circuit board, reducing thermal stresses induced during work. The use of a back plane heater also reduces the effects of multiple internal layers and the presence of heat sinks, because the thermal gradient between these objects and the joint under work is reduced. The back plane heater will require more power than operations with just a soldering iron, and require more care by the crew to avoid injury or damage to the circuit board, and it does not relieve the need for higher temperature soldering iron tips with better thermal recovery and control. The use of a back plane heater will make the repair tasks easier for the crew, and help improve the results of a repair task.

#### **4.2.2 Improved Magnification and Containment**

A second area for improving electronics repair tools is in magnification and containment. As noted earlier, the crew felt that the current magnification, a visor magnifier with 15X magnification, limited their capabilities to standard pitch surface mount components such as U4 or larger. The results of CRE-1 in replacing component U4 and removing components U6 and U7 support this statement. Providing improved magnification to the crew will both increase the types of components they may work on as well as reducing the difficulty of working with standard pitch surface mount components.

Two options for providing enhanced magnification are the use of a video system and/or the use of a microscope. Both systems are portable, require power (lighting for both, power for the camera and monitor if video magnification is used), and require some training and experience so the crew becomes accustomed to working by watching a monitor or looking through eye pieces. These magnification systems would be useful in a wide range of repair, operational, and research tasks and would be part of a larger tool kit, not necessarily limited to an electronics repair kit. An additional magnification aid, available to crew now, is the still camera with a macro lens. This lens can focus in on small features in the joint and, with training and reference photos, allow the crew to use still images to judge the quality of a repair and what, if any, additional work is required. This would help improve the end product, but would not improve the ability or ease of the crew to perform the work.

The containment area provided to the crew could also be improved. During CRE-1 operations, the crew left the front panel of the MWA containment area open primarily to allow for better visibility. A solution should be provided which allows both good visibility and containment of debris and fumes. Other factors include comfortable operations for the crew, including the use of the soldering iron, magnification tools, hand tools, and other instruments as required, while keeping the work area closed to contain debris or vapors. The area will need feed through for power, video, a vacuum line, and possibly other instrumentation such as thermocouples. Finally, the containment area should be easy to set up and disassemble (the current MWA requires approximately 30 min to assemble and another 30 min to disassemble).

### **4.2.3 Expanded Set of Hand Tools**

The third general area for improving electronics repair capabilities is to expand the set of hand tools available to the crew. Currently there are very few tools on the ISS appropriate for electronics repairs, which required the CRE-1 team to provide a small tool kit for operations. These tools are typically small, such as the dental tools; small, pointed tweezers; and the two cutters, both of which have smaller heads than those available on the ISS. These tools remain on the ISS for any future use by the crew, but need to be augmented for a robust electronics repair capability. Increasing the amount of tools will expand the capabilities of the crew for handling and manipulating different components, repairing circuit boards, and make tasks easier by using the appropriate tool for a task rather than inappropriately adapting a tool. Note that the tools discussed here are in addition to the soldering tools (including soldering iron tips) and magnification aids already provided.

The crew should have access to a variety of probes or dental tools with varying head shapes and sizes. These varying shapes are used for components with narrow lead spacing, removing various types of conformal coating from a circuit board, and preparing damaged land, trace, and open circuit board areas for repair. Additionally, an electronics repair tool kit should include a variety of cutters, with different head shapes and cutting angles to allow work on a variety of components. The varying sizes are important because small cutters, appropriate for small components, may be damaged when cutting leads or other parts of larger components, while cutters appropriate for larger components may be too big for small components. Varying cutter angles allow crew members to access components on tightly spaced circuit boards and provide cut leads with the appropriate shape for the application. The authors, in conjunction with the US Navy, have developed a recommended set of tools to enable a manual repair capability (Ref. 4).

Additional tools, such as small sized sockets, wrenches, screwdrivers, hex drivers, and similar tools are also necessary. While these types of tools are found in the ISS tool kit, they do not always accommodate the small size parts found in electronics applications. Finally, specialized tools such as forming tools which bend component legs into specific dimensions and configurations, wire strippers, crimping tools, and specialized commercial repair kits for filling in damaged circuit boards and repairing traces and lands will all increase the capabilities of the crew.

## **4.3 Future Work**

Component Repair Experiment-1 demonstrated that with a small set of tools and limited training crew members can perform electronics repair tasks in-situ with a degree of success. This work also demonstrated areas for improvement, ranging from the focus and amount of time training the crew to improvements in the tools and facilities provided for these tasks. The next step is to begin exploring and implementing these suggestions. NASA should expand the training available to the crew, perhaps with consultation with other agencies, to develop an in-situ electronics repair capability. An improved soldering iron will require work to select an existing tool from a vendor or design one, and make this tool compatible with operations within a space vehicle or habitat. Designers should consult with astronauts who have performed repair tasks during a mission for guidance in designing a containment area, and should extensively test it for both containment and human factors considerations. Finally, the tools provided should be augmented for the small, and sometimes specialized, nature of electronics repairs. Adding an electronics repair capability will allow future missions to become more self sufficient, and save mass and volume by replacing a large spares capability with the repair capability.

## **5.0 Conclusion**

The CRE-1 experiment demonstrated the feasibility of astronauts performing electronics repairs during a mission. CRE-1 provided circuit boards, replacement parts, tools, and training to two astronauts, who conducted work on the ISS during February and March, 2009. Both astronauts were able to remove

and replace components on the circuit boards, and one crew member was able to work beyond the test matrix and extend the experiment. The results showed a number of areas that will improve and expand the capability for electronics repairs. Future crews should receive more training prior to a mission, and should have access to training videos and practice circuit boards during a mission for refresher training or to practice specific techniques prior to a repair. An improved soldering iron, with higher operating temperature and more robust power supply will make the repair tasks easier. Increasing the number and type of soldering iron tips available to the crew will expand the types of components that can be repaired. Increasing and varying the hand tools available to the crew will also improve the quality and type of work feasible, as will improving the magnifying and visualization aids and the containment of the work debris and vapors. CRE-1 has shown that electronics repair is feasible during a mission, with the improvements described.



