NASA/TM—2012-217119

Soldering in a Reduced Gravity Environment (SoRGE)

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January 2012

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Acknowledgments

The SoRGE team would like to thank Astronaut Sunita Williams for her outstanding work on the SoRGE experiment during Expeditions 14 and 15 on the International Space Station, and for graciously providing time after the mission for a debriefing as well as generating the normal gravity samples used in this analysis. Ivy Apostolakopoulos of the Operational Support Office and Arthur Perry and Alyssa Mueller of the SDTO Office at NASA Johnson Space Center provided support for preparing and operating SoRGE aboard the ISS. The team would also like to thank Richard Pettegrew, formerly with the National Center for Space Exploration Research, Cleveland, Ohio, who was one of the original Principal Investigators and instrumental in the early work on reduced gravity aircraft as well as in the design, implementation, and operation of this work. Eric Anderson, formerly with ZIN Technology and currently with Arctic Slopes Research Corporation, Cleveland, Ohio, who designed the circuit board layout for this experiment. Gregory Funk of ZIN Technologies helped with the approval process and packaging for flight of the SoRGE hardware. Gary Gorecki of NASA Glenn Research Center provided soldering expertise and performed the inspections of the video record and circuit boards. Former students Anthony Rotella of Case Western Reserve University, Cleveland, Ohio, Joseph Ferry of the University of Missouri Science and Technology, Rolla, Missouri, and Robert Banks of Shaker Heights High School, Shaker Heights, Ohio all provided assistance with the analysis and measurement of the internal void structure and fillet length. YXLON International, Akron, Ohio, provided the CT x-ray scanning service generating the still images of the joint internal structure for this work. This work was funded by the Supportability Project of the Exploration Technology Development Program Office at NASA Langley Research Center.

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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. Currently, crew members on the International Space Station (ISS) recover from faults by removing and replacing, using backup systems, or living without the function of Orbital Replacement Units (ORUs). These ORUs are returned to a depot where the root cause of the failure is determined and the ORU is repaired. The crew has some limited repair capability with the Modulation/DeModulation (MDM) ORU, where circuit cards are removed and replace in faulty units. 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 future spaceflight operations. To this end, the Soldering in a Reduced Gravity Environment (SoRGE) experiment studied the effect of gravity on the formation of solder joints on electronic circuit boards.

This document describes the SoRGE experiment, the analysis methods, and results to date. This document will also contain comments from the crew regarding their experience conducting the SoRGE experiment as well as recommendations for future improvements. Finally, this document will discuss the plans for the SoRGE samples which remain on ISS.

1.1 Background

This SoRGE experiment is a first step in developing a capability for crew members to perform repairs on electronic equipment at the component level, a potentially enabling capability for long duration missions, such as those to the moon and to Mars. The development of this capability is the objective of the Component Level Electronic Assembly Repair (CLEAR) task under the Supportability Project of NASA's Exploration Technology Development Program. CLEAR has grown from and includes earlier reduced-gravity aircraft testing of the formation of solder joint in low-gravity. An electronics repair capability may also reduce some of the logistics burden imposed on the International Space Station (ISS) by the retirement of the space shuttle through the gradual testing and implementation of tools and techniques developed by the CLEAR effort.

The original research leading to the development of SoRGE focused on the formation of solder joints using plated through-hole components and circuit boards in reduced gravity (Ref. 1). The researchers conducted tests aboard NASA Reduced Gravity Aircraft (Ref. 2) using various fluxes with tin/lead solders, and compared these results with similar solder joints formed in normal gravity. One part of this analysis included sectioning the solder joints and analyzing the solder joint interior at the midplane. This research found that forming the solder joint in reduced gravity affected the inner structure of the joint.

Solder joints formed in reduced gravity had more internal voids than similar joints formed in normal gravity. Internal voids form due to gasses evolved during the soldering process, from volatiles or other chemicals present in solder flux to water vapor released from the circuit board, as well as other possible sources. These voids are potential sources of reduced circuit performance, as the voids can reduce the electrical conductivity, thermal conductivity, and provide less support to mechanical loads, board stresses, and vibration. A hypothesis for the increase in void formation at low gravity focuses on the reduction of buoyant forces driving the gas bubble out of the solder joint before the solder freezes.

In 2000, this team proposed the SoRGE to be flown as a Station Development Test Objective (SDTO) task aboard the ISS to assess the effect of true micro-g on the soldering process. The g-jitter present during aircraft operations is not present on ISS, and may affect the creation and distribution of gas pockets and voids within the solder joint. Furthermore, the previous research also evaluated potential mitigation techniques to minimize the void formation—these techniques were to also be tested as part of the SDTO. The SoRGE SDTO was delayed several years due to the Return to Flight activities and re-emerged as an activity for the newly formed CLEAR task. The CLEAR team felt that exploring this question is important to developing an electronics repair capability. Later, as the CLEAR task evolved, the SoRGE opportunity was viewed as a first chance to attempt training an astronaut, who most likely will not have previous experience in performing electronics repairs, to perform this type of work in reduced gravity. At that time, the CLEAR team felt that repairs were a contingency item and that crewmembers would get only very limited training for this activity. As such, the training consisted only of video and written procedures that were uplinked to the crew.

This document will begin by describing the experiment, including the solder and flux combinations used, the layout of the circuit boards used for forming joints, and the process and tools used by the astronaut to form the solder joints. The experiment description will also include the methods used to view and inspect the video record of the operations, the inspection of the circuit boards themselves, measuring the fillet lengths, and measuring the amount of voids formed within the solder joints. The results section will present the data acquired from these analyses, and briefly compare them to previous work. The document will conclude 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 and Data Analysis

The SoRGE experiment focused on the formation of solder joints in reduced and normal gravity. In particular, the experiment focused on the ability and difficulties for a minimally trained crew member to perform the task, and on the formation of voids within the solder joint as a function of gravity. The following sections describe the experiment, including the three types of solder and flux used as well as the circuit boards and tools and facilities available on the ISS. These sections also discuss the returned materials and data analysis.

2.1 Experiment Description

The SoRGE flight experiment examined three solder and flux combinations, described in Table 1. All fluxes were active rosin (RA), type “44” manufactured by Kester, Inc., and all wires were 0.031 in. in diameter. The first combination consisted of a 60% tin, 40% lead solder wire with a core of rosin solder flux, referred to as “Flux Core Kit A” in the experiment kit. Solder joints formed on returned circuit boards labeled as either “A” or “B” as well as the board “GA” produced on Earth used this solder and flux combination. This solder is identical to the solder currently part of the US Soldering Kit. The second combination was similar to the first, but used a eutectic[1] tin-lead solder while using the same flux as used in the “Flux Core Kit A” samples. These flight kits are referred to as “Flux Core Kit B”, and the returned circuit boards using this solder and flux are labeled either “E” or “F”. The third combination used a solid 60% tin, 40% lead solder wire and a liquid rosin flux supplied in a syringe which was applied to the circuit board and component immediately before soldering; these are referred to as “Liquid Flux Kits” in the flight manifest, and joints formed with this solder and flux combination are from boards “J” and “K”, with ground samples formed on board “GC”. Figure 1 shows one of these kits, including the circuit board, solder wires, solder return bag, and flux syringe, and Table 1 shows the solder, flux, gravity level, and board designations. Each kit contained a circuit board (Figure 2) with 16 standard resistors fixed to the board with a RTV adhesive and each resistor lead positioned within a through hole on the circuit board. This provides the astronaut-operator with thirty-two solder joints to form on each circuit board. The kit also contains 32 individually weighed solder wires of the appropriate type, one for each solder joint. The SoRGE team recorded the weight of the solder wires prior to launch; weighing the returned wires provided a measure of the solder used to form the joint.

TABLE 1.—LIST OF SOLDER, FLUXES AND GRAVITY LEVELS USED IN SoRGE EXPERIMENT

Solder	Flux	Gravity level (g)	Board letter
60% tin-40% lead	RA, core of solder wire	0	A
60% tin-40% lead	RA, core of solder wire	0	B
60% tin-40% lead	RA, core of solder wire	1	GA
Eutectic	RA, core of solder wire	0	E
Eutectic	RA, core of solder wire	0	F
60% tin-40% lead	RA, external liquid	0	J
60% tin-40% lead	RA, external liquid	0	K
60% tin-40% lead	RA, external liquid	1	GC

Once on orbit, the crew assigned to this task used the kits described with ISS materials to form solder joints. The astronaut assembled the Containment Area, a tent-like glovebox which mounts on the Maintenance Work Area (MWA), a table that attaches to rack frames in the walls of the ISS. With this equipment in place, the U.S. Soldering Kit and board clamp were installed within the Containment Area (Figure 3). The U.S. Soldering Kit is a commercial soldering iron wand with a 600 °F tip, modified to accept a power tool battery for power. Finally, the astronaut installed a camera and mounting arm within the Containment Area to record the soldering process. Reference 3 contains more information on these items. After assembling this equipment, the astronaut then placed one of the SoRGE kits in the Containment Area, placed the circuit board in the circuit board clamp, and arranged the solder wires and flux (if used) as comfortable. Prior to soldering, the astronaut closed the access port of the Containment Area, using glove ports to work with objects and viewing the work through the clear plastic side walls or a Fresnel lens (0.9X magnification) mounted in the wall. Based on the previous work already described, the SoRGE experiment called for a specific process for forming a solder joint, described in the written experiment procedures and a training video developed by the team. In this process, the crew member applied the hot soldering iron tip to the joint area for a “mental count” of 3 sec to preheat the area, then applied the appropriate solder wire to form the joint, removed the wire, and finished with a post-heating period of 3 sec (again using a “mental count”) prior to removing the soldering iron. The astronaut applied the soldering iron and solder wire to the component leg on the side of the circuit board opposite the component. In the analysis, this fillet is referred to as the soldered fillet. The fillet formed on the component side of the circuit board, from solder flowing through the through-hole, is referred to as the flowed fillet.

[1]Eutectic alloys are alloys where, for a specific ratio of constituents, the constituents completely melt at the same temperature. Non-eutectic alloys have states where one constituent does not completely melt for a given temperature. This plastic state may contribute to the formation of voids or other flaws in the soldering process. For tin-lead alloys commonly used in electronics soldering, the eutectic ratio of constituents is 63% tin and 37% lead.

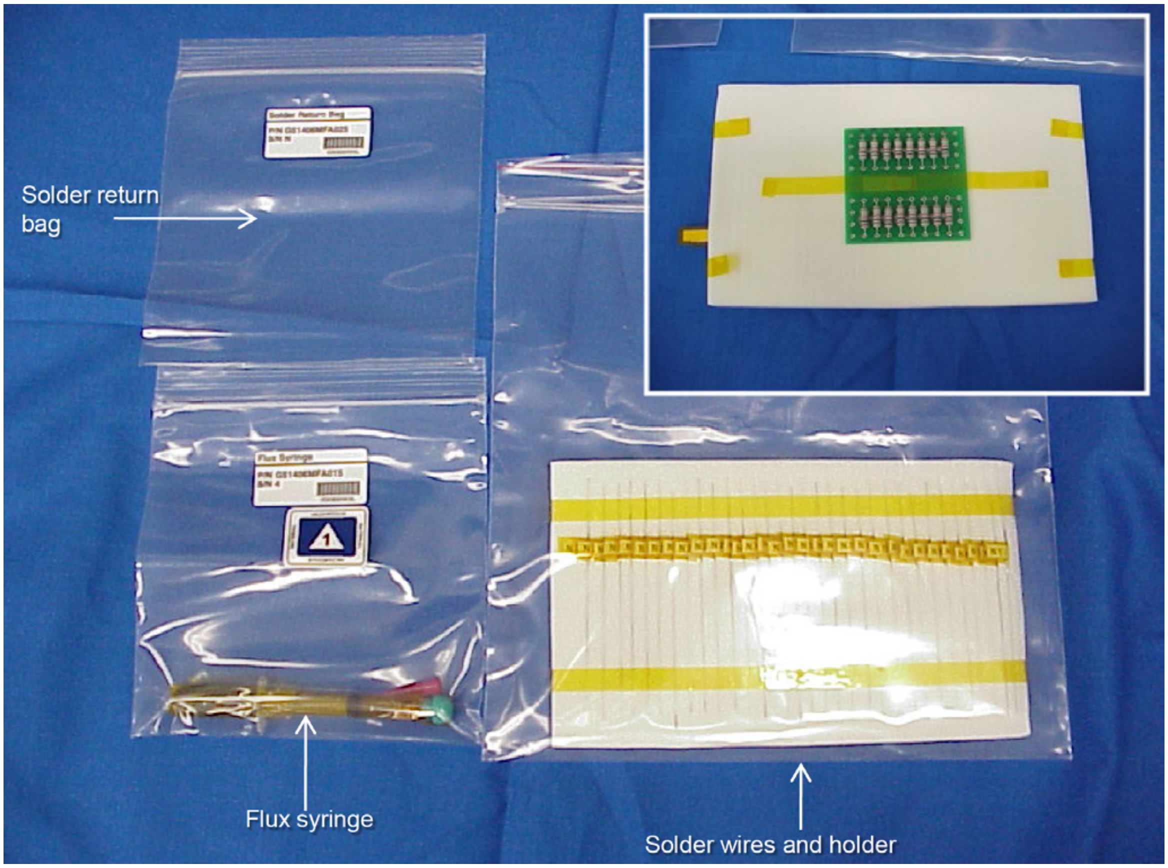

Figure 1.—A SoRGE soldering kit, including numbered solder wires, flux syringe, and solder return bag. The inset photo shows the circuit board taped to the back of the solder wire holder.

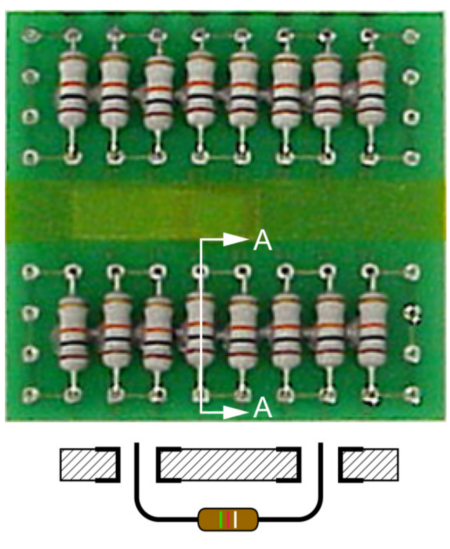

Figure 2.—An unused SoRGE circuit board and drawing of a resistor and two joint locations. The soldering occurs on the bare leg of the resistor, forming the soldered fillet. Solder flows into the through hole and forms the flowed fillet on the resistor body side of the circuit board.

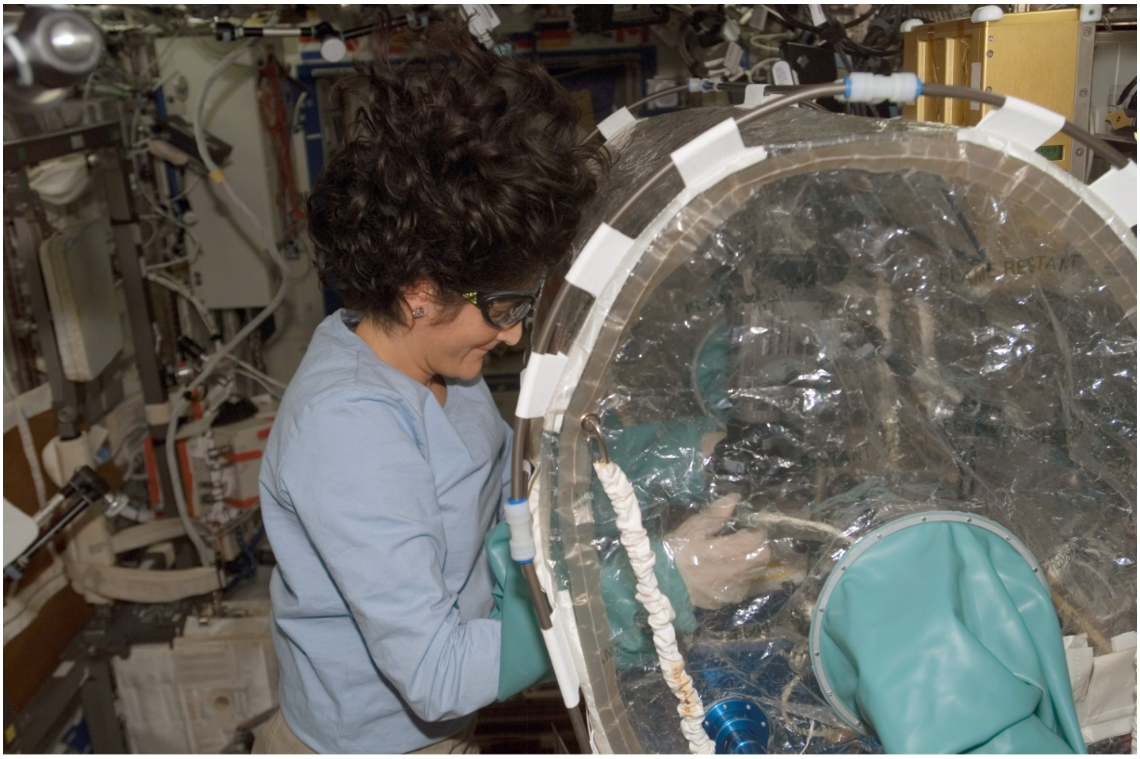

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Figure 3.—Astronaut Sunita Williams performing the SoRGE experiment in the Containment Area on the International Space Station.