## Appendix A.—Original CRE-1 Kit Design

Due to volume constraints, the flown CRE-1 kit was substantially reduced compared with the original design. The original CRE-1 hardware contained additional spare tools, conformal coating, more circuit boards, and more replacement parts, reflecting a more ambitious experiment. This expanded test matrix included removing a thicker layer of conformal coating, and attempting the removal and replacement of additional standard pitch surface mount devices as well as fine pitch surface mount devices. Two foam trays, which were held together face-to-face by Velcro when not in use, held the various tools, parts, and circuit boards, and is shown in Figure 14 and Figure 15.

The additional tools and conformal coating reflect the original plan, for crew members to replace conformal coating after soldering a new component in place. The conformal coating was Dow Corning 3140. This material was used to coat the original boards, and the crew would apply the material to new solder joints after soldering a new component into place. The tool kit included a second spudger, which the crew would have used to apply and spread the conformal coating material in place. The kit also contained three types of solder: the eutectic, no-clean flux kept in the CRE-1 experiment as well as a 60 percent tin, 40percent lead no-clean flux wire and a 60 percent tin, 40 percent lead wire with no flux core. These other two solders were selected based on previous work (Ref. 2) in mitigating internal void formed during soldering.

The extra circuit boards and parts provided additional conditions for the crew to test. The original kit contained four circuit boards with a thin (0.004 in.) primed layer of conformal coating, four boards with a thick (0.010 in.) unprimed layer of conformal coating, and four boards with no conformal coating. The thick coating generated larger debris when removed, compared to the boards with a thin coating; testing would determine which type of coating was easier to remove and manage debris. Uncoated boards were provided, in the original and flown kits, as contingency boards if the crew encountered problems removing coating or if additional time was provided. The extra parts allowed for testing with a larger variety of components: through hole chips with different configurations (C2, Q1) or more legs (U5); standard pitch surface mount components of different sizes and legs (R5, U5, Q2); and similar fine pitch components (U6, R11, C15, R10), which would also challenge the crew to the limit of visibility and tool size available.



Figure 14.—Top half of original CRE-1 tool kit, containing tools and materials.



Figure 15.—Bottom half of original CRE-1 kit, containing circuit boards and spare parts bags.

Ultimately, many of the circuit boards, tools, and parts were not flown. The expanded test matrix, using the various solder types, conformal coating thicknesses, and component types, was reduced to accommodate limited crew time. Reducing the types of conformal coatings used, components removed and replaced, and solders tested decreased the amount of time necessary to train the crew before flight and the amount of crew time used during a mission. These reductions resulted in the removal of many components, decreasing the mass and, most importantly, volume of the kit, providing an opportunity to perform the experiment on the ISS. The reduced test matrix did not reduce the importance of the CRE-1 SDTO; the crew was still able to demonstrate the capability to perform electronics repairs during mission, and provided insight on the capabilities and improvements towards an in-situ repair capability.



## **Appendix B.—Day-By-Day Operations**

### **B.1 Day 1, February 19, 2009**

Michael Fincke performed operations on this day, setting up the Maintenance Work Area (MWA), the Containment Area (CA), and CA support equipment as well as collecting the CRE-1 Kit, U.S. Soldering Kit, rechargeable batteries, vacuum, and other materials. The poles for the CA were not used during assembly, as the CA held its shape on its own. He also assembled the PC Circuit Board Clamp with the 12.75 in. shaft included in the CRE-1 Kit, with the clamp jaws aligned so the circuit board plane was (almost) parallel to the shaft. After completing these tasks, work began on CRE-1 Board 1, which is a coated circuit board.

Work on Board 1 began by removing the conformal coating from the joints on R1. This task required at least 15 min, followed by a 20 min Loss of Signal (LOS) period. At the end of this period (and 35 min after beginning work) the conformal coating, original R1, and solder from the circuit board through holes had been removed. Fitting a new R1 into the circuit board, trimming the leads, and soldering new joints required 10 min. During this process, the ground team noticed the crew member leaving the soldering iron tip on the joint area for 10 or more seconds; the training, written procedures, and training video recommend leaving the soldering iron tip on the joint no longer than 5 sec.

Following work on R1, work began on U2 with the removal of conformal coating at the start of a 35 min LOS. At the end of this period, the U2 chip and legs were removed and cleaning the remaining conformal coating and solder was in progress. This continued for 25 min; the U2 joints were cleaned and ready for a new component, with the day's session ending.

After performing the work, the crew member provided general comments on the work. Astronaut Fincke noted that soldering took longer in 0g than in the 1g training, and that he was trying various techniques for soldering in reduced gravity. He also commented that the tools are helpful, but need a better way to restrain them in 0g for temporary stowage; going back and forth to the tool kit was cumbersome.

### **B.2 Day 2, February 20, 2009**

Michael Fincke worked on Board 1 again today, with the goal of completing the tasks (replacing U2 and removing and replacing U4) left over from the last session. Prior to beginning, the crew member provided comments on the previous day's work. First, he noted that the batteries used to power the soldering iron were not charging properly; the batteries should recharge in approximately 2 hr, but some had not received a full charge after charging overnight. He also noted that the solder wants to "grab itself" rather than flow more in microgravity than on the ground, and he had to work out slightly different soldering techniques than on the ground, mostly by holding the solder wire further from the soldering iron in 0g than on the ground. These problems may have occurred due to the low power provided by the battery, reducing the tip temperature and making soldering difficult. He also seemed to have difficulties holding the soldering iron tip and solder wire in position in microgravity, compared to ground tests. This day's work began with soldering a new U2 component to Board 1. The crew member completed 3 or 4 joints in 15 min. During the subsequent 30 min LOS Mike completed soldering the remaining U2 joints, removed the conformal coating on U4 as well as the chip, and took still photos of the completed U2 and found a good battery to power the soldering iron. After cleaning the solder pads, the crew member required 20 min to review the procedures and solder a new U4 chip to the circuit board. He used an additional 5 min to take photos of the circuit, and resolder one of the U4 joints.

The ground team sent up a question based on a still photo from the first day's operations, showing conformal coating debris in one of the U2 through holes. The team asked the crew member if he could see to that magnification, and to try and clean the joint areas more thoroughly. He was unable to answer these points today.

### **B.3 Day 3, February 23, 2009**

The day began with Michael Fincke calling down comments based on operations the previous day, as well as a note sent to the ISS based on earlier work. He commented that the solder is flowing differently in 0g than in 1g, and is positioning the soldering wire a little differently. He commented that using a tape loop for debris is difficult, and it is easier to simply allow the vacuum to suck debris from the tool tip (tweezers, dental pick, or fiberglass stick). Using good, charged batteries also helps soldering, and may alleviate problems encountered earlier. He is also going to use the still camera as a magnification aid in addition to a record of work. He is using a 105 mm lens for this work; he used a 70 mm lens for each of the first two days.

The day's work included attempting to remove and replace R1, U2, and U4 on Board 2. The crew member will work task by task (remove all conformal coating from all components, then remove components, etc.) rather than work component by component. In the first task, the crew member removed conformal coating, removed components, and cleaned solder from R1 and U2. These tasks required 110 min, and include making sure conformal coating is removed after removing the component and solder from the original joints, a task influenced by the note sent by the ground team at the end of day 2. The crew member then took another 25 min to clean conformal coating from and remove U4, and then broke for lunch.

After returning, the crew member required 9 min to solder a new R1 into place, noting that the solder flowed through the through hole. After this, he took 22 min to place and solder a new U2 component on the circuit board (including LOS time). He noted in a call down that solder flowed off the soldering iron tip into the plated through hole, and asked why—the ground team did not have a good answer called up. During a 14 min LOS, the crew member began soldering a new U4 component onto the circuit board, and was using the still camera to inspect joints.

During a 20 min LOS, the crew member finished work on U4, then attempted to remove U6. This work is outside the range of tasks for CRE-1, but was added to find the limits of the crew's capabilities and to use the remaining time scheduled for CRE-1. The suggested method of removal is to use fine cutters to cut the legs, similar to the process used for U4. The crew member called down that working on U6 was feasible, but work on U7, the next task, would be more difficult. He used the next 14 min to clean the pads for U6. Note that these times all include taking and looking at still photos, analyzing the images for good solder joints, clean pads, etc. The crew member then spent 43 min cutting and cleaning U7, including taking photos. He commented that the fine cutters did not fit between individual component legs, requiring him to cut 2 or 3 legs at a time. As a result, the lower right pad on U7 was pulled. He felt that working this far with U7 is the limit of his abilities.

With a surplus of time, the crew member then moved on to Board 9, which is not coated. Over the course of 39 min, he removed and replaced R1 and U2 on this circuit board. After performing that day's activities the crew member commented that the soldering process was easier today. He spent more time and attention cleaning the circuit board, and used the still camera as a magnification aid, looking for conformal coating debris and new joint quality.

### **B.4 Day 4, February 24, 2009**

This is the first session Sandra Magnus worked, removing and replacing components on Board 3. She began working on R1, taking approximately 25 min to remove conformal coating, then spending 29 min removing the component and clearing solder. Inserting and soldering a new R1 component required 14 min. The ground team noted that the crew member left the soldering iron on the joint for a long time, as seen in earlier work. After soldering, she commented that the back side of each joint has a nice fillet, but that the solder didn't want to flow through the plated through hole.

The crew member began work on U2 by stating that she will cut the component off before removing the conformal coating; this seemed easier to her, as the component will be out of the way while removing the coating. She spent approximately 20 min completing these tasks. Sandy then spent 55 min removing

leg debris and solder from the plated through holes, a period which included two LOS times, and periods where she was out of the field of view, presumably watching the training video or reading procedures, or conducting other ISS tasks. Sandy then takes 14 min to insert and solder U2 in place. She commented that it was “tricky” removing the conformal coating. She also notes that the solder wets to the iron, instead of flowing to the joint area. The crew member developed a process where she adds a small amount of solder to the joint, moves on to another joint, then comes back and uses the initial solder to help flow new solder and form a joint.

The crew member began work on U4 by first replacing the battery in the soldering iron. This task, with removing the component, required 13 min. After 12 min, the crew member called up that she had removed the original solder from the joints, but had also removed three of the circuit board pads (corresponding with legs 5, 6, and 7). The crew member stated she would use the remaining 5 pads to attach a new component, which was accomplished during a 21 min LOS. At the end of the work, the crew member noted that when removing the U4 legs, she heated the pad and removed the leg with tweezers, similar to the method used to remove leg debris for U2. Her initial guess is that the pads came off with the legs, though she noted that the pads “looked strange” after removing the chip. Photos of the board show that the pads and some of the traces had been removed; the damage may have occurred during chip removal, rather than leg debris removal.

## **B.5 Day 5, February 26, 2009**

Michael Fincke worked a brief, 1 hr session on this day to complete tasks begun on Day 3 with Board 9. His work began with removing U4 from the board for 5 min, followed by removing the leg debris by heating the joint and removing it with tweezers, similar to the method used by Sandra Magnus in the previous session for this component. This task required 5 min as well. The crew member required a further 18 min to solder a new U4 into place. This included re-soldering joint 2, based on a visual inspection using the still camera.

After this work, the crew member began attempts to remove U6 and U7, similar to the work performed on Board 2. In these cases, he attempted to heat the solder joints and lift the legs off the pad on each side of the board, rather than cut the leads. This process began with component U6, but the crew member was attempting to heat one pad at a time with the iron perpendicular to the board, rather than laying the tip along all the joints at once. He is able to heat the solder and use the dental pick to lift one side of the chip up, but may have pulled pads off the board. He then heats the other side of U6, and lifts the component off the board with tweezers. This process requires 10 min. The crew member tried the same process on U7, without success. During a LOS, he was able to wick solder off the pads on one side of the component, and lift each leg off the lead with the dental pick. He then heated the other side at once and lift the chip off. His inspection did not reveal any damage to U7. This process required 20 min, including a LOS.

As a general comment, the crew member noted that working on objects the size of U6 or U7 required improved magnification; working on objects the size of U4 is currently feasible, using a still camera as a vision aid to check work.

## **B.6 Day 6, March 7, 2009**

On this day Sandra Magnus worked on Board 10 (an uncoated board), removing and replacing the primary (R1, U2, U4) components. The work began on R1 during a LOS, and after 14 min had the old component removed, cleared the old solder, and had inserted the new R1 and trimmed the leads. Over the next 18 min, she soldered the two R1 joints, taking photos during the process; it appeared that she soldered each joint multiple times, and that she had trouble keeping the soldering iron tip in place on the joint, which seemed to “slip off” the joint in the downlinked video.