Over the course of Increments 14 and 15 aboard the ISS (March and May of 2007) Astronaut Sunita Williams conducted six runs of the SoRGE experiment (Figure 3), using two kits from each of the three solder-flux combinations. Circuit boards A and B were soldered using a 60% tin-40% lead, rosin flux cored solder wire in reduced gravity, while joints on board GA were soldered with this material in normal gravity. Joints from boards E and F were formed using a eutectic solder wire with a rosin flux core. Normal gravity samples formed with this solder and flux were taken from previous work (Ref. 4). Circuit boards J and K were formed using 60% tin-40% lead solid solder wire with an external liquid flux in reduced gravity, while joints on board GC were formed with this solder and flux combination in normal gravity. These kits were returned to the SoRGE team in fall 2007, with the six unused kits remaining on the ISS for potential future use. In addition, the SoRGE team received video tapes and some limited photographs of the solder process to determine the effectiveness of and future improvements to the training materials, and to document any difficulties encountered during the soldering process.

2.2 Description of Data Analysis

The following sections describe the analysis of the returned SoRGE solder samples and the accompanying video recordings of the work, as well as a later debriefing of the astronaut who performed the work. The first section discusses the measurement of fillet length, for a comparison of the lengths between joints formed in normal gravity to those formed in reduced gravity. Next, the discussion focuses on the inspection of the joint quality based on NASA standards, and an inspection of the video record for techniques used and problems encountered while forming the solder joints. The final section describes the method for selecting and preparing solder joints for analysis of the internal structure, and how the series of images describing the internal structure of the joints are analyzed.

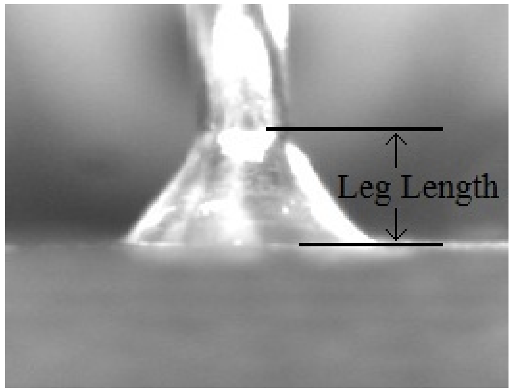

Figure 4.—Side view of a solder joint, showing the leg length of the joint's bottom fillet.

2.2.1 Fillet Length Analysis

Measuring the length of the soldered fillet and the flowed fillet and comparing these measurements for joints formed in reduced gravity with those formed in normal gravity gives an indication of the gravitational effects on joint formation. Earlier work (Ref. 1) has shown a gravitational effect. Measuring the fillet lengths from the SoRGE samples will show if a lower gravity level, with less variation in gravity due to g-jitter, has an effect on the joint shape. The first step to measuring fillet lengths is to photograph the fillets. Two fixtures constructed on an optical table with optical mounts allowed for positioning a video camera at the same height and parallel to the sample circuit card edge. Individual still images of each fillet are taken from the video, with a sample shown in Figure 4. This figure also shows the leg length, defined as the distance from the circuit board face to the point on the resistor lead where the applied solder stops and no longer wets the lead. A macro written for the image analysis software ImageJ (Ref. 5) records the pixel location of the solder/circuit board and solder/component leg interfaces, which are manually determined by the user. The calculated distance between these two points is reported as the fillet length.

2.2.2 Visual Inspection and Selection of Joints for Analysis

This section summarize the results of a visual inspection performed by a NASA trained, flight qualified electronics technician. The technician used a stereo microscope set to 4X magnification to inspect for a variety of surface flaws in the solder joint, described in the NASA soldering standards (Ref. 6) and indicative of problems with the soldering process for that specific joint. The inspection included analysis of the topside (component side) of the circuit board, the bottom (soldering) side, and the overall acceptance of the solder joint, requiring acceptance of both the top and bottom sides of the joint. Each board side passed, marginally passed, or failed inspection. Joints that marginally passed had some problem with the soldering process that would have lead to a failing evaluation for an experienced technician, but may be allowed given the astronaut's experience level and minimum impact to the circuit. The top and bottom side analyses included notes on why the joint did not pass inspection, but no notes when the joint passed. Marginally acceptable solder joint sides also had notes on the potential problem with the solder joint.

2.2.3 Sample Preparation and Computed Tomography (CT) Analysis

After examining the exterior features of the solder joints and evaluating them against the NASA Standard criteria, the next analyses focused on the joint interior. The results give a measure of the interior voids within the solder joint, and the effect of gravity and solder and flux combinations on the amount of voids. This process begins with a NASA soldering technician and instructor conducting a secondary examination of the SoRGE flight and ground solder joints. Additional examination is required because, in the case of the flux cored solder, more than ten joints passed the original inspection, while the solid core solder with liquid flux cases yielded fewer than ten acceptable joints, requiring a selection of joints that did not initially pass inspection. Selecting samples from those made with a solid cored solder (again using 60% tin, 40% lead solder) with a liquid flux required choosing joints that did not pass the initial selection in order to provide samples for CT analysis. Selecting flawed joints focused primarily on the appearance of the flowed fillet side of the solder joint. Joints with the best flowed fillet indicated that the solder flowed through the through-hole properly, forming an effective joint even with problems forming the soldered fillet. Further, the soldered side of the joint must not show excessive problems; it must have good wetting, but may exhibit excessive solder amounts or small spikes. Joints with large spikes, solder drags, or poor wetting on the bottom were not selected. Joints where the soldered fillet was overheated were accepted in this analysis. The methods of selection apply to ground samples as well as flight samples.

After selecting the solder joints for internal analysis, a technician removes the joints from the circuit board by cutting the lead close to the resistor body, preserving the bend in the lead, and then cutting the joint area out of the circuit board. The bend in the resistor lead is preserved to distinguish between the flowed fillet (fillet closest to the bend) and soldered fillet (fillet farthest from the bend) in the x-ray images. The individual solder joints are then encapsulated in a plastic disk, using a technique developed to prepare samples for metallographic grinding. Each disk contains between one and three solder joints such that each disk only contains joints from one of the circuit boards. The plastic disk protects the solder joints from damage or loss after removal from the circuit board, and prepares the joints for potential destructive testing where the joint is ground to a specific depth and the revealed inner plane is analyzed for voids.

After encapsulating the solder joints in plastic disks, the samples were sent to a commercial non-destructive testing laboratory, YXLON International in Akron, Ohio. This laboratory performed CT scanning of the individual solder joints in a process described in (Ref. 7), producing a series of images numbering from 250 to 300 for each solder joint, each image taken along the center axis (parallel to the component lead) of the solder joint. Figure 5 shows a sequence of images from one of these joints, with a resolution of 0.018 mm/pixel for this joint. Images a and b show the increasing diameter of the soldered fillet, while images i and j show the decreasing diameter of the flowed fillet. The remaining images are from the interior through-hole region. These images show the solder as a bright white, with gray lead and gray-to-black internal voids. The resolution of these images ranges from 0.015 to 0.020 mm/pixel.

With the sequence of images describing the internal structure of the solder joints, the analysis begins to determine the fraction of voids within the solder joint, and compare these values for the various flux combinations in both reduced and normal gravity. The SoRGE team used ImageJ (Ref. 5). The process for measuring void areas and volumes requires two steps. First, the total area of the solder joint in each image is measured, using a grayscale threshold (a minimum gray level, counting pixels above this level and ignoring those below) to isolate the joint area from external features in the image, such as x-ray reflections or plating. This process counts the area (or pixels) highlighted by the thresholding process and includes any interior holes not highlighted by thresholding. In the through-hole area of the joint, threshold levels that excluded reflections and plating did not always close and include voids near the edge of the joint. For these images, the user drew in a line, based on the line of plating, to close off these voids and include them in the total area measurement. Measuring the total area required few changes in the threshold level throughout the joint; typically, the fillets and the through-hole regions required different, though similar, threshold levels, with little if any change in threshold within these regions. Figure 6 shows this process.

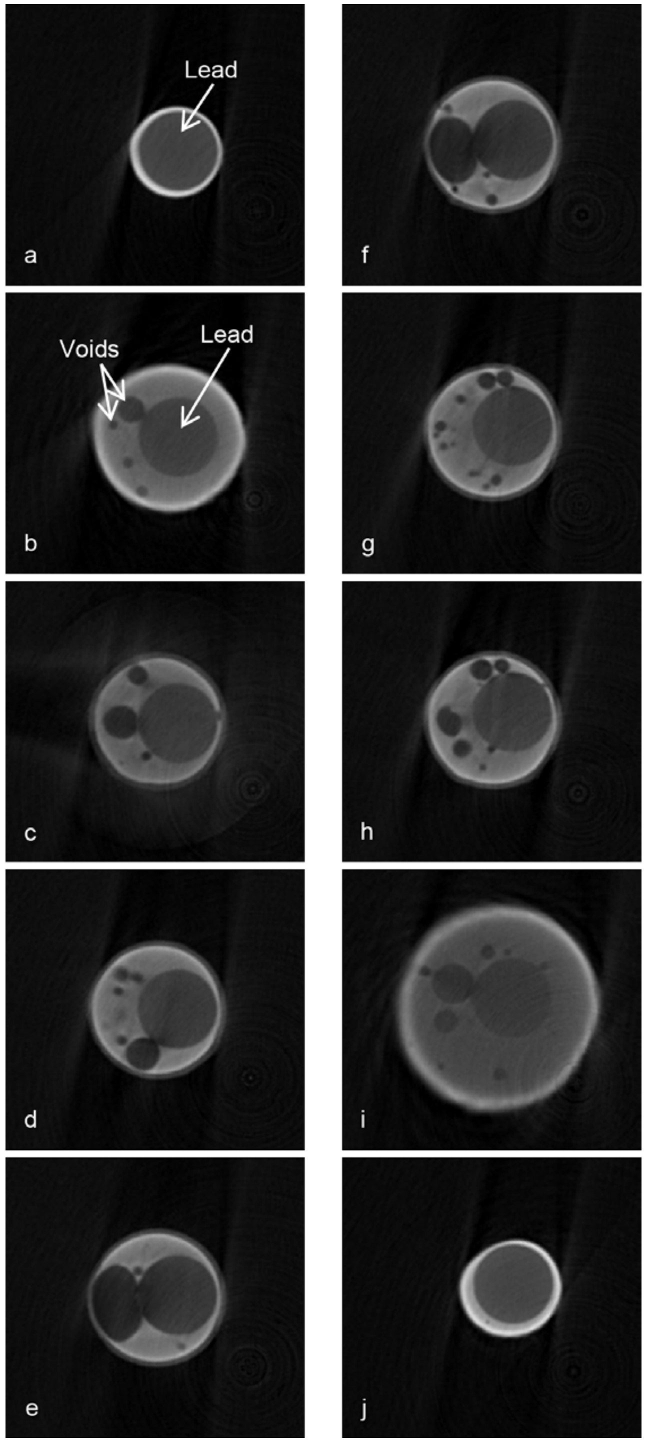

Figure 5.—Sequence of images describing the interior of a solder joint. The images show the lead and voids within the equally spaced images. Images a and b are taken from the soldered fillet, images c through h from the annular region, and images i and j from the flowed fillet. Image b demonstrates the lead and typical voids.

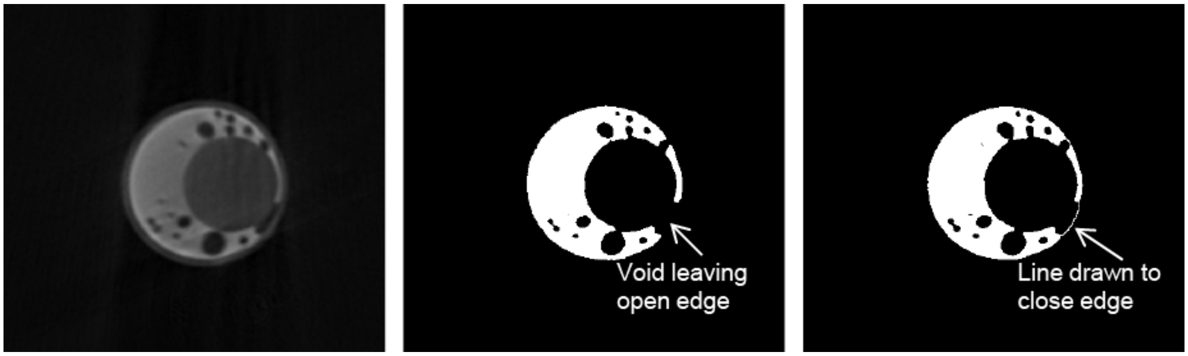

Figure 6.—Applying threshold to measure total joint area. The process begins with the original image (left), applies a threshold (center), then draws a line or lines to close the image (right).

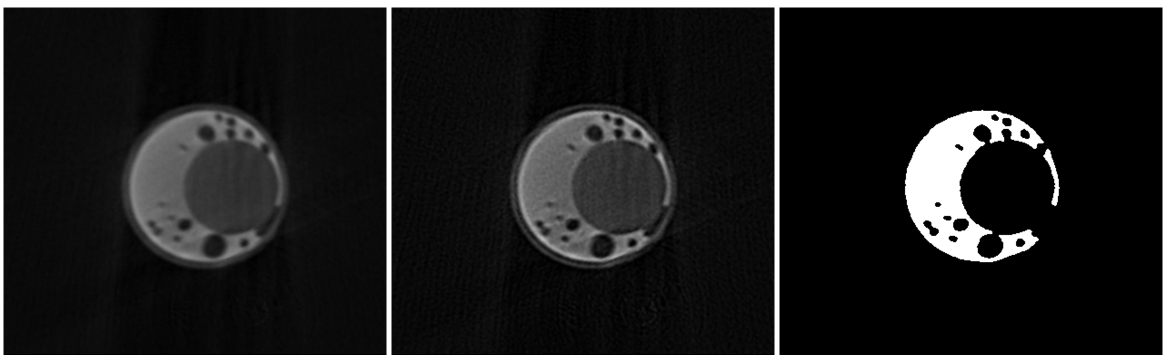

Figure 7.—Process for measuring solder area. Begin with the original image (left), then apply Unsharp Mask and Smooth (center), followed by threshold and Despeckle (right).

The next step in the void measurement process is to measure the area (or pixels) of solder, isolating and removing the voids. This process begins by using the Unsharp Mask function in ImageJ, to increase the contrast between the gray levels of the solder and voids, followed by a smoothing function to reduce granularity introduced by the Unsharp Mask. The user then sets the threshold level for the image. While only one level is typically used for the through-hole region, a range of levels is required for the fillet regions. The fillet images require a range of threshold levels because the amount of solder varies from image to image, with more solder near the plating region decreasing the contrast between solder and void, while near the ends of the joint the small amount of solder leads to greater contrast between the voids and the solder. After setting the threshold, the routine then performs a Despeckle operation to remove more noise, then a Watershed operation to isolate voids from the solder. After this operation, the routine then counts the highlighted pixels representing solder in the joint area. (All the functions and operations used in the analysis routine are described in Ref. 5.) This is shown in Figure 7. For both the total area and solder area measurements, regions near the circuit board, transitioning from fillet to or from through-hole region, were difficult to measure due to plating on the circuit board and the sudden change in joint diameter. For this reason, these areas are not included in the analysis and calculations. The transitions from fillet to through-hole region to opposite fillet also mark the boundaries for three regions of the joint, as shown in Figure 8. The soldered fillet and flowed fillet have already been described. The region of solder filling the through-hole of the circuit board is referred to as the annular region. The use of “annular region” is restricted to the analysis of voids within the joint interior.

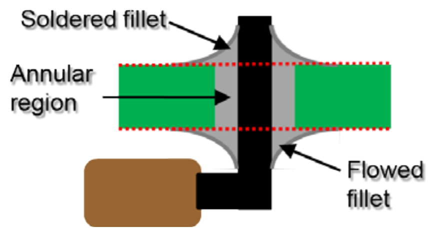

Figure 8.—Drawing of the three regions of a solder joint: the soldered fillet, where heat and solder are applied, the annular region within the circuit board through-hole, and the flowed fillet near the resistor.