The crew member next worked on removing and replacing U2. She took 4 min to cut the component off the circuit board, then an additional 4 min to remove the leg debris from the joints. This included time

attempting to use the curved tweezers to remove legs, then switching to the straight tweezers with more success. The crew member then spent 15 min clearing solder from the through holes, and then broke for lunch. She returned to work during a LOS; the new U2 component was attached to the board at AOS, ready for soldering. Over the next 13 min, she soldered the U2 joints, using photos to check the joints, reworking joints 1, 2, 7, and 8 during this process. At completion, she commented that she does not have fillets on all the joints. Two joints have solder balls sticking on the joints. She thinks solder went into the plated through hole, but there is no topside fillet. She is leaving the joints “as is” for ground analysis.

The final task for this day is to remove and replace U4. The crew member took 6 min to remove the chip, then an additional 6 min to wipe the pads clean of solder and leg debris. She did this using the technique described in the training materials, wiping the pad with solder wick and the soldering iron tip, rather than heating each joint and plucking the leg off the pad. She then spent 19 min soldering the new U4 onto the circuit board, alternating from one side of the chip to the other when soldering each leg to the pad. She commented at the end of the work that it was hard to tell if U4 was on the circuit board. On the left side of the chip, the solder climbed up the leg during soldering, and commented that a smaller soldering iron tip might be helpful. On the right side of the chip, the middle legs (joints 6 and 7), she used the following technique to solder the joint: she'd position the iron tip near the far edge of the pad, then position the solder wire near the leg, and this technique seemed to work well. She commented that working on the right hand side of the chip was easier than the left, and that she used the 1/32 in. soldering iron tip for all tasks (R1, U2, and U4) during this session.

## Appendix C.—Specific Circuit Board Inspection Results

The following sections describe the results of visual inspection of each circuit board used in CRE-1. These visual inspections were conducted by a NASA certified electronics technician and instructor, using NASA Standard 8739.3 (or “NASA Standard”) as a basis for judging the quality of the work. The inspector also noted when a joint did not pass the NASA Standard, but was never the less functional. The inspection also included a functional test of each circuit board, providing 9 VDC to the power section of the circuit board with a bench-top power supply, current limited to 100 mA. This power supply provided a measure of the current used by the circuit, accurate to 10 mA. The peak current draw is reported with the results of the functional test.

### C.1 Circuit Board 01

The visual inspection for R1 revealed good fillets on both the soldered side and flowed side of the component, passing the NASA Standard criteria. For component U2, all fillets on the soldered side of the circuit board passed inspection as well. On the flowed side, pins 1, 4, 5, 6, and 7 passed the NASA Standard without comments. Pin 2 passed, though no fillet formed; solder in the board through hole is sufficient for passing the NASA Standard. Pin 3 did not pass, with no solder in the board through hole. Figure 10 in the Section 3.0 shows this defect. Pin 8 passed, though no fillet formed on the flowed side of the circuit board. For component U4, generally there was good contact between the legs and the pads with good fillets, though there was excessive solder. While this would not pass the NASA standard, rework would not normally be required. Additionally, the left side (pins 1, 2, 3, and 4) were slightly elevated, with the legs not flat on the pads. Figure 16 shows both the elevated legs and excess solder. The legs on the right side of the component (pins 5, 6, 7, and 8) were flat on the circuit board pads, and acceptable. When powered, all LEDs on the circuit board blinked normally, with a peak current draw of approximately 40 mA.

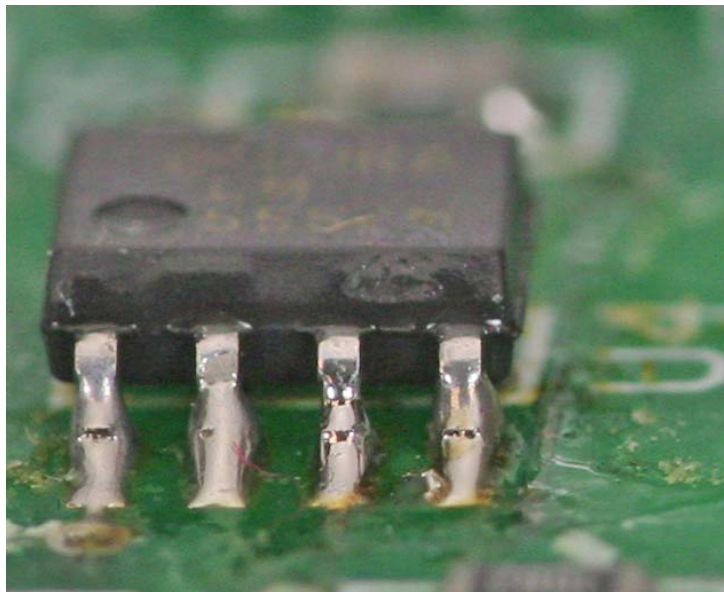


Figure 16.—An image of pins 1 through 4 from component U4, board 01. This images shows both excess solder and the component legs floating above the board. This would not pass NASA inspections, but is usable.

## C.2 Circuit Board 02

Both joints for component R1 passed inspection, as did the fillets on the soldered side of component U2. On the flowed side of U2, pins 1, 2, 3, 4, 5, 6, and 7 passed inspection. Pin 8 on the flowed side of component U2 was acceptable, but on the border of not passing due to insufficient solder, as no fillet formed though the plated through hole is filled with solder. The joints for component U4 were generally good, though all had too much solder. In addition, the part is tilted, with pins 1 and 8 higher than pins 4 and 5, which are flat on the circuit board pads, similar to the results seen for component U4 on board 01. This does not pass the NASA Standard, but the solder joints are functional. The removal of component U6 was acceptable, with no damage seen on the circuit board, as shown in Figure 17. The removal of component U7 did show some damage, as pad 8 was lifted from the circuit board, and other pads showed some damage from removing the component, as shown in Figure 18. The circuit board passed the powered functional test, with the LEDs in the plated through hole and standard pitch surface mount regions blinking as expected, drawing a peak current of approximately 20 mA. The LED in the fine pitch surface mount region did not blink as expected, due to the removal of components U6 and U7.

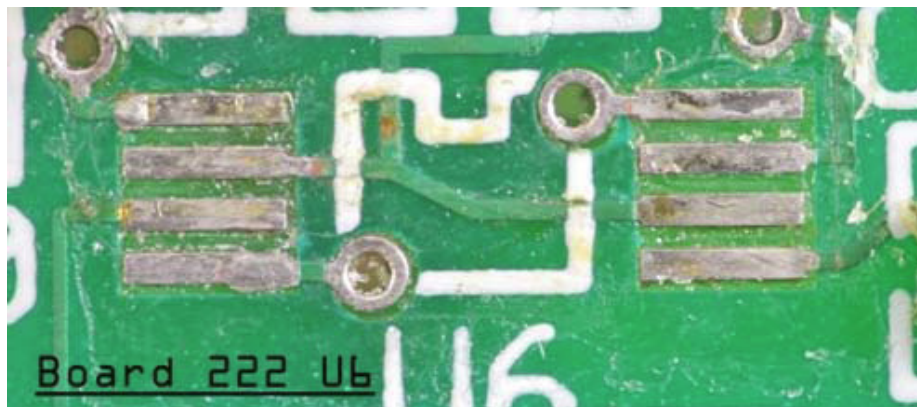


Figure 17.—Removal of component U6 from board 02. The removal was successful, with no damage to the circuit board.

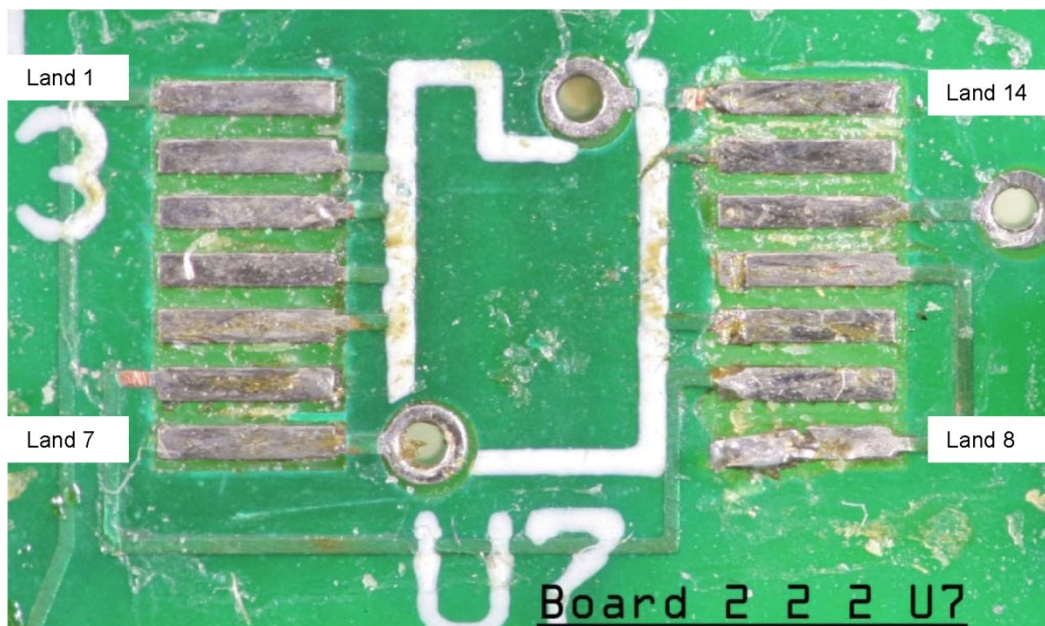


Figure 18.—Lands from removed component U7, board 02. Land 8 shows damage to the land, while lands 9, 10, and 11 show minor damage.



### C.3 Circuit Board 03

For component R1, the flowed-side solder joints show minimal but acceptable solder flow through. The soldered side joints show excessive solder, though possibly acceptable. The joints are functional. The excessive solder on the soldered side and minimal solder on the flowed side is due to insufficient heat to drive the solder through the circuit board and form a flowed side fillet. This is a technique problem and not indicative of a problem with the soldering iron. Figure 19 shows these problems. For component U2, the fillets on the soldered side of the circuit board all passed NASA Standards, though the leads were not clinched (that is acceptable). For the flowed side of the circuit board, pins 3, 4, 5, 6, and 8 passed the NASA Standard. Pins 1, 2, and 7 did not, due to insufficient solder, though the joints are functional. For component U4, pin 1 had solder on the component lead, but not on the pad, while pins 2, 3, and 4 were acceptable but with excessive solder. A trace near pad 4 is exposed, which may have occurred when removing solder. Pins 5, 6, 7, and 8 demonstrated some difficulties, arising largely from removing the original component and cleaning the pads. The pads for pins 5, 6, and 7 were removed from the circuit board, and traces from pads 6 and 7 were also removed. Much of this damage occurred during component removal because the component leads were not fully cut, and the component pulled from the board. Figure 13 shows the area around U4 after removing the component. The pad for pin 5 is still attached to the original component lead. Leg 5 on the original component was not cut completely, and the pad was pulled off the circuit board when removing the component, also seen in Figure 20. This also damaged the trace leading from pad 5, run under the component location. In functional testing, the LED in the plated through hole and fine pitch surface mount regions operated normally, drawing approximately 30 mA. The LED in the surface mount region did not blink normally, due to the issues described for component U4.