After making these two measurements, total joint area and solder area, the user must then measure the area of the component lead. This is done manually, using the average of the lead area in five evenly-spaced images along the image set for the joint. Once this is done, the void area may be calculated. First, the average lead area and solder area are subtracted from the total area measurement for each image. The remaining value is the area of voids in the image. Dividing the void area by the total area, minus lead area, for each slice gives the slice void fraction. Plotting the slice void fraction as a function of position along the joint gives a measure of the distribution of voids within the joint and a method for determining any trends in this distribution among flux types and/or gravity levels. Additionally, integrating the total joint area (minus lead area) as well as the void area over the joint gives the total volume and void volume. The integrations were calculated using the trapezoidal rule (Ref. 8). The ratio of the void volume and total volume, the void volume fraction, gives a measure of the total amount of voiding in a particular joint, and is used to compare joints across solder and flux type and in varying gravity.

3.0 Results

The following section describes the results of the SoRGE operations and analysis. It begins with a summary of the comments of Astronaut Sunita Williams, who conducted the SoRGE experiment during Expeditions 14 and 15, in March and May 2007. It is followed by the results of viewing the video record of SoRGE operations aboard the ISS, and then by the results of a visual inspection of the returned circuit boards and formed solder joints. Next, the results of measurements of the fillet lengths are reported, and finally the results of examining the internal voids of the solder joints are reported as well.

3.1 Crew Debrief

On August 27, 2007, the SoRGE team had the opportunity to speak with and debrief Astronaut Sunita Williams, who conducted the SoRGE testing during Expeditions 14 and 15, March and May 2007. The following section summarizes her comments, focusing mainly on prior training and experience, comments on conducting the soldering tests, and comments on requirements for a future capability, based on performing the SoRGE experiment.

Astronaut Williams commented that she did not have any soldering experience prior to performing SoRGE operations. Pre-launch familiarization sessions introduced Astronaut Williams to the various tool kits available on the ISS, including the U.S. Soldering Kit used for SoRGE. This familiarization did not include any demonstrations or hands-on experience in soldering, either with a SoRGE sample or with a standard training circuit board. The SoRGE written procedures and training video were the first exposure to soldering provided by NASA. Astronaut Williams found both the written procedures and, particularly, the training video helpful. She read the procedures prior to working on SoRGE. During operations she conducted the various soldering tasks without referring to the step-by-step procedures, as reading during this process is not possible.

The initial set-up of the MWA and the Containment Area took quite a bit of time in the initial stages of the SoRGE experiment, though the soldering progressed quickly afterwards. Astronaut Williams commented that she used the procedures for forming a solder joint (described earlier) consistently, and became more comfortable with the work as it progressed. One area of difficulty with this experiment arose from working with the Containment Area, mostly focusing on visibility. The Containment Area effectively provided visibility only through a small (approximately one foot long and a half foot wide) lexan viewport with a small amount of magnification. The clear plastic side walls were difficult to see through due to wrinkles introduced by packing and storing the Containment Area for extended periods. The use of safety glasses while working within the Containment Area may have also contributed to the visibility problems, but many of the difficulties arose from the Containment Area itself. Astronaut Williams used the video camera installed in the Containment Area as a visual aid, watching the work area with the camera view finder and using the lens zoom function to improve joint visibility. Another problem with the Containment Area was the size of the area, which physically increased the distance from the work area and the operator. One of the purposes of the Containment Area, preventing the release of solder balls into the module cabin, did not arise. Soldering and forming joints on the circuit board did not generate solder balls, though they were formed when cleaning solder from the soldering iron tip with a damp sponge. Astronaut Williams kept track of these solder balls, which typically stuck to the side walls or other objects within the Containment Area and were removed with the vacuum. Due to noise, the vacuum was run periodically to clean solder balls rather than continuously.

Based on her first-hand experience soldering in reduced gravity with the SoRGE experiment, Astronaut Williams had some recommendations for a future repair capability. A repair capability will require good training, including on-the-job training, and ground support. Training videos and a “cheat sheet” outline common repair steps should be provided to the crew conducting a repair, as well as resources and materials for practicing soldering techniques, both for a specific job as well as for general skill maintenance. Real time downlink and communications with a ground support team will also improve the repair, with the support team providing help and critiques of the work in a timely manner. Also, as crew size increases, a member of the crew should be knowledgeable about performing soldering repairs, and have experience and training before the mission begins. Another area for improvement is the Containment Area. The Containment Area should be smaller, allowing the operator to position themselves closer to the work area, improving visibility and comfort. Magnification should also be improved. This can include the use of a video camera and monitor, requiring the camera to be oriented and focused correctly, and after some practice by the crew working to a monitor rather than with direct viewing.

3.2 Inspection of Operations Video Record

The video record of SoRGE operations provided information on the tools and operating environment of the ISS, as well as the effectiveness of the training video provided by the SoRGE team. In general, the circuit board fills the camera field of view, providing a close enough view to see the soldering techniques used, as well as any difficulties encountered during soldering. The still image shown in Figure 9 demonstrates a typical view from the video record. This view generally was not sufficient to judge the quality of a solder joint, except in some cases where the operator encountered problems while soldering the joint.

The video record showed a problem with the ISS Soldering Iron Kit that was not expected by the SoRGE team, and may have negatively impacted the solder joint quality. As seen in Figure 10, the soldering iron tip used was curved, with an approximate 45° bend at the approximate middle of the tip. The ISS Soldering Iron Kit does not include any soldering iron tips with a bend; all provided tips are straight. This indicates that the soldering iron tip was damaged prior to use on the SoRGE experiment. Additionally, the soldering iron tip appeared discolored, which could be indicative of reduced performance.

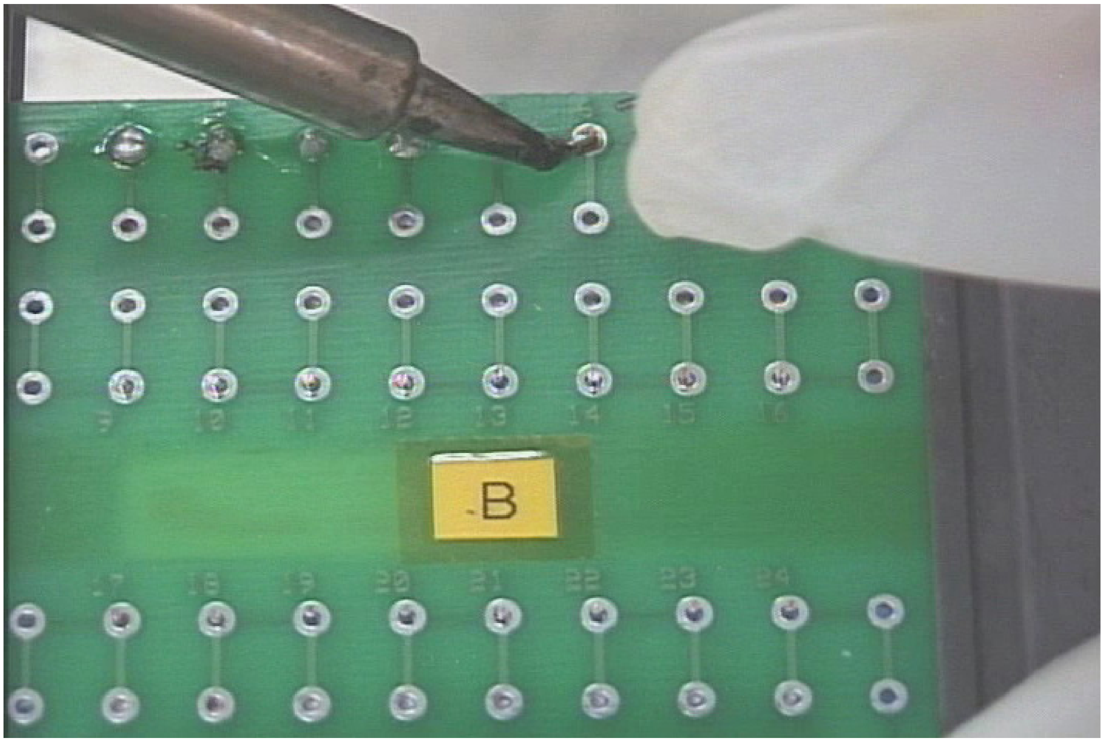

Figure 9.—Typical image from videotaped record of SoRGE solder joint formation by Sunita Williams aboard the ISS.

Figure 10.—Close-up image of the ISS Solder Kit soldering iron tip. The bent section of the tip is in contact with the solder wire, component lead, and circuit board land.

The damaged soldering iron tip has a number of implications in terms of effectiveness for both the SoRGE experiment and general use during other ISS operations. First, the bend could indicate a change in tip temperature. The soldering iron tip is resistively heated, and the action that caused the tip to bend may have damaged the electrical connection between the tip and the soldering iron, connections between layers of material in the tip, electrical connections within the tip, or any combination of these effects. The change in tip shape could also affect the contact between the soldering iron tip and the circuit components—the resistor leg and circuit board through hole or land—in a way that reduces the rate of heat transfer from the soldering iron tip to the joint area. While the tip used did provide enough heat to melt the solder wire and form solder joints, the potential reduction in performance of the tip may have made the astronaut’s task more difficult than expected, and adversely affect the results of the experiment.

Analysis of the videotaped operations also pointed out a problem with the video training that the SoRGE team provided. The training video did not adequately emphasize proper soldering technique for someone who never soldered previously. This video focused on an end-to-end process for forming solder joints, including applying an external liquid flux if necessary, the time required to preheat the joint prior to adding solder, and the post-heat time which occurs after adding solder to the joint but prior to removing the soldering iron. Although the video showed the end-to-end process, more emphasis needed to be placed on the proper position of the soldering iron relative to the resistor leg and circuit board, forming a heat bridge between the soldering iron and joint area with a small amount of solder, and the proper techniques for applying and removing the solder wire and removing the soldering iron. As a result, only a limited number of solder joints passes the post-flight visual inspection as discussed below. Nonetheless, the SoRGE team feels that the training video format can be effective provided that it emphasizes certain key techniques of the soldering process.

3.3 Visual Inspection

As the data in Table 2 through Table 7 show only one circuit board had joints with over 50 percent pass rate, a kit with a flux cored solder wire. Two other kits showed an overall pass rate of approximately 20 percent, both of which were also flux cored kits. The other three kits, two with solid cored solder wire and external liquid flux and the third with a flux cored wire, demonstrated problems with forming solder joints, with pass rates of 6 percent or less. Figure 11 and Figure 12 show a good solder joint, which passes NASA Standard 8739.3. This joint’s fillets are concave, relatively smooth and symmetric about the lead, and have a bright surface finish. Problems with wetting the solder joint were one of the most common problems with the soldering process. In a number of cases, the operator added solder to the bottom of the board, sometimes in large or excessive amounts such as Figure 13, but the solder did not flow, or flowed poorly, through the circuit card through hole and did not wet the component leg and circuit board pad on the top side of the circuit board, seen in Figure 14. The poor wetting occurred with all solder-and-flux combinations. This problem can be caused by insufficient heating of the solder joint, whether through technique (such as not forming a heat bridge prior to adding solder for the joint, or through improper placement of the soldering iron tip in the solder joint area) or through damage to the soldering iron tip not allowing the tip to reach full operating temperature. Contamination of the solder joint as evidenced by the discolored soldering iron tip is, in general, another potential cause.

TABLE 2.—VISUAL INSPECTION RESULTS FOR SOLDER JOINTS FORMED IN REDUCED GRAVITY USING 60% TIN-40% LEAD FLUX CORED SOLDER, BOARD A

Location	Number passed	Percentage passed
Flowed fillet	7	22%
Soldered fillet	16	50%
Both fillets	7	22%

TABLE 3.—VISUAL INSPECTION RESULTS FOR SOLDER JOINTS FORMED IN REDUCED GRAVITY USING 60% TIN-40% LEAD FLUX CORED SOLDER, BOARD B

Location	Number passed	Percentage passed
Flowed fillet	16	50%
Soldered fillet	18	56%
Both fillets	6	19%

TABLE 4.—VISUAL INSPECTION RESULTS FOR SOLDER JOINTS FORMED IN REDUCED GRAVITY USING EUTECTIC FLUX CORED SOLDER, BOARD E

Location	Number passed	Percentage passed
Flowed fillet	11	34%
Soldered fillet	8	25%
Both fillets	2	6%

TABLE 5.—VISUAL INSPECTION RESULTS FOR SOLDER JOINTS FORMED IN REDUCED GRAVITY USING EUTECTIC FLUX CORED SOLDER, BOARD F

Location	Number passed	Percentage passed
Flowed fillet	18	56%
Soldered fillet	22	69%
Both fillets	18	56%

TABLE 6.—VISUAL INSPECTION RESULTS FOR SOLDER JOINTS FORMED IN REDUCED GRAVITY USING 60% TIN-40% LEAD SOLDER WITH EXTERNAL LIQUID FLUX, BOARD J

Location	Number passed	Percentage passed
Flowed fillet	15	47%
Soldered fillet	2	6%
Both fillets	1	3%

TABLE 7.—VISUAL INSPECTION RESULTS FOR SOLDER JOINTS FORMED IN REDUCED GRAVITY USING 60% TIN-40% LEAD SOLDER WITH EXTERNAL LIQUID FLUX, BOARD K

Location	Number passed	Percentage passed
Flowed fillet	8	25%
Soldered fillet	2	6%
Both fillets	2	6%

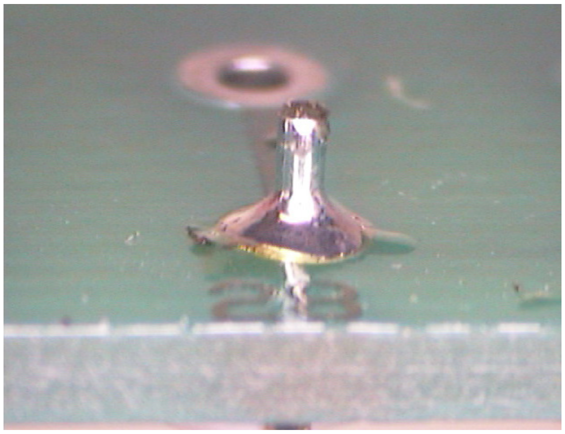

Figure 11.—Example of a successful solder joint, seen from the soldered fillet of the circuit board (Eutectic flux cored solder, joint F28).

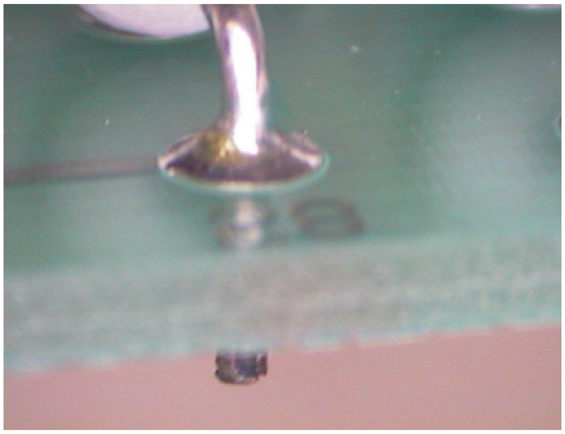

Figure 12.—Example of a successful solder joint, seen from the flowed fillet of the circuit board (Eutectic flux cored solder, joint F28).

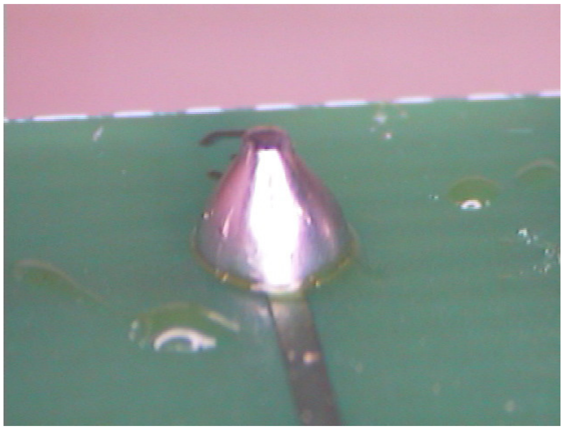

Figure 13.—Example of excessive solder, seen from the soldered fillet side of the circuit board (60%tin-40% lead flux cored solder, joint B3).

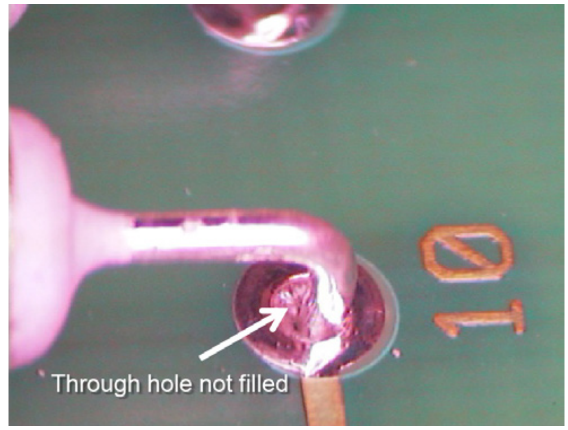

Figure 14.—Example of poor wetting seen from the flowed fillet side of the circuit board (Eutectic flux cored solder, joint E10).

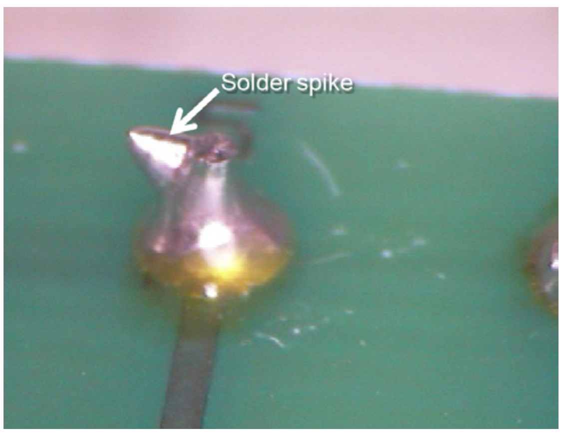

Figure 15.—Example of a solder spike, seen from the soldered fillet side of the circuit board (Eutectic flux cored solder, Joint E5).

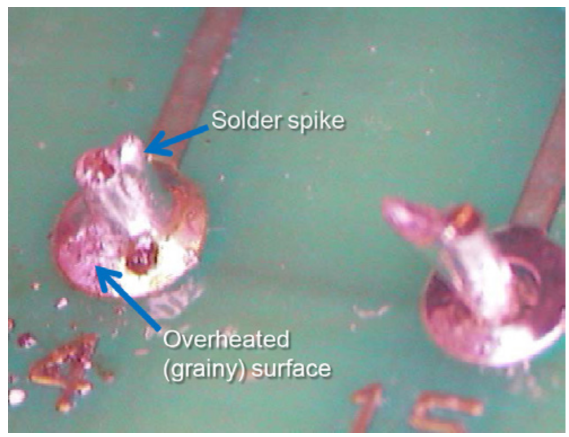

Figure 16.—Example of an overheated joint with a solder spike, seen from the soldered fillet side of the circuit board (60% tin-40% lead external liquid flux, joint K14).

Other problems, typically seen on the bottom side of the circuit board, include solder spikes and solder drag. Solder spikes, such as the one shown in Figure 15, occur when the soldering iron is removed before the solder wire; the solder cools and solidifies as the wire is removed, leaving a spike. Solder drag deforms the bulk of the solder fillet when the iron tip drags along the fillet while removing the iron. In both cases, molten solder does not immediately detach from the soldering iron as the iron is removed from the joint. The solder does not release from the soldering iron tip for several potential reasons, including overheating of the joint, the operator not removing the tip fast enough, or the flux in the joint area deactivating due to time or overheating. Underheating may also be a cause of solder spikes and drags, as it can lead to decreased solder wetting and the flux not activating properly. This pulling action can form a spike of solder, while moving the soldering iron tip through the bulk solder of the joint can form a drag. Solder spikes can create a region prone to arcing in high voltage applications; spike should also be avoided in low voltage applications, but may be permissible in limited circumstances. Solder drag can redistribute solder through the joint, leading to voids and poor wetting on the opposite side of the circuit board. In other cases, the operator did not add enough solder to form a solder joint, or added the solder to the end of the component lead, not at the lead-circuit board land interface. These joints failed simply because there was not enough solder to form the joint. Another problem found in the inspection was overheating the solder joint, shown in Figure 16, where the operator leaves the soldering iron tip in contact with the joint too long. An overheated solder joint may become brittle or develop more voids than

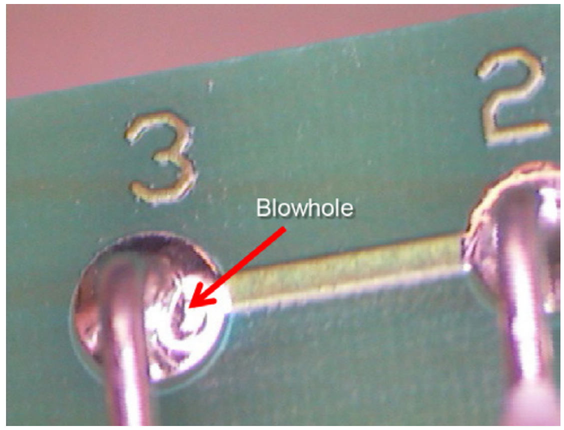

Figure 17.—Example of a blowhole seen from the flowed fillet side of the circuit board (Eutectic flux cored solder, joint F3).

joints formed with shorter soldering iron tip contact times. A final problem found during inspection was voids (sometimes referred to as "blowholes") seen in the surface of the solder joint, as in Figure 17. Trapped gases within the solder joint escaped just before the solder solidified, leaving a dimple in the surface of the solder joint. This is usually indicative of voids remaining within the solder joint, and leads to rejection during the visual inspection. The detailed inspection results for each board and joint are shown in 0.

3.4 Fillet Length

The fillet ratio is defined as the ratio of the height of the soldered fillet to the flowed fillet measured along the resistor lead (Figure 4 and Figure 8). Table 8 through Table 12 list the fillet height ratio for each solder joint that passed visual inspection[2]. The tables list the joint, the fillet ratio, and the average and standard deviation of the corresponding data set. In reduced gravity (Table 8, Table 10, and Table 11), the data show that the fillet lengths are not equal with the soldered fillet typically being longer than the flowed fillet (i.e., the fillet ratio of 1.61 ± 0.33, 1.20 ± 0.16, 2.25 ± 0.54). Previous work using NASA's Reduced Gravity Aircraft (Ref. 1) showed mean values of 1.08±0.04 for flux-cored solder in normal gravity. For solid-core solder with external flux, the reduced-gravity ratio was similar, specifically 1.16 ±0.04. Although the number of samples in the current tests were limited making true statistical comparisons difficult, the results are generally consistent with the results obtained in the previous aircraft experiments and show that the absence of gravity has an effect on drawing solder from the soldered to flowed fillet.

In normal gravity (Table 9 and Table 12), the fillet ratio were 0.98 ± 0.40 and 1.38 ± 0.29, for flux-cored and solid solder, respectively. The previous work showed mean values of 0.76 ± 0.03for flux-cored solder in normal gravity and 0.71± 0.10 for solid-core solder with external flux. The solders and fluxes used in both cases were similar, with the exception of the eutectic solder in this study, as were the circuit board layouts and soldering techniques. While the results for the flux-cored solder are consistent (within the confidence intervals) with the previous normal gravity results, the authors believe that the higher fillet ratio for solid-core wire was due to the inherent difficulty experienced by the operator in making the solid core wire flow properly leaving more solder on the soldered side of the joint.

[2] For some cases using an external liquid flux, solder joint were select that did not pass inspection but were functional to allow for large sample sizes.

TABLE 8.—SOLDERED FILLET TO FLOWED FILLET LENGTH RATIO FOR REDUCED GRAVITY, 60% TIN-40% LEAD ROSIN FLUX CORED SAMPLES

Joint	Fillet ratio
A13	1.14
A14	1.29
A25	2.00
A29	0.95
A30	1.32
B6	2.00
B8	1.39
B13	1.91
B21	1.40
B29	2.72
Average	1.61
Standard deviation	0.53
95% confidence int.	0.33

TABLE 9.—SOLDERED FILLET TO FLOWED FILLET LENGTH RATIO FOR NORMAL GRAVITY, 60% TIN-40% LEAD ROSIN FLUX CORED SAMPLES.

Joint	Fillet ratio
GA1	0.83
GA4	1.78
GA5	0.68
GA6	0.83
GA7	0.78
Average	0.98
Standard deviation	0.45
95% confidence int.	0.40

TABLE 10.—SOLDERED FILLET TO FLOWED FILLET LENGTH RATIO FOR REDUCED GRAVITY, EUTECTIC ROSIN FLUX CORED SAMPLES

Joint	Fillet ratio
E26	1.13
F6	1.69
F9	1.00
F11	1.14
F13	1.07
F31	1.21
F32	1.19
Average	1.20
Standard deviation	0.22
95% confidence int.	0.16

TABLE 11.—SOLDERED FILLET TO FLOWED FILLET LENGTH RATIO FOR REDUCED GRAVITY, 60% TIN-40% LEAD EXTERNAL LIQUID FLUX SAMPLES

Joint	Fillet ratio
J19	1.68
J20	3.81
J22	3.11
J28	1.38
J29	2.48
K7	1.90
K14	2.17
K22	3.12
K23	1.15
K25	1.70
Average	2.25
Standard deviation	0.86
95% confidence int.	0.54

TABLE 12.—SOLDERED FILLET TO FLOWED FILLET LENGTH RATIO FOR NORMAL GRAVITY, 60% TIN-40% LEAD EXTERNAL LIQUID FLUX SAMPLES

Joint	Fillet ratio
GC3	1.64
GC6	1.61
GC7	1.62
GC8	1.04
GC10	0.99
Average	1.38
Standard deviation	0.33
95% confidence int.	0.29

The key differences between the two studies were the prior experience of the operator and the soldering iron temperature. The operator in this study had less soldering experience and training than those individuals in the earlier work. Also, the solder iron tip temperature in reduced gravity aircraft tests was higher (~700 °F) compared with the ISS maximum tip temperature (~600 °F). Both of these make soldering with solid-core solder more difficult and could prevent proper solder flow.

3.5 Internal Void Analysis

Analyzing the sequence of images provided by CT scans of the solder joints provides two sets of data. One is a graph of the void fraction for each image, which shows the distribution of voids within a solder joint. The second set of data is the result of integrating the void volume and total volume of the joint in the soldered fillet, annular, and flowed fillet regions, and using those data to find the void volume fraction in each region and for the entire joint. The first part of this section will present typical results of the distribution of voids within a joint for each solder and flux type and gravity level (reduced and normal). The second section will present the integrated void volume fraction for each joint.

The data in Figure 18 and Figure 19 show the total joint area for each slice and the void area for each slice, respectively, for a 60% tin-40% lead, flux cored solder joint formed in reduced gravity. These data are representative of the general trends seen in all the analyzed joints, and illustrate the process of analyzing the data. The “Position Along Joint” begins with the first instance of solder on the soldered fillet, and progresses along the lead towards the circuit board. Red vertical lines on the graph indicate the region where the widening fillet transitions to the constant area of the annular region, which combined with the effects of plating on the circuit board make analysis in this region difficult. The data in Figure 18 shows how the fillets increase in size along the lead, reaching a maximum at the circuit card plating surface. The opposite trend is seen in the flowed fillet, as expected. The annular region has a relatively constant area, which is expected since the circuit card through-hole itself has a constant area. Figure 19 shows the void area for each slice along the solder joint, demonstrating how the voids can appear in clusters, and grow in size to a maximum, then decrease in size. The slice void fraction is the ratio of the void area to the total area for each slice, or data point in Figure 18 and Figure 19, respectively. The total joint volume is the integrated area under the curves in Figure 18, while the total void volume is the integrated area under the curves in Figure 19. The ratio of total void volume to total joint volume is reported later as the void volume ratio.

Figure 20 shows the void fraction distribution in a typical joint formed in reduced gravity using 60% tin-40% lead solder with a rosin flux core, plotting the image or slice void fraction as a function of distance along the joint. The results presented in Figure 20 are typical for other joints with 60% tin-40% lead flux cored solder formed in reduced gravity. The majority of voids form in the annular region, and usually show growing and shrinking void fractions as new voids form, grow to a maximum, then begin shrinking. The void fraction in this region also typically has a minimum, non-zero level as voids are always present in some amount for each location within the joint. The fillets in this, and similar, joints have smaller void fractions than the annular region of the joint. The annular region has several areas where the void fraction grows to a maximum then decreases, while the fillets typically have only one such area.

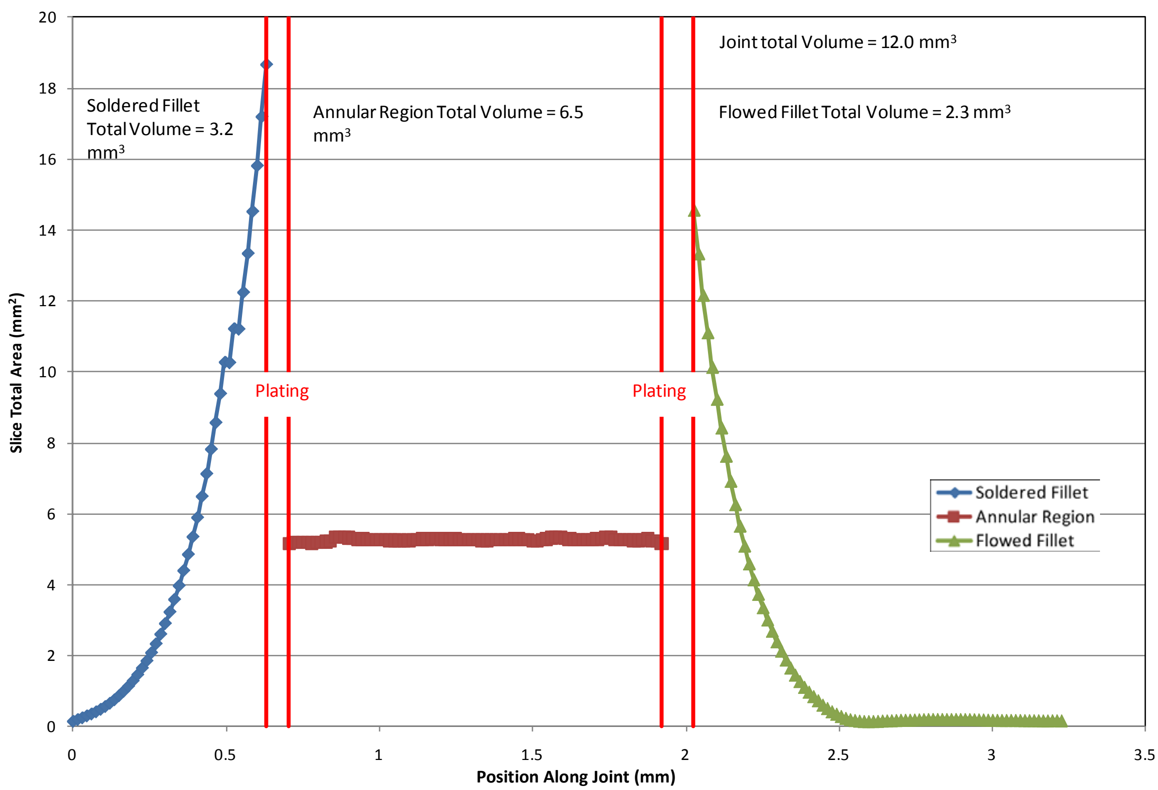

Figure 18.—Slice total area along a joint formed in reduced gravity using 60% tin-40% lead flux cored solder wire (Joint A29).

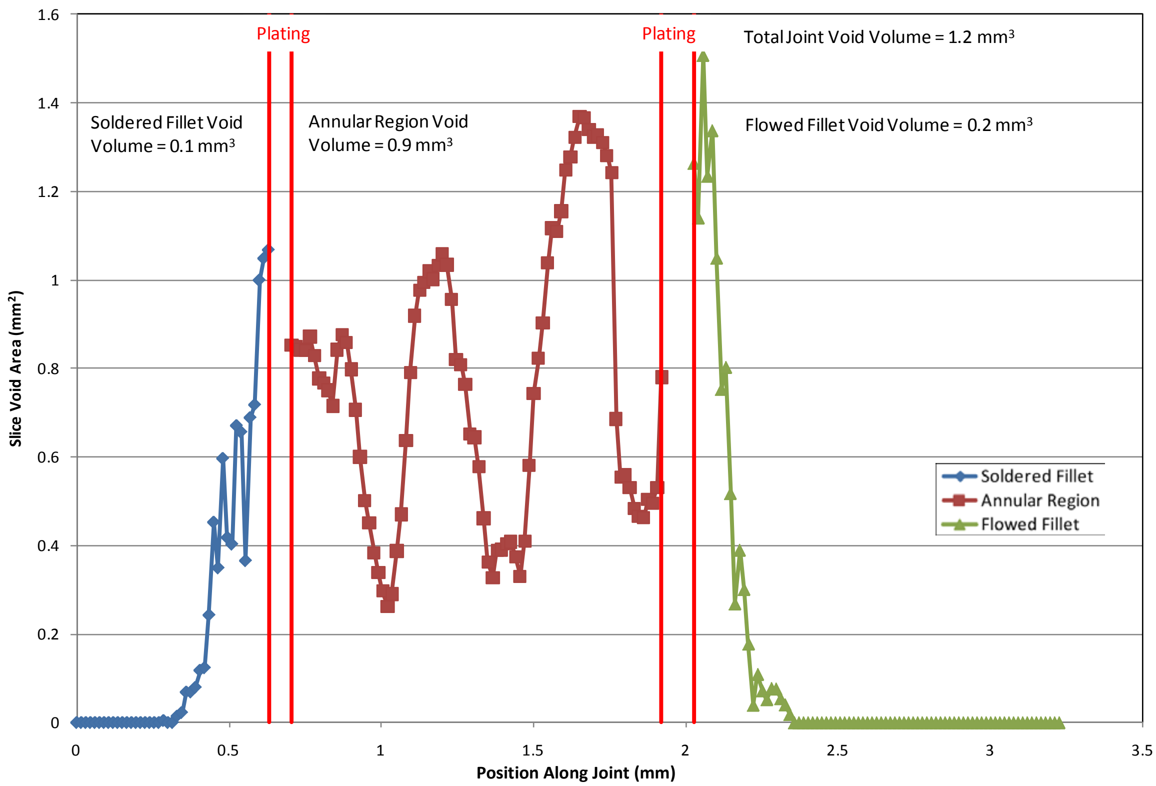

Figure 19.—Slice void area along a joint formed in reduced gravity using 60% tin-40% lead flux cored solder wire (Joint A29).