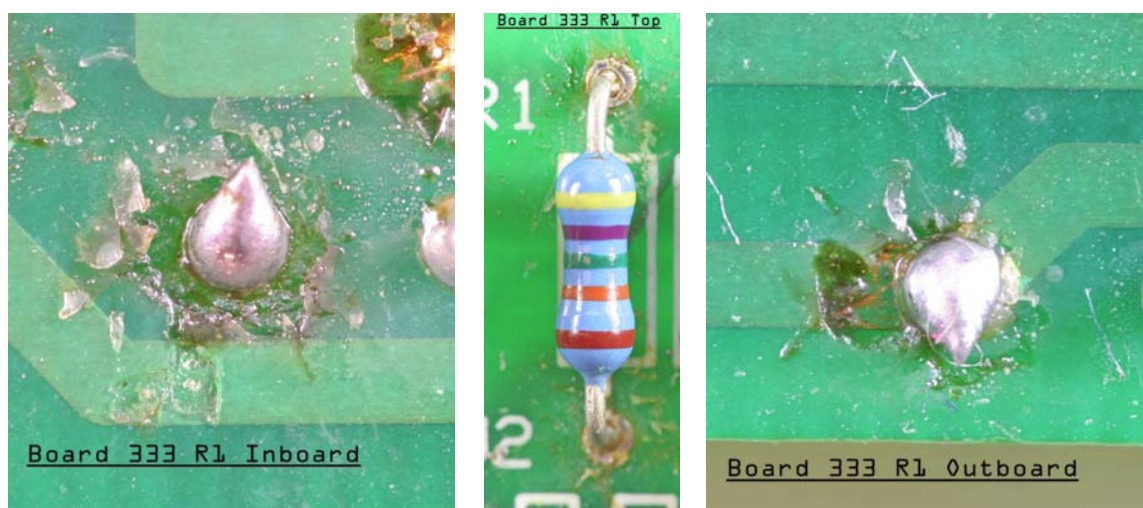


Figure 19.—Solder joints for R1, board 03. The images of flowed side joints (left, right) show excess solder, while the topside joints (middle) show problems with the solder flowing through the through-holes.

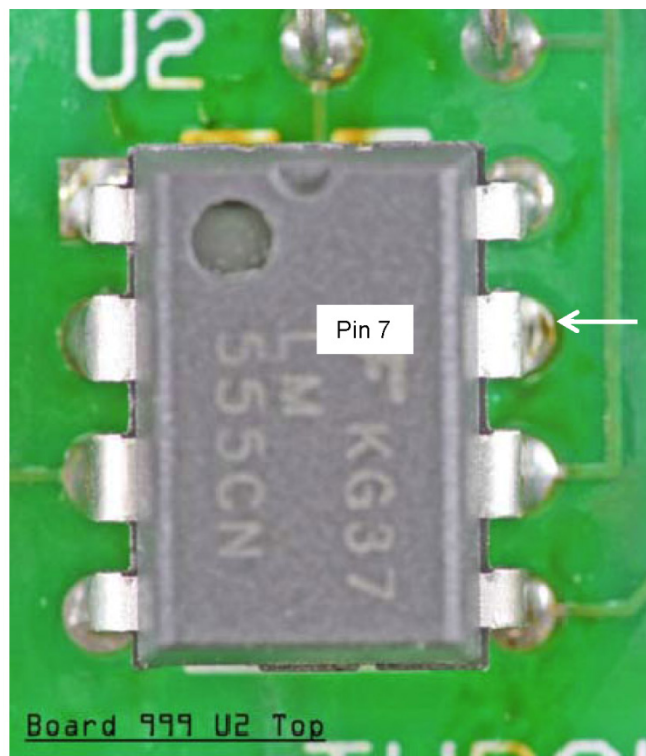


Figure 20.—Component U2 from board 09, showing poor wetting on pin 7. This defect would not pass inspection criteria, but the component is functional.

#### C.4 Circuit Board 09

The inspection of component R1 showed that both the soldered and flowed fillets were good and passed NASA Standards, though the “outside” lead was cut short; this is still acceptable work. The soldered side fillets for component U2 all pass inspection, as do all the flowed side fillets except for pin 7, shown in Figure 20. This joint had insufficient solder, where the solder did not flow through the board’s plated through hole. Component U4 showed problems with coplanarity, where pin 5 was low and pin 1 was high. Pin 1 was not flat on the pad, though solder bridged from the pad to the lead. Pin 2 was also not on the pad, and showed excessive solder, with solder dabbed on the joint with the soldering iron. Pin 3 does not appear soldered to the pad, though both the pad and lead are wetted with solder. Pin 4 has excessive solder and was reheated, but is function. Figure 21 shows these four legs. Pin 5 passed inspection. Pins 6 and 7 had excessive solder, but were otherwise good. Pin 8 had very excessive solder, a solder spike, and overheated solder. The removal of components U6 and U7 also presented challenges to the crew. For U6, the pads show little damage; there is minor damage to the solder mask on land 7, as shown in Figure 22. The solder was not cleaned off the pads in any joint, as the solder was heated and lead debris removed or peeled from the pad. For component U7, pads 4 and 5 showed damage to traces from these pads which run under the component, shown in Figure 23. The damage may have arisen from use of the dental pick, which may have gotten under the trace and removed a piece of the circuit board. All other pads for this component pass visual inspection. The functional test showed only the plated through hole region of the circuit board operating normally, with a maximum current draw of approximately 30 mA. The fine pitch SMD section of the circuit is expected not to function, due to the removal of U6 and U7.



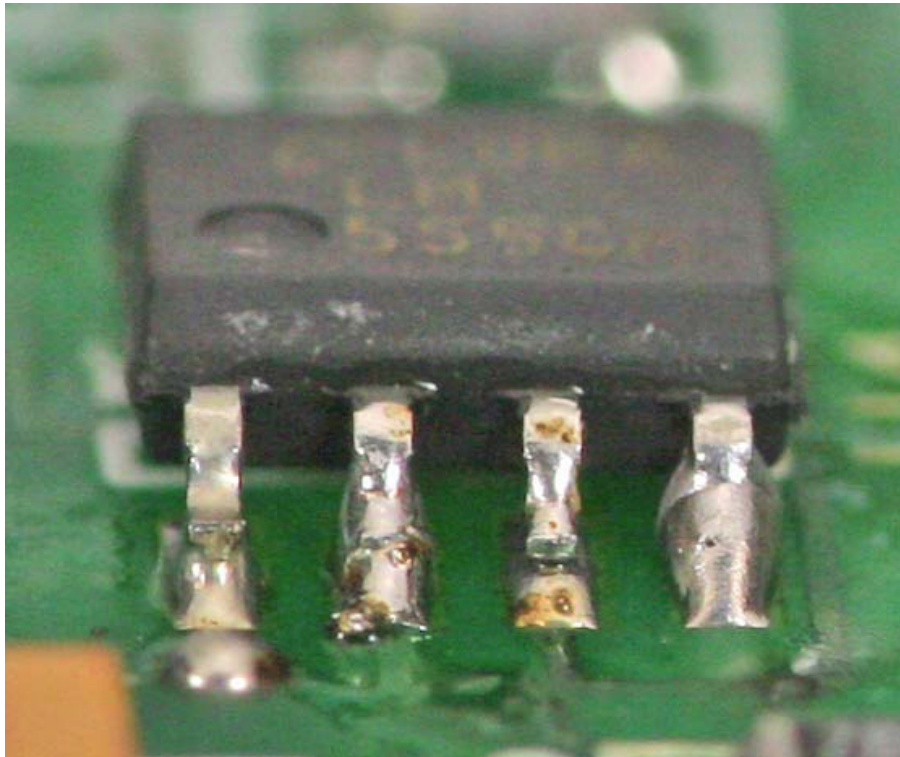


Figure 21.—Component U4, Board 09. Leg 3 is not soldered to the circuit board, while the other legs show excess solder and do not rest on the circuit board pad. This component would not work, due to the problems with leg 3.