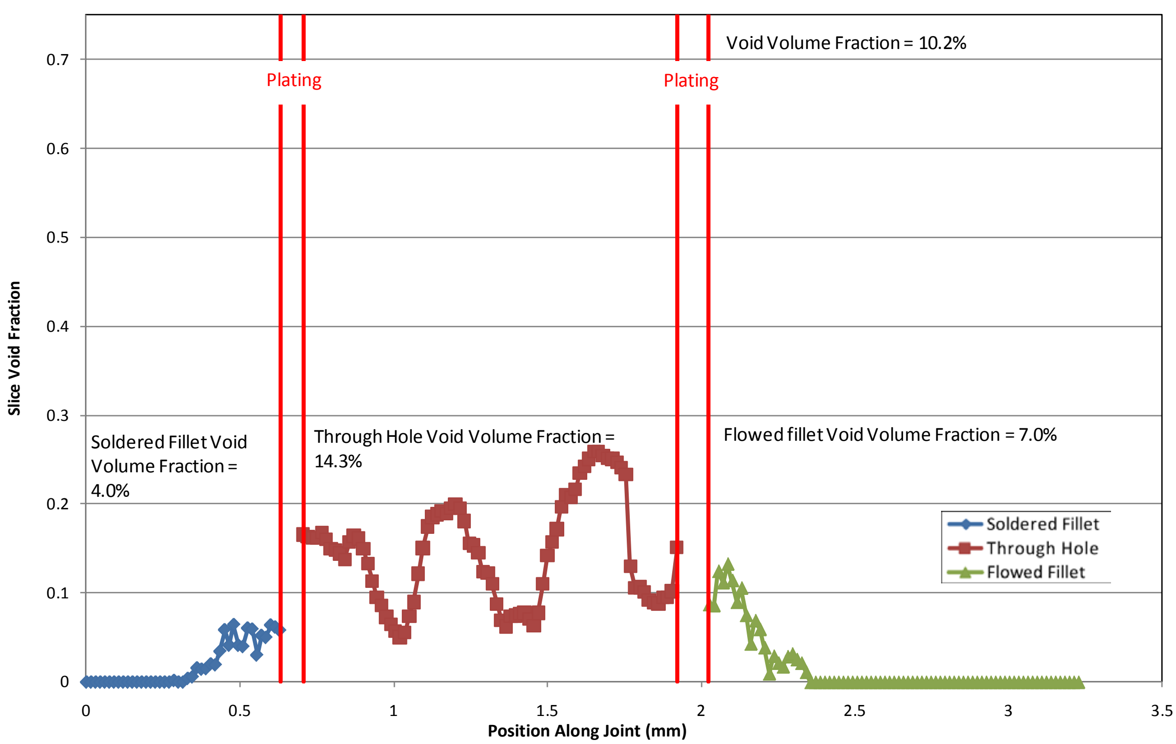

Figure 20.—Slice Void Fraction along the interior of a joint formed in reduced gravity with 60% tin-40% lead, rosin flux cored solder (Joint A29).

Figure 21 shows the void fraction distribution for a solder joint formed in normal gravity with the same 60% tin-40% lead rosin flux cored wire as shown in Figure 20. As was typical when comparing joints formed in normal gravity to those formed in reduced gravity, the normal gravity case presented fewer internal voids than in the reduced gravity cases. The results in the case shown indicate a larger void fraction in the normal gravity soldered fillet than in the one formed in reduced gravity, but variation from joint to joint makes this difficult to conclusively demonstrate. The large void fraction at the top of the soldered fillet (small "Position Along Joint" values) is unusual for the solder joints studied in this experiment.

The data in Figure 22 shows the void fraction distribution in a solder joint formed with eutectic solder wire with a rosin flux core in reduced gravity. The distribution of voids in this joint is typical for other joints formed in reduced gravity with this solder wire or with the 60% tin-40% lead solder wire. The annular region has a larger void volume fraction, and maximum slice void fraction, than in the fillets, and the distribution of voids in each section tends to be random. The distribution again shows regions where the void fraction, and the number and size of voids, increases to a maximum, then falls, with the cycle repeating in the annular region.

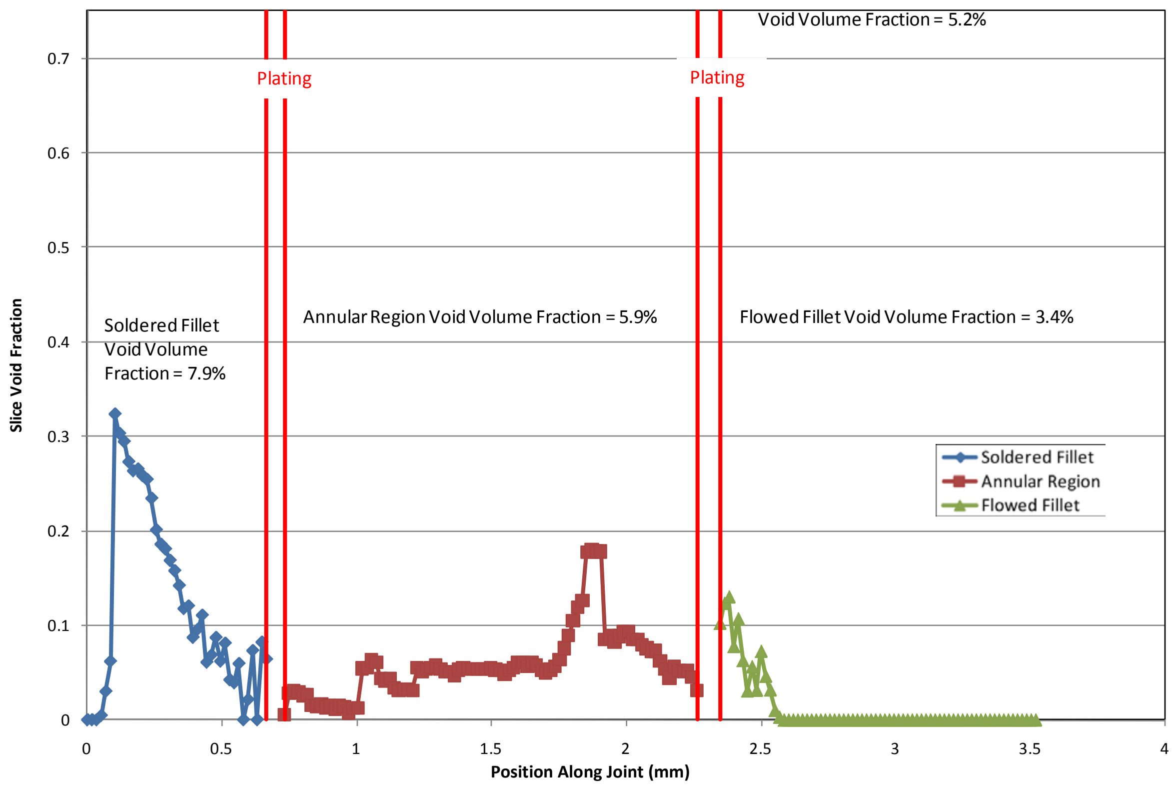

Figure 21.—Slice Void Fraction along the interior of a joint formed in normal gravity with 60% tin-40% lead, rosin flux cored solder (Joint GA6).

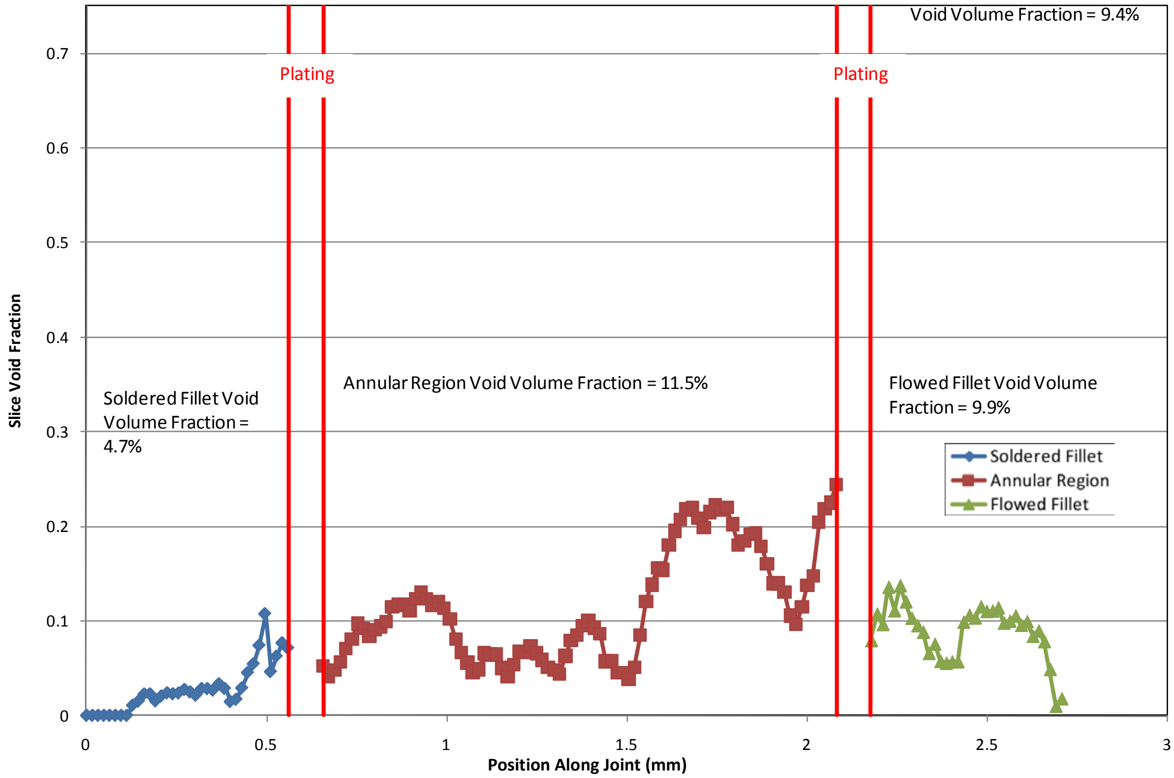

Figure 22.—Slice Void Fraction along the interior of a joint formed in reduced gravity with eutectic, rosin flux cored solder (Joint F9).

The graph in Figure 23 shows the void fraction distribution for a joint formed in reduced gravity with a solid 60% tin-40% lead solder wire and external liquid flux. As with other cases, the annular region had the largest amount of voids, both overall and as a maximum for a particular image or slice. This joint, as with others, has a larger amount of voiding in the annular region than in the fillets, with regions where the amount and/or size of the voids grows towards a maxima, then decreases, only to increase at a point further along in the joint.

Figure 24 presents the void fraction distribution in a joint formed in normal gravity, with solid 60% tin-40% lead solder with an external liquid flux. As is typical with these joints, the overall void volume fraction, and the void volume fraction for the joint as a whole, is very low compared to all other solder and flux types. Also typical for these joints, each region only shows one area where a void or small number of voids forms, grows, then shrinks, with the rest of the joint virtually free of voids. Void fraction distribution for all joints analyzed are shown in Appendix B.

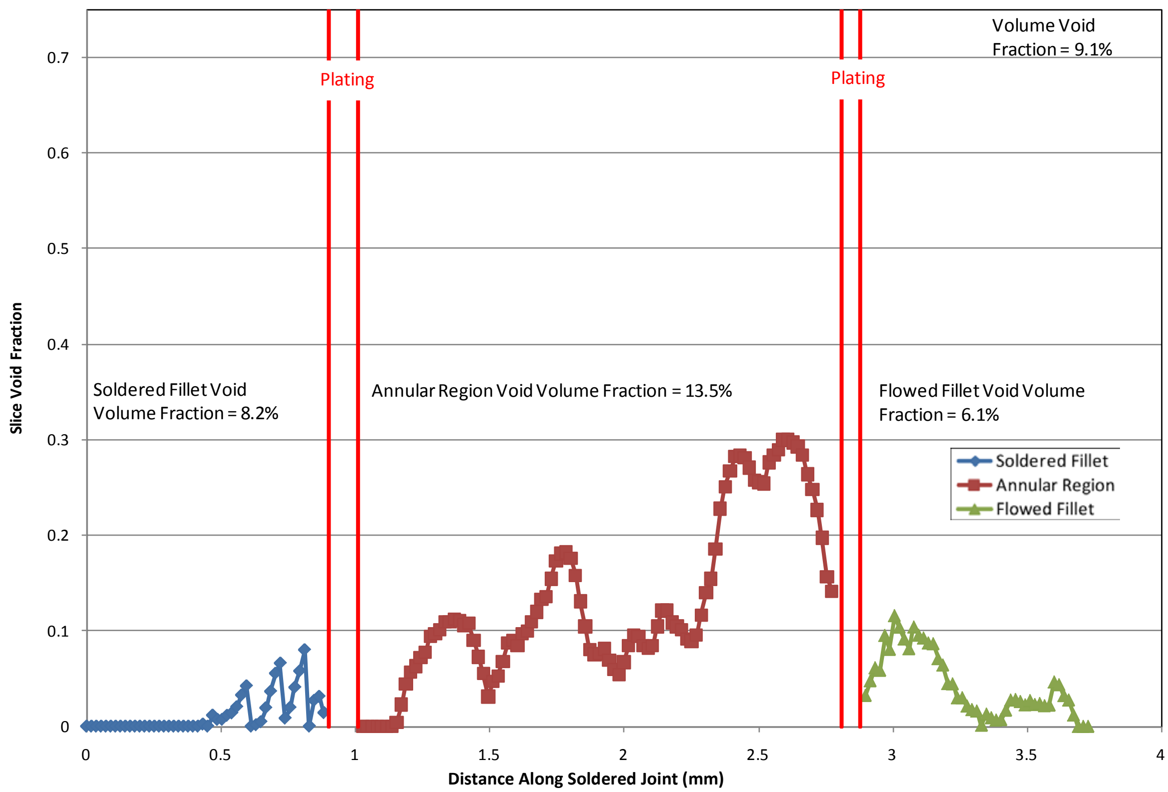

Figure 23.—Slice Void Fraction along the interior of a joint formed in reduced gravity with 60% tin-40% lead solder wire, external liquid rosin flux (Joint K23).

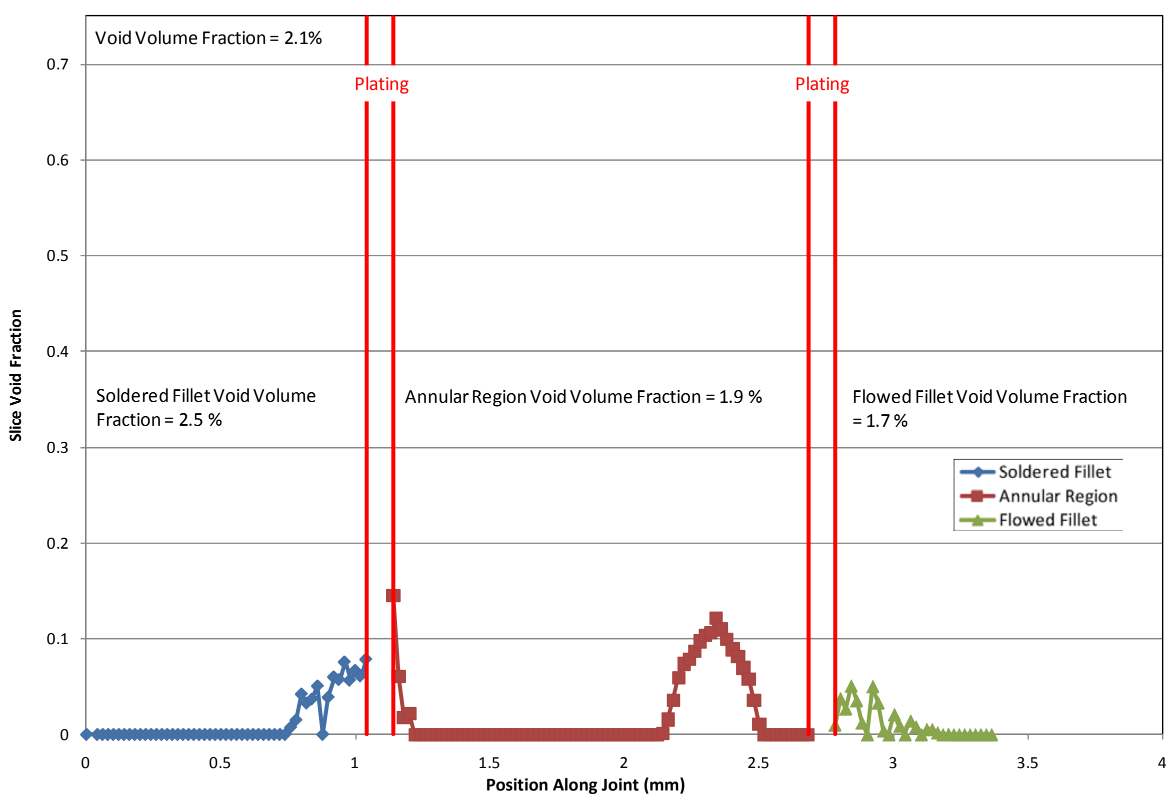

Figure 24.—Slice Void Fraction along the interior of a joint formed in normal gravity with 60% tin-40% lead solder wire, external liquid rosin flux (Joint GC3).

After analyzing individual images from the joints, the statistics for each solder and flux combination, in both reduced and normal gravity, was analyzed. Table 13 through Table 17 present the void volume fraction in the soldered fillet, annular region, and flowed fillet for each joint, as well as the overall void volume fraction for that joint. The tables also include the average and standard deviation of the void volume fraction for each joint region, providing an overall metric on the internal voiding typical for a solder and flux as well as the variation in voiding from joint to joint. The first of these tables, Table 13, shows the void volume fractions for joints produced in microgravity with 60% tin-40% lead rosin flux cored solder. These results show quite a bit of variation in void volume fraction from joint to joint, demonstrated by the large standard deviations, relative to the average values, of the void volume fractions. In all cases shown in Table 13, the annular region had a larger void volume fraction than either of the fillet regions.

Table 14 includes the void volume fraction results for solder joints formed in normal gravity with 60%tin-40% lead rosin flux cored solder. Overall, total void volume fraction for these joints is smaller than the void volume fraction for joints formed in reduced gravity using the same solder and flux type. The distribution of voids within the joint has also changed, with more voids in the soldered fillet and fewer voids in the annular region for normal gravity joints, compared to those in joints formed in reduced gravity. The graphs of individual slice void fraction show this trend in some cases, but the large variation from test to test in both gravity regimes makes a definite conclusion difficult.

TABLE 13.—VOID VOLUME FRACTION FOR REDUCED GRAVITY, 60% TIN-40% LEAD ROSIN FLUX CORED SAMPLES

Solder joint	Soldered fillet void volume fraction (%)	Annular region void volume fraction (%)	Flowed fillet void volume fraction (%)	Void volume fraction (%)
A13	1.3	39.5	4.4	15.5
A14	15.1	45.2	16.1	23.8
A25	1.7	23.3	5.8	13.5
A29	4.0	14.3	7.0	10.2
A30	2.4	19.6	12.4	12.6
B6	3.0	9.2	1.8	4.8
B8	3.8	21.7	8.4	9.4
B13	3.3	29.9	3.2	12.8
B21	2.3	8.8	2.8	4.7
B29	4.0	21.5	5.2	11.0
Average void volume fraction	4.1	23.3	6.7	11.8
Standard deviation	4.0	12.0	4.5	5.5

TABLE 14.—VOID VOLUME FRACTION FOR NORMAL GRAVITY, 60% TIN-40% LEAD ROSIN FLUX CORED SAMPLES

Solder joint	Soldered fillet void volume fraction (%)	Annular region void volume fraction (%)	Flowed fillet void volume fraction (%)	Void volume fraction (%)
GA1	1.8	18.4	4.1	11.0
GA4	15.3	10.2	13.4	11.4
GA5	7.2	12.5	0.7	8.1
GA6	7.9	5.9	3.4	5.2
GA7	3.7	5.0	0.7	3.3
Average void volume fraction	7.2	10.4	4.5	7.8
Standard deviation	5.2	5.4	5.2	3.5

TABLE 15.—VOID VOLUME FRACTION FOR REDUCED GRAVITY, EUTECTIC ROSIN FLUX CORED SAMPLES

Solder joint	Soldered fillet void volume fraction (%)	Annular region void volume fraction (%)	Flowed fillet void volume fraction (%)	Void volume fraction (%)
E26	3.6	8.8	7.1	6.6
F6	2.7	28.9	6.7	12.9
F9	4.7	11.5	9.9	9.4
F11	4.2	26.5	7.7	17.1
F13	0.8	7.4	3.2	4.3
F31	9.5	10.2	19.7	13.2
F32	1.2	13.8	1.3	4.4
Average void volume fraction	3.8	15.3	7.9	9.7
Standard deviation	2.9	8.7	5.9	4.9

TABLE 16.—VOID VOLUME FRACTION FOR REDUCED GRAVITY, 60% TIN-40% LEAD EXTERNAL LIQUID ROSIN FLUX SAMPLES

Solder joint	Soldered fillet void volume fraction (%)	Annular region void volume fraction (%)	Flowed fillet void volume fraction (%)	Total void volume fraction (%)
J19	3.8	26.5	7.3	10.9
J20	1.0	3.2	1.0	1.7
J22	1.4	9.3	2.5	4.0
J28	1.9	10.7	2.2	4.9
J29	12.1	17.5	3.8	11.3
K7	3.5	8.0	3.5	4.9
K14	4.0	18.1	12.4	10.7
K22	6.4	21.9	3.3	9.4
K23	8.2	13.5	6.1	9.1
K25	0.9	7.4	6.4	4.5
Average void volume fraction	4.3	13.6	4.9	7.1
Standard deviation	3.6	7.3	3.3	3.5

TABLE 17.—VOID VOLUME FRACTION FOR NORMAL GRAVITY, 60% TIN-40% LEAD EXTERNAL LIQUID ROSIN FLUX SAMPLES

Solder joint	Soldered fillet void volume fraction (%)	Annular region void volume fraction (%)	Flowed fillet void volume fraction (%)	Void volume fraction (%)
GC3	2.5	1.9	1.7	2.1
GC6	3.6	10.9	1.1	5.3
GC7	3.1	1.2	0.6	1.8
GC8	0.1	0.8	0.6	0.5
GC10	0.9	10.5	2.9	4.2
Average void volume fraction	2.0	5.1	1.4	2.8
Standard deviation	1.5	5.2	1.0	1.9

The void volume fraction data for eutectic, rosin flux cored samples formed in reduced gravity are shown in Table 15. As with the 60% tin-40% lead solder joint results shown in Table 13, the eutectic joint samples had a wide range of void volume fractions in all three joint regions, as well as for the joints as a whole. The eutectic solder joints showed less void formation in the soldered fillet and annular regions, but somewhat more void formation in the flowed fillet, than the 60% tin-40% lead joints. Overall, the eutectic solder showed less void formation.

Due to time constraints, the SoRGE team was unable to obtain normal gravity samples using the eutectic solder with a rosin flux core. The team decided to use samples produced in normal gravity with this solder and flux combination from previous work (Ref. 4), and use this data as a basis of comparison. The previous tests produced two analyzed solder joints, and report a "total voiding" measure by summing the void area in each image describing the entire joint, and dividing by the sum of the total area in each image. This is similar, but not equal, to the integration method used for the SoRGE data, and will provide a relative comparison for the results. The "total voiding" for these earlier samples are 0.2 and 0.6 percent, and are significantly smaller than the void volume fractions seen in this work.

The data included in Table 16 shows the void volume fraction for joints formed in reduced gravity using 60% lead-40% tin solder with an external liquid flux, used in previous work (Ref. 4) as a method for reducing internal voids. As with the other solder and flux combinations formed in reduced gravity, the majority of voids are found in the annular region of the joint in most of these cases, with a high degree of variability in void volume fraction from joint to joint, both in the three sub-sections of the joint as well as in the whole joint. The average void volume fraction for the whole joint is smaller for these cases using external flux than the other cases using a flux cored solder.

The results from forming solder joints in normal gravity using 60% tin-40% lead solder with an external liquid flux are shown in Table 17. These results show a large reduction in void formation in all three regions of the joint, as well as for the joint overall, compared to all other results. These normal gravity results show that most of the voids formed in the annular region, and that the soldered fillet developed more internal voids than the flowed fillet, in most cases. As with the other cases, the results have a large standard deviation and therefore large variability in void formation from joint to joint.

4.0 Discussion and Recommendations

A key finding of the SoRGE SDTO is the capability of crew members to perform soldering operations, and potentially electronics repair operations, in the reduced gravity, closed environment of a space vehicle or habitat. As the data in Table 2 through Table 7 show, the astronaut was able to form solder joints that pass NASA standards with all the solder and flux types, though all the solder operations generated fewer passing joints than expected. The results of interviews and inspections provide some reasons for these results. The astronaut did not receive training prior to the mission, and did not have any previous experience to use as a reference. While the astronaut stated, and the video record shows, that the written procedures and training video were helpful, some additional training and experience prior to launch would have provided a better foundation for performing the soldering work. Many of the difficulties seen in the video record and in the inspection of the circuit boards point to a lack of practice and instruction prior to the SoRGE operations, not to difficulties inherent to operating in reduced gravity. Practice boards and other "on the job" training would also have been helpful, allowing the astronaut to gain experience prior to performing the soldering work. The astronaut also commented that contact with a ground support team would have been helpful, to provide pointers or answer questions as problems arose, or feedback based on previous work for techniques to try or to reinforce good practices.

Another area where the astronaut encountered difficulty was in the tools available. The SoRGE team did not expect the damaged soldering iron tip in the U.S. Soldering Kit, and while the tip was able to melt solder and form useful joints, it is not known how this damaged tip affected the crew's performance. A second difficulty mentioned by the crew was visibility. This difficulty manifested in two ways. First, the soft sides of the MWA Containment Area were difficult to see through, due to many wrinkles in the soft sides of the Containment Area due to unpacking, packing, and storing in a confined space. This left only a small view port for direct viewing access into the Containment Area. A second problem was magnification. While the Containment Area required a larger distance between the crew and the joint on the circuit board than normally found in work in normal gravity, the joint size itself is small enough to warrant some magnification, if only to improve the comfort of the person performing the work. One technique developed by the crew which alleviated both the visibility and magnification problems was to use the viewfinder screen on the video camera as a magnification aid, and to use this screen to see the soldering process in real time.

Another issue affecting the joint inspection results is the solder and flux combinations used. As the comments from the crew and the results presented in Table 2 through Table 7 show, it was more difficult to form solder joints using the solid solder wire with external liquid flux than with flux cored solder. Use of liquid flux is more difficult because once activated, by heating the joint area with the soldering iron, the flux will lose effectiveness with additional time and heat, making the application of solder critical. Another difficulty is the liquid flux may not wet all the areas where solder must wet and flow to form a joint, such as into or through a through-hole or onto the plating on the flowed fillet side of the circuit board. Flux cored solder wires do not experience this problem, because the flux is mixed with the liquid solder and flows with the solder, preparing the surface as it flows.

One reason to use an external liquid flux, despite the difficulties found soldering with this material, is a reduction in void formation. As the data in Table 13 through Table 17show, the use of an external liquid flux lead to the smallest values of void volume fraction compared to other solder and flux combinations in reduced and normal gravity. The amount of voids present in a joint decreased when using a eutectic, flux cored solder compared to the 60% tin-40% lead cored solder case in reduced gravity. The void volume fraction was further reduced for joints with the solid 60% tin-40% lead solder with an external liquid flux. While these average void volume fraction data are encouraging, it should be noted that, from joint to joint, the void volume fraction varies quite a bit, and the performance of the person soldering, for inexperienced and experienced technicians (or crew members), can affect the presence of voids within a solder joint.

The results of the joint analysis also point out some gravitational effects on the formation of solder joints. First, the amount of voiding in the joints, measured by the void volume fraction, decreased for joints formed in normal gravity compared to those formed in reduced gravity with the same solder and flux combination. The SoRGE team has two hypotheses for this result. First, the crew may exhibit differences in soldering technique from reduced to normal gravity, and the improved techniques help alleviate void formation. Examination of the soldering techniques used during the flight by the crew, as well as after the flight during the production of ground samples, does not reveal any substantive differences in soldering technique, in terms of iron placement, amount of time the iron tip is in contact with the joint area, or amount or rate of solder wire fed into the joint. Since the crew did not show improved soldering techniques between normal and reduced gravity, there must be another explanation for the increase in voids. This second hypothesis is a gravitational effect where buoyancy in normal gravity forces the trapped gas bubbles within the still-liquid solder joint to escape during heating, but the absence of this force in reduced gravity likely helps to trap the gas bubbles within the solder and leads to an increase in void formation.

The void volume fraction results for the three sections of a solder joint supports the hypothesis that buoyancy, or the absence of it, affects the formation and presence of void defects in the solder joint. In the case of 60% tin-40% lead solders, with either a flux cored wire or solid wire with external liquid flux, the void volume fraction decreased in the through-hole section of the joint when comparing normal gravity results to reduced gravity results. Further, the ratio of void volume fraction of the soldered fillet to the through-hole region increased in normal gravity cases compared to reduced gravity cases. This trend can be seen in many, though not all, of the graphs of slice void fraction to joint position, found in the Appendix. This trend seems to indicate that the gas bubbles evolved within the liquid solder while forming the joint are escaping by travelling upward through the joint from the through-hole region, and perhaps the flowed fillet, up to the soldered fillet and escaping to the atmosphere when performing work in normal gravity. (Recall that the gravity vector, in normal gravity operations, points down from the soldered fillet to the flowed fillet.) This difference in void distribution with respect to gravity seems to indicate a buoyancy effect, but more analysis and testing is required to understand the role of buoyancy and other forces, such as surface tension, within a molten solder joint in various gravitational environments.

Future work, specifically for the SoRGE program, is to complete work on the remaining six kits (two for each solder and flux type) on the ISS. Increasing the amount of data available will help improve the statistical validity of these results, and provide a measure of the differences between operators. The future work will also provide an opportunity to work with a new soldering iron tip, as the current tip may have been damaged prior to the SoRGE work. Future operations may provide an opportunity for training the crew in soldering prior to launch, which will make the operations easier for the crew and return a larger number of solder joints. Finally, future experiments beyond SoRGE should explore the feasibility and improvements required for performing other electronics repair tasks, including removing conformal coating, removing and replacing other types and sizes of components, repairing damage to a circuit board, and other tasks that simulate repairs a future crew may face.

4.1 Recommendations

As the results of this work show, it is feasible to perform soldering in reduced gravity, which is a key step in performing electronics repairs during a space mission. Enabling an electronics repair capability will help alleviate launch mass and spares storage issues, as the ability to perform repairs allows mission planners to stock components, parts, circuit boards, and tools rather than full sized replacement ORUs. A repair capability also provides flexibility for crew members and ground support teams to recover from unexpected failures, or to take advantage of unexpected opportunities if they arise. NASA should perform future studies and planning to enable a repair capability, some of which have been highlighted in SoRGE.

Based on the results of the SoRGE testing performed to date, NASA should provide crews with a eutectic, flux cored solder wire for general electronics repairs in future missions. The eutectic solder wire used here was easy to work with, compared to the solid solder wire with external liquid flux, returning many solder joints that passed the NASA standards (Ref. 6) as well as joints that did not pass but were functional. Joints formed with the eutectic solder wire generally presented fewer internal voids than those formed with the 60% tin-40% lead flux cored solder as well. While specific applications may require more extensive void mitigation, and therefore other solder, flux, and solder techniques, a flux cored eutectic solder wire presents a compromise between void formation and ease of use appropriate for most repair tasks. Additionally, NASA should determine what repairs call for additional void mitigation techniques and materials, such as the use of solid solder wire and external liquid flux. In industry the amount of acceptable voiding depends on the function and criticality of the overall product, and each manufacturer must decide this on their own, with very few “rules of thumb” to guide the decision.

To make an electronics repair capability a success, NASA should increase the training available to crew members. This can include increased training prior to the mission, with refresher courses to maintain and improve skills with structured practice. NASA may also consider selecting a crew member with experience in working with and repairing electronics to lead this effort during a mission, while still providing other crew members additional training. The SoRGE work has shown that a training video is very useful for the crew, and ground support teams should provide training videos for expected activities and have the capability to produce and transmit new ones as the need arises. The crew should also have access to practice materials—circuit boards and components—during a mission both to maintain competence as well as to practice a repair prior to performing it. An additional aspect of this training is determining the criteria for acceptable and unacceptable repair outcomes in terms of inspections and testing. While NASA has standards in place (Ref. 6, for example) they reflect work performed in well-equipped manufacturing and laboratory settings which may not be available to a crew performing a repair in a space vehicle. The existing standards and tests also include circumstances applicable for the original unit, but not for the repaired item. For example, manufacturers must test circuit boards and electronic assemblies to survive launch stresses and vibrations. A repair to that unit on the ISS may not require such testing; it is already in orbit, and will never experience launch stresses.