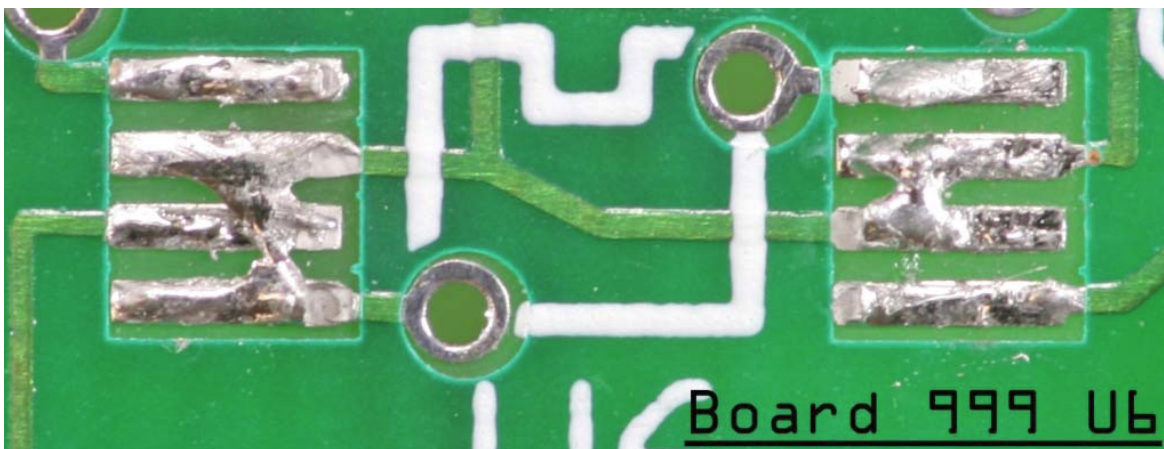


Figure 22.—A photo of the lands after removing component U6, board 09. Land 7 shows some minor removal of the solder mask. The original solder and leg debris remains on the pads.

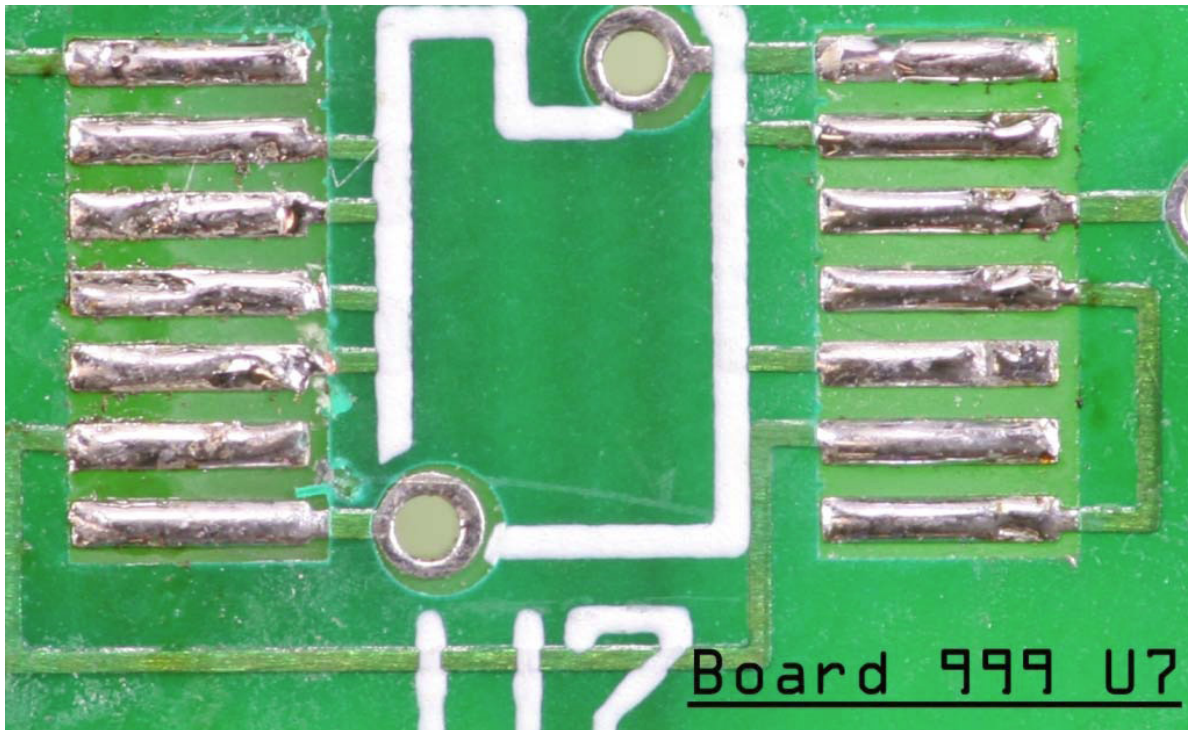


Figure 23.—Board 09 after removing component U7. Lands 4 and 5 show some damage to the traces.