NASA should also pursue an improvement to the tools available to the crew for performing electronics repairs. These include small tools, such as tweezers and cutters and other electronics hand tools, for grasping and manipulating small components. The crew should also have access to a better soldering tool. This includes a soldering wand with temperature control and hotter operating temperatures, which will improve the range of components that may be worked on, alleviate heat loss through the circuit card conducting layers and heat sinks, and make the soldering tasks easier for the crew. The electronics repair tool kit should also include a wide variety of soldering iron tips. The soldering iron tips are designed for removing and replacing components of specific size and shape, from resistors to chips, and make these work tasks easier for the crew. The Containment Area should also be redesigned, improving the visibility of the work within the area, and perhaps making the area smaller and easier to work within, as the astronaut performing SoRGE work suggested. The crew should also have access to magnification aids, such as magnifying visors of different powers, a microscope mounted on a swivel or mounting arm in the Containment Area and MWA, and/or video magnification improving the method used by the crew during SoRGE operations. These tools, particularly the magnification improvements, will not only aid in the removal and replacement of electronics parts, but will also prove useful in other repair or operational tasks.

An area of electronics repair not included in the SoRGE work is the diagnosis and testing of electronics. These steps are necessary to isolate a fault, not only to find the components requiring replacement but to trace the failure to a root cause, allowing the crew and ground support teams to alleviate that risk and help prevent future failures. Additionally, the testing of a circuit after a repair must occur to ensure that the repair was successful, that no additional damage occurred during the repair, and that the circuit will function and not cause further damage when returned to service. While these aspects are outside the scope of SoRGE, they are necessary parts to enabling an electronics repair capability. More details regarding a concept for diagnostics and test capabilities aboard a space vehicle proposed by the CLEAR team can be found in other work (Ref. 9).

While SoRGE is one of the first steps to providing an electronics repair capability, it does show that these repairs are feasible, and with further work NASA missions to the ISS and beyond can benefit from this repair capability.

Appendix A.—Tables of Board Visual Inspection Results

TABLE 18.—INSPECTION RESULTS FROM 60% TIN-40%LEAD, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD A, SOLDERED FILLET

Joint number	Pass/fail	Notes
1	Fail	Insufficient solder, poor wetting, void
2	Fail	Insufficient solder, poor wetting, void
3	Fail	Very little solder on lead only
4	Fail	No solder
5	Pass	
6	Fail	Very little solder on lead only, spike
7	Pass	
8	Fail	Very little solder on lead only, spike
9	Pass (-)	Solder drag
10	Pass	
11	Fail	Solder on lead only
12	Pass (-)	Wetting on pad
13	Pass	
14	Pass	
15	Fail	Very little solder on lead only
16	Pass	
17	Pass (-)	Pit
18	Pass	
19	Fail	Solder on lead only, spike
20	Fail	Poor wetting, drag
21	Fail	Poor wetting, void
22	Fail	Very little solder on lead only
23	Pass	
24	Pass	
25	Pass	
26	Fail	Poor wetting, void
27	Fail	Very little solder on pad
28	Pass	
29	Pass (-)	
30	Pass	
31	Fail	Very little solder on lead only, spike
32	Fail	Little solder on lead only, spike

TABLE 19.—INSPECTION RESULTS FROM 60% TIN-40%LEAD, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD A, FLOWED FILLET

Joint number	Pass/fail	Notes
1	Fail	No fillet, poor wetting in through hole
2	Fail	No fillet, no solder in through hole
3	Fail	No fillet, no solder in through hole
4	Fail	No fillet, no solder in through hole
5	Fail	No fillet, no solder in through hole
6	Fail	No fillet, no solder in through hole
7	Fail	No fillet, poor wetting in through hole
8	Fail	No fillet, no solder in through hole
9	Fail	No fillet, no solder in through hole
10	Fail	No fillet, poor wetting in through hole
11	Fail	No fillet, no solder in through hole
12	Pass	
13	Pass	
14	Pass	
15	Fail	No fillet, no solder in through hole
16	Fail	No fillet, poor wetting in through hole
17	Fail	No fillet, poor wetting in through hole
18	Fail	No fillet, poor wetting in through hole
19	Fail	No fillet, no solder in through hole
20	Fail	No fillet, poor wetting in through hole
21	Fail	No fillet, poor wetting in through hole
22	Fail	No fillet, no solder in through hole
23	Fail	No fillet, poor wetting in through hole
24	Fail	No fillet, poor wetting in through hole
25	Pass	
26	Fail	No fillet, poor wetting in through hole
27	Fail	No fillet, no solder in through hole
28	Pass	
29	Pass	
30	Pass	
31	Fail	No fillet, no solder in through hole
32	Fail	No fillet, no solder in through hole

TABLE 20.—INSPECTION RESULTS FROM 60% TIN-40%LEAD, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD B, SOLDERED FILLET

Joint number	Pass/fail	Notes
1	Fail	Excessive solder
2	Pass	Burnt flux
3	Fail	Excessive solder
4	Fail	Spike
5	Pass	
6	Pass	
7	Pass	
8	Pass (-)	Little spikes
9	Pass (-)	Borderline excessive solder, solder drag
10	Pass	
11	Pass	
12	Pass	
13	Pass	
14	Pass (-)	Spike
15	Fail	Big spike, drag
16	Fail	Big spike, drag
17	Fail	Spike
18	Pass (-)	Borderline excessive solder
19	Pass	
20	Fail	Poor wetting, void, spike
21	Pass	
22	Fail	Solder on lead only, spike
23	Pass (-)	Spike
24	Fail	Big spike
25	Pass	Borderline excessive solder
26	Fail	Spike
27	Fail	Spike
28	Fail	Excessive solder, spike
29	Pass	
30	Pass	
31	Fail	Solder on lead only, spike, burnt flux
32	Fail	Spike

TABLE 21.—INSPECTION RESULTS FROM 60% TIN-40%LEAD, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD B, FLOWED FILLET

Joint number	Pass/fail	Notes
1	Pass	
2	Fail	No fillet, poor wetting in through hole and lead
3	Pass	
4	Pass (-)	
5	Fail	Partial fillet, poor wetting in through hole and lead
6	Pass	
7	Fail	No fillet
8	Pass	
9	Pass	
10	Fail	Partial fillet, poor wetting in through hole and lead
11	Fail	No fillet
12	Fail	Reflow line of solder on periphery of pad
13	Pass	
14	Fail	No fillet
15	Pass	
16	Pass	
17	Pass	
18	Fail	No fillet
19	Fail	Partial fillet, poor wetting in through hole and lead
20	Fail	No fillet, poor wetting in through hole and lead
21	Pass	
22	Fail	No fillet, no solder in through hole
23	Fail	No fillet
24	Pass	
25	Fail	No fillet, no solder in through hole
26	Pass	
27	Pass	
28	Pass	
29	Pass	
30	Fail	No fillet
31	Fail	No fillet, no solder in through hole
32	Fail	No fillet

TABLE 22.—INSPECTION RESULTS FROM EUTECTIC, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD E, SOLDERED FILLET

Joint number	Pass/fail	Notes
1	Pass (-)	Little spike
2	Fail	Spike
3	Pass	
4	Fail	Spike
5	Fail	Spike
6	Fail	Spike
7	Fail	Spike
8	Fail	Spike, excessive solder
9	Fail	Spike
10	Fail	Spike
11	Fail	Spike
12	Fail	Spike
13	Fail	Spike
14	Fail	Spike
15	Fail	Spike
16	Fail	Solder on lead only, spike
17	Fail	Solder on lead only, spike
18	Fail	Spike
19	Fail	Solder on lead only, spike
20	Fail	Spike
21	Fail	Spike
22	Fail	No solder, flux only
23	Pass	
24	Fail	Very little solder on pad only
25	Pass	
26	Pass	
27	Pass	
28	Pass	
29	Fail	Spike
30	Pass (-)	Little spike
31	Fail	Spike
32	Fail	Solder on lead only, spike

TABLE 23.—INSPECTION RESULTS FROM EUTECTIC, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD E, FLOWED FILLET

Joint number	Pass/fail	Notes
1	Pass	No Notes
2	Fail	No fillet
3	Pass (?)	No fillet, may be absolute minimum (after cleaning)
4	Pass	
5	Pass	
6	Pass	
7	Pass	
8	Pass	
9	Fail	No fillet, no solder in plated through hole
10	Fail	No fillet, poor wetting in through hold and lead
11	Pass	
12	Fail	No fillet, poor wetting in through hole and lead
13	Fail	No fillet, may be absolute minimum
14	Fail	No fillet, poor wetting in through hole and lead
15	Pass	
16	Fail	No fillet, no solder in through hole
17	Fail	No fillet, no solder in through hole
18	Fail	No fillet, no solder in through hole
19	Fail	No fillet, no solder in through hole
20	Fail	No fillet, poor wetting in through hole and lead
21	Pass (?)	May be OK (minimum) (cleaning)
22	Fail	No fillet, no solder in through hole
23	Pass (?)	May be OK (minimum) (cleaning)
24	Fail	No fillet, no solder in through hole
25	Pass (?)	May be OK (minimum) (cleaning)
26	Pass	
27	Pass	
28	Fail	No fillet, poor wetting through hole and lead
29	Fail	No fillet, poor wetting through hole and lead
30	Pass	
31	Pass -	Wetting on pad
32	Fail	No fillet, no solder in through hole and lead

TABLE 24.—INSPECTION RESULTS FROM EUTECTIC, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD F, SOLDERED FILLET

Joint number	Pass/fail	Notes
1	Pass (-)	Solder drag
2	Fail	Very little solder on lead only, no fillet
3	Pass (-)	Small spike
4	Pass	
5	Fail	Very little solder on lead only with spike, no fillet
6	Pass	
7	Fail	Spike
8	Pass	
9	Pass	
10	Pass (-)	Spike
11	Pass	
12	Pass	
13	Pass	
14	Pass (-)	Spike
15	Fail	Very little solder on lead only with spike, no fillet
16	Fail	Very little solder on lead only with spike, no fillet
17	Fail	Solder ball on lead only, no fillet
18	Fail	Solder on lead only, large spike
19	Pass (-)	Small spike
20	Pass	
21	Fail	Poor wetting in hole, no fillet, large spike
22	Pass	
23	Pass	
24	Fail	Solder on lead only, large spike, no fillet
25	Pass	
26	Fail	Solder on lead only, no fillet, small spike
27	Pass (-)	
28	Pass	
29	Pass	
30	Pass	
31	Pass	
32	Pass	

TABLE 25.—INSPECTION RESULTS FROM EUTECTIC, ROSIN FLUX CORED SOLDER IN REDUCED GRAVITY, BOARD F, FLOWED FILLET

Joint number	Pass/fail	Notes
1	Fail	Poor wetting, void
2	Fail	No fillet, no solder in through hole
3	Fail	Blowhole
4	Fail	Poor wetting
5	Fail	No fillet, no solder in through hole
6	Pass	
7	Fail	No fillet, poor wetting in through hole
8	Pass	
9	Pass	
10	Pass	
11	Pass	
12	Pass	
13	Pass	
14	Pass	
15	Fail	No fillet, no solder in through hole
16	Fail	No fillet, no solder in through hole
17	Fail	No fillet, no solder in through hole
18	Fail	No fillet, no solder in through hole
19	Pass	
20	Pass	
21	Fail	No fillet, no solder in through hole
22	Pass (-)	Poor wetting, void
23	Pass (-)	Re-heat line
24	Fail	No fillet, no solder in through hole
25	Pass (-)	Poor wetting, void
26	Fail	No fillet, no solder in through hole
27	Pass	
28	Pass	
29	Pass	
30	Fail	Poor wetting, void
31	Pass	
32	Pass	

TABLE 26.—INSPECTION RESULTS FROM 60% TIN-40%LEAD SOLDER, EXTERNAL LIQUID ROSIN FLUX IN REDUCED GRAVITY, BOARD J, SOLDERED FILLET

Joint number	Pass/fail	Notes
1	Fail	Very little solder on lead only
2	Fail	Excessive solder, excessive heat, spike
3	Fail	Poor wetting
4	Fail	Big spike, excessive solder
5	Fail	Giant spike, excessive solder
6	Fail	Very little solder on lead only, spike
7	Fail	Poor wetting, void
8	Fail	Little solder on lead only, spike
9	Fail	Poor wetting, little spike
10	Fail	Excessive solder, overheated, big spike
11	Fail	Excessive solder, overheated, big spike
12	Fail	Excessive solder, overheated, medium spike
13	Fail	Excessive solder, overheated, big spike
14	Fail	Solder drag
15	Fail	Excessive solder, overheated, small spike
16	Fail	Poor wetting, overheated, big spike
17	Fail	Excessive solder, overheated, big spike
18	Fail	Excessive solder, overheated, medium spike
19	Fail	Excessive solder, overheated, small spike
20	Fail	Excessive solder, overheated, small spike
21	Fail	Solder on lead only, overheated, large spike
22	Fail	Overheated, solder drag
23	Fail	Poor wetting, overheated, medium spike
24	Fail	Excessive solder, overheated, medium spike
25	Fail	Excessive solder, overheated, large spike
26	Fail	Overheated, small spike
27	Pass (-)	Solder drag
28	Fail	Solder spike
29	Pass (-)	Excessive solder, overheated, drag
30	Fail	Excessive solder, overheated, large spike
31	Fail	Excessive solder, overheated, large spike
32	Fail	Excessive solder, large spike, poor wetting

TABLE 27.—INSPECTION RESULTS FROM 60% TIN-40%LEAD SOLDER, EXTERNAL LIQUID ROSIN FLUX IN REDUCED GRAVITY, BOARD J, FLOWED FILLET

Joint number	Pass/fail	Notes
1	Fail	No fillet, poor wetting in through hole and lead
2	Pass	
3	Fail	No fillet, poor wetting in through hole and lead
4	Fail	No fillet, poor wetting in through hole and lead
5	Fail	No fillet, poor wetting in through hole and lead
6	Fail	No fillet
7	Fail	No fillet, poor wetting in through hole
8	Fail	No fillet, poor wetting in through hole
9	Fail	Insufficient solder, poor wetting
10	Pass	
11	Pass	
12	Pass	
13	Fail	No fillet, poor wetting in through hole and lead
14	Fail	No fillet, poor wetting in through hole and lead
15	Pass	
16	Fail	No fillet, poor wetting in through hole and lead
17	Fail	Insufficient solder, poor wetting
18	Pass	
19	Pass	
20	Pass	
21	Fail	No fillet
22	Pass	
23	Fail	No fillet
24	Fail	No fillet, poor wetting in through hole
25	Pass	
26	Pass	
27	Fail	Insufficient solder, poor wetting
28	Pass	
29	Pass	
30	Pass	
31	Pass	
32	Fail	Insufficient solder, poor wetting

TABLE 28.—INSPECTION RESULTS FROM 60% TIN-40%LEAD SOLDER, EXTERNAL LIQUID ROSIN FLUX IN REDUCED GRAVITY, BOARD K, SOLDERED FILLET.