### C.5 Circuit Board 10

The visual inspection of R1 showed good fillets on both sides of the circuit board, though the outside leg was cut short (as before, this is acceptable). For component U2, the visual inspection found some issues. On the soldered side of the circuit board, pin 1 showed insufficient solder, and pin 2 had a large solder ball where the solder attached to the joint, and reheating the joint formed a ball. Pins 3 and 4 passed inspection, while pin 5 showed evidence that the operator removed the soldering iron prior to removing the solder wire. Pin 6 passed, pin 7 had a piece of solder wire attached to the joint as in pin 5, and pin 8 passed, though had the same problem as pin 7 with a small piece of solder wire attached to the joint. On the flowed side of the circuit board, only pins 3 and 8 passed visual inspection. All other fillets showed evidence of insufficient solder, as described previously. These results are shown in Figure 24. Component U4 showed coplanarity problems, where leads 5, 6, 7, and 8 (the “right” side of the component) were flat on the circuit board pads, but leads 1, 2, 3, and 4 (the “left” side of the component) were off the board. Further, pin 1 was not soldered to the circuit board, and pin 2 was soldered with a reasonable amount of solder, but was overheated. Lead 3 was soldered, but there is no solder on the circuit board pad. The lead and pad for pin 4 were soldered together, forming a bridge; while functional, this is not ideal. Leads 5, 6, 7, and 8 passed the visual inspection. Figure 25 shows these results. The plated through hole and fine pitch surface mount section of the circuit functioned properly, while the standard pitch surface mount region did not. The circuit drew a peak current of approximately 40 mA.



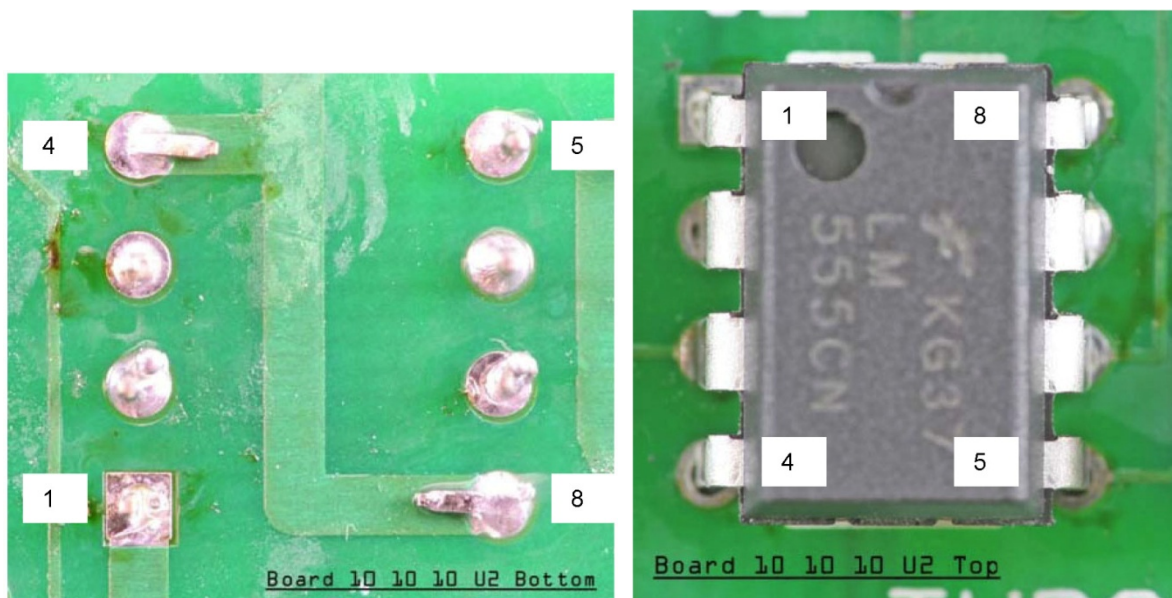


Figure 24.—Soldered (left) and flowed (right) views of component U2, board 10

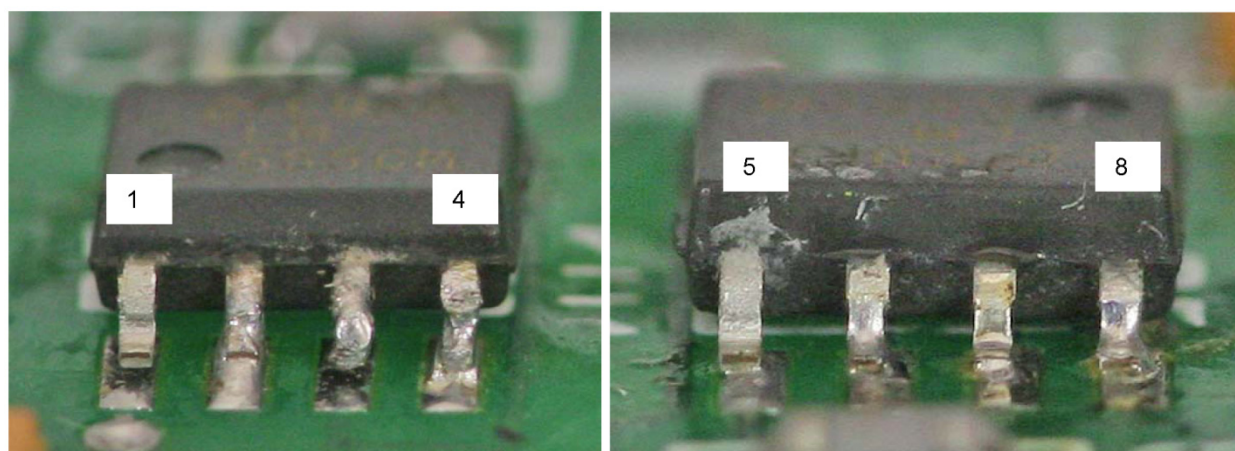


Figure 25.—Side views of component U4, board 10. Leads 1 and 3 are not soldered to the circuit board, while lead 4 shows the joint was remelted. Leads 5 through 8 are acceptable, though lead five has insufficient solder.

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14. ABSTRACT The Component Repair Experiment-1 (CRE-1) examines the capability for astronauts to perform electronics repair tasks in space. The goal is to determine the current capabilities and limits for the crew, and to make recommendations to improve and expand the range of work that astronauts may perform. CRE-1 provided two-layer, functional circuit boards and replacement components, a small tool kit, written and video training materials, and 1 hr of hands on training for the crew slated to perform the experiment approximately 7 months prior to the mission. Astronauts Michael Fincke and Sandra Magnus performed the work aboard the International Space Station (ISS) in February and March 2009. The astronauts were able to remove and replace components successfully, demonstrating the feasibility of performing component-level electronics repairs within a spacecraft. Several unsuccessful tasks demonstrated areas in need of improvement. These include improved and longer training prior to a mission, an improved soldering iron with a higher operating temperature and steady power source, video training and practice boards for refresher work or practice before a repair, and improved and varied hand tools and containment system.					
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