Joint number	Pass/fail	Notes
1	Fail	Over heated, excessive solder, spike
2	Fail	Over heated, excessive solder, spike
3	Fail	Solder on lead only, spike
4	Fail	Solder on lead only, spike, overheated
5	Fail	Overheated, drag
6	Fail	Over heated, poor wetting, excessive solder, spike
7	Fail	Over heated, poor wetting, spike
8	Fail	Poor wetting, spike, solder bridge between lead and pad
9	Fail	Over heated, excessive solder, spike
10	Fail	Solder on lead only, spike
11	Fail	Overheated, poor wetting, spike
12	Fail	Solder on lead only, overheated, spike
13	Fail	Overheated, spike
14	Fail	Overheated, spike
15	Fail	Solder on lead only, spike
16	Fail	Solder on lead only, large spike
17	Fail	Overheated, excessive solder, spike
18	Fail	Poor wetting on lead and pad, insufficient solder, spike
19	Fail	Solder on lead only, spike
20	Fail	Overheated, drag and spike
21	Fail	Solder on lead only, spike
22	Fail	Overheated, excessive solder, drag
23	Pass	
24	Fail	Very little solder on tip of lead only
25	Pass	
26	Fail	Poor wetting on pad, spike
27	Fail	Overheated, spike, excessive solder
28	Fail	Solder on lead only, spike
29	Fail	Very little solder on lead only, spike
30	Fail	Spike
31	Fail	Solder on lead only, spike
32	Fail	Solder on lead only, spike

TABLE 29.—INSPECTION RESULTS FROM 60% TIN-40%LEAD SOLDER, EXTERNAL LIQUID ROSIN FLUX IN REDUCED GRAVITY, BOARD K, FLOWED FILLET

Joint number	Pass/fail	Notes
1	Fail	No fillet, poor wetting in through hole and lead
2	Pass	
3	Fail	No fillet, no solder in through hole
4	Fail	No fillet, no solder in through hole
5	Fail	Partial fillet, poor wetting of pad, lead
6	Fail	No fillet, poor wetting in through hole and lead
7	Pass	
8	Fail	No fillet, no solder in through hole
9	Pass	
10	Fail	No fillet, no solder in through hole
11	Fail	Partial fillet, poor wetting on pad and lead
12	Fail	No fillet, no solder in through hole
13	Fail	No fillet, poor wetting in through hole and lead
14	Pass	
15	Fail	No fillet, no solder in through hole
16	Fail	No fillet, no solder in through hole
17	Pass	
18	Fail	No fillet, no solder in through hole
19	Fail	No fillet, no solder in through hole
20	Fail	Partial fillet, poor wetting on pad
21	Fail	No fillet, no solder in through hole
22	Pass	
23	Pass	
24	Fail	No fillet, no solder in through hole
25	Pass	
26	Fail	No fillet, poor wetting on lead
27	Fail	No fillet, poor wetting on lead
28	Fail	No fillet, no solder in through hole
29	Fail	No fillet, no solder in through hole
30	Fail	Partial fillet, poor wetting on pad and lead
31	Fail	No fillet, no solder in through hole
32	Fail	No fillet, no solder in through hole

Appendix B.—Graphs of Void Fraction Distribution

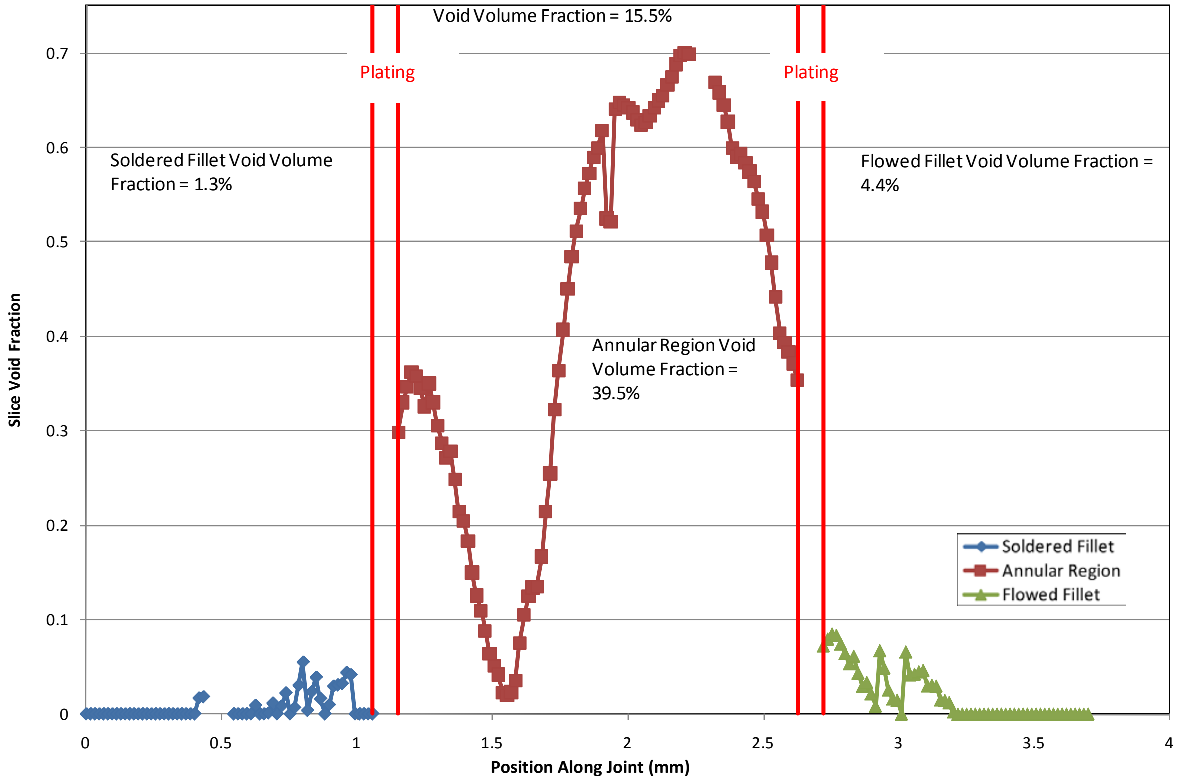

Figure 25.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (A13).

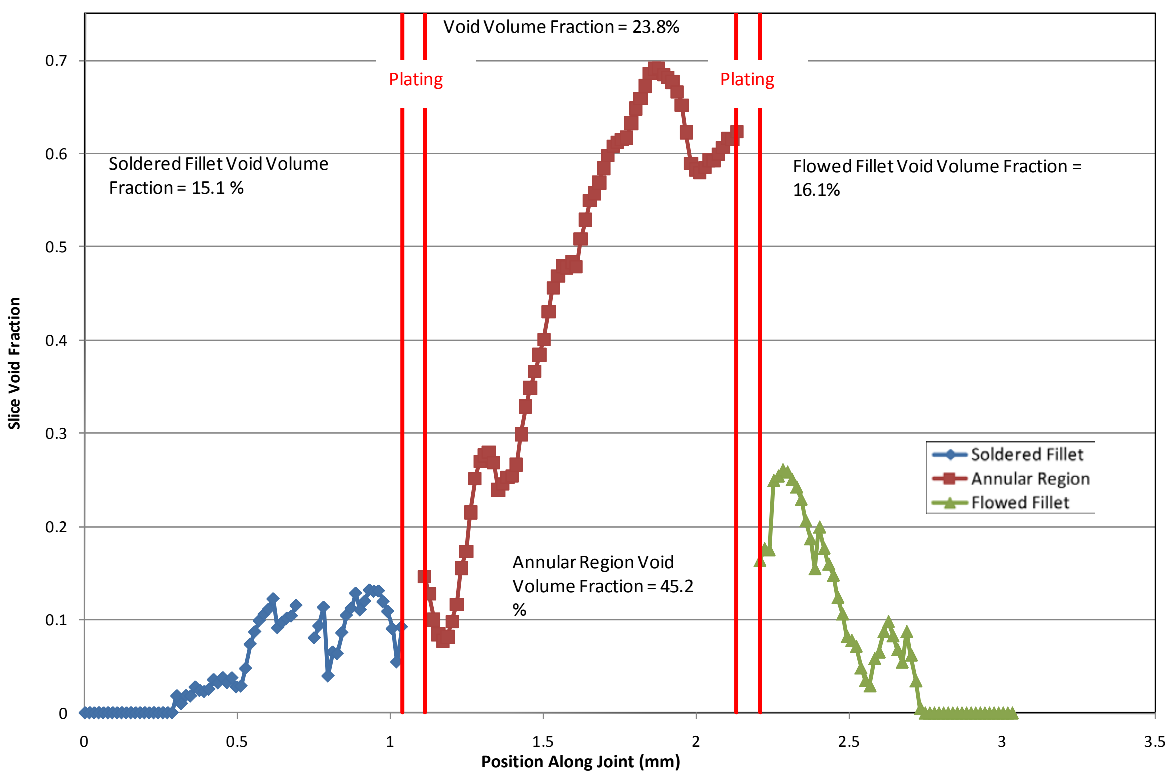

Figure 26.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (A14).

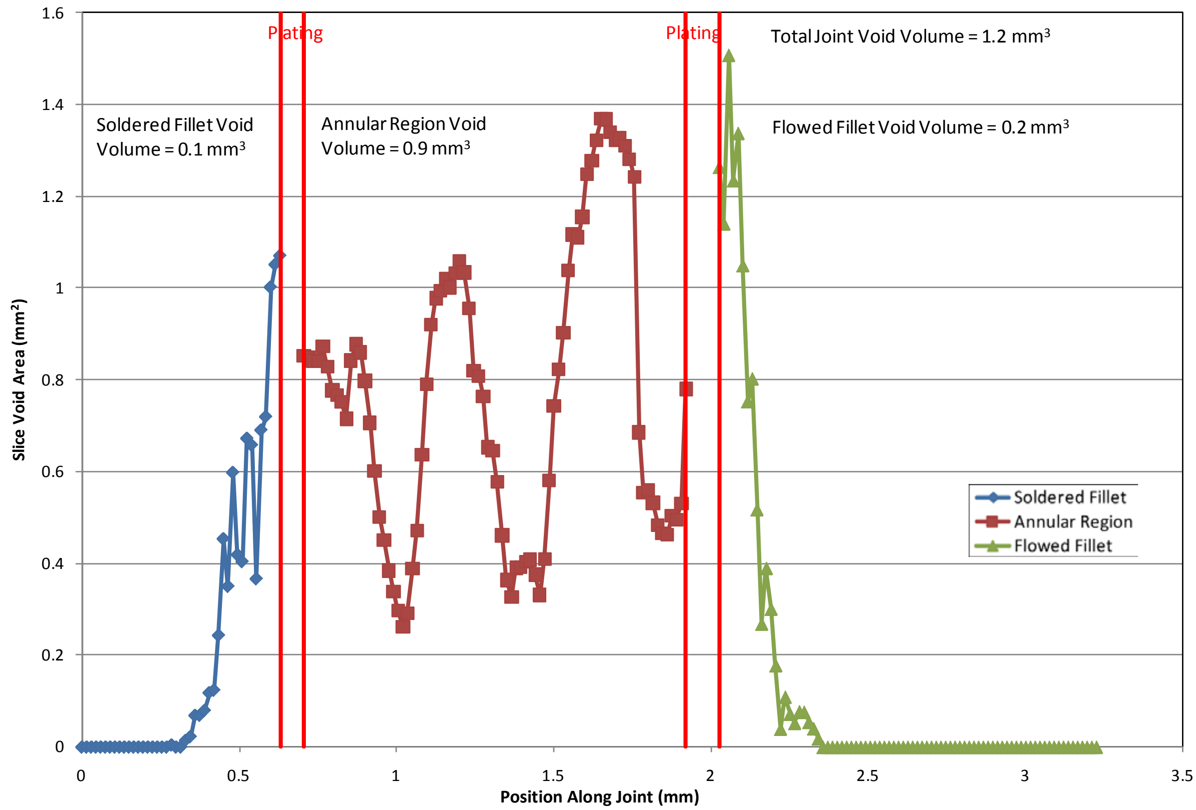

Figure 27.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (A29).

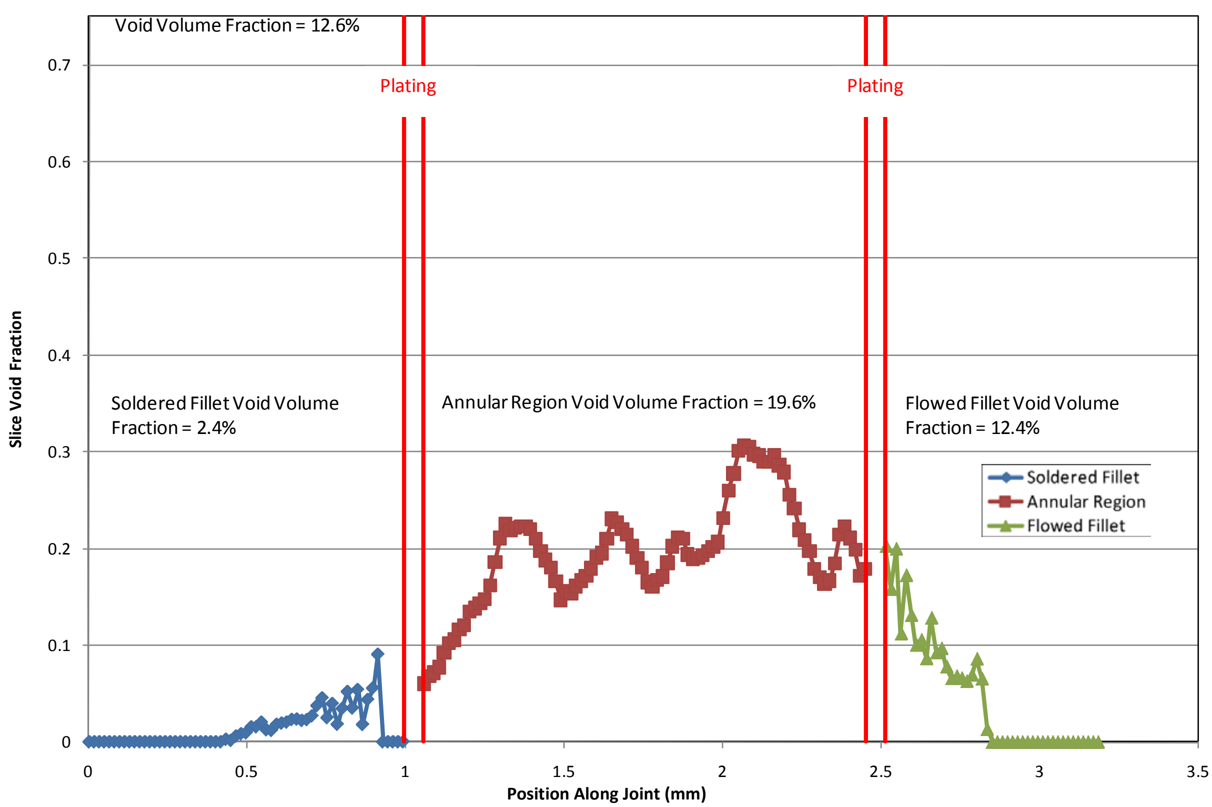

Figure 28.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (A30).

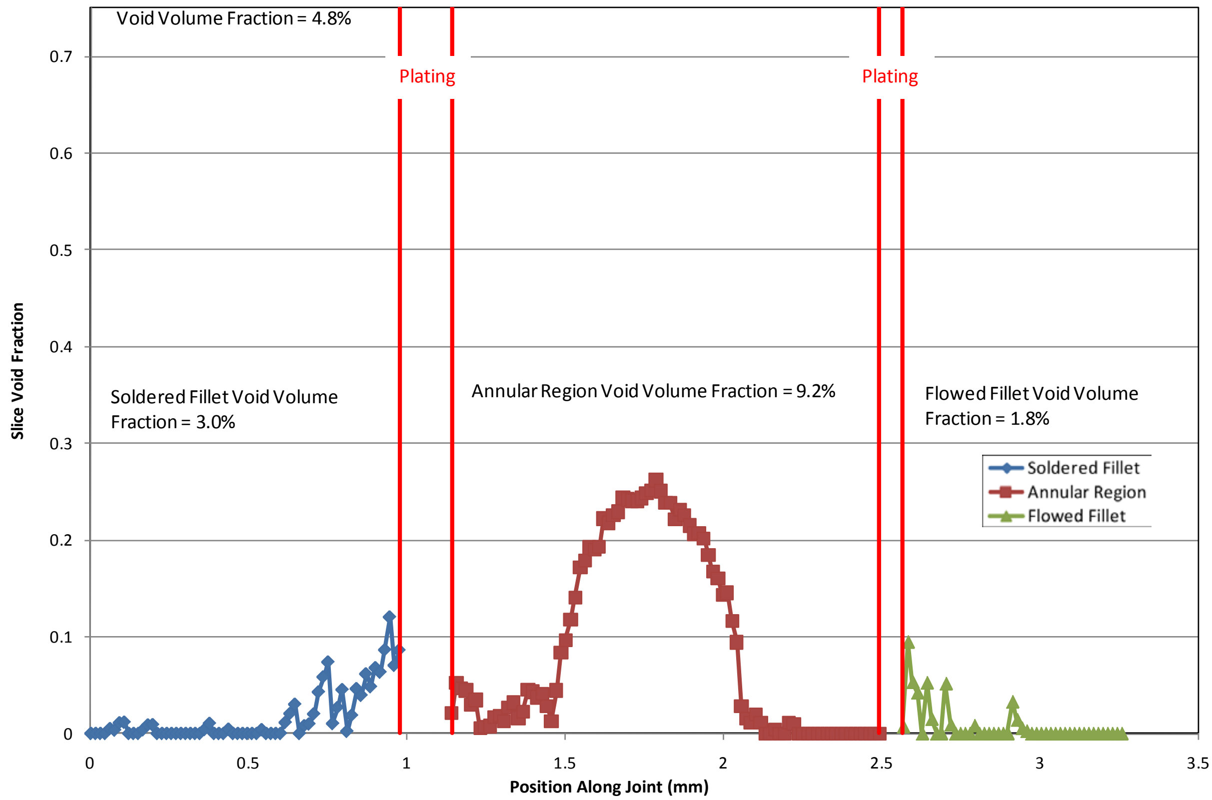

Figure 29.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (B6).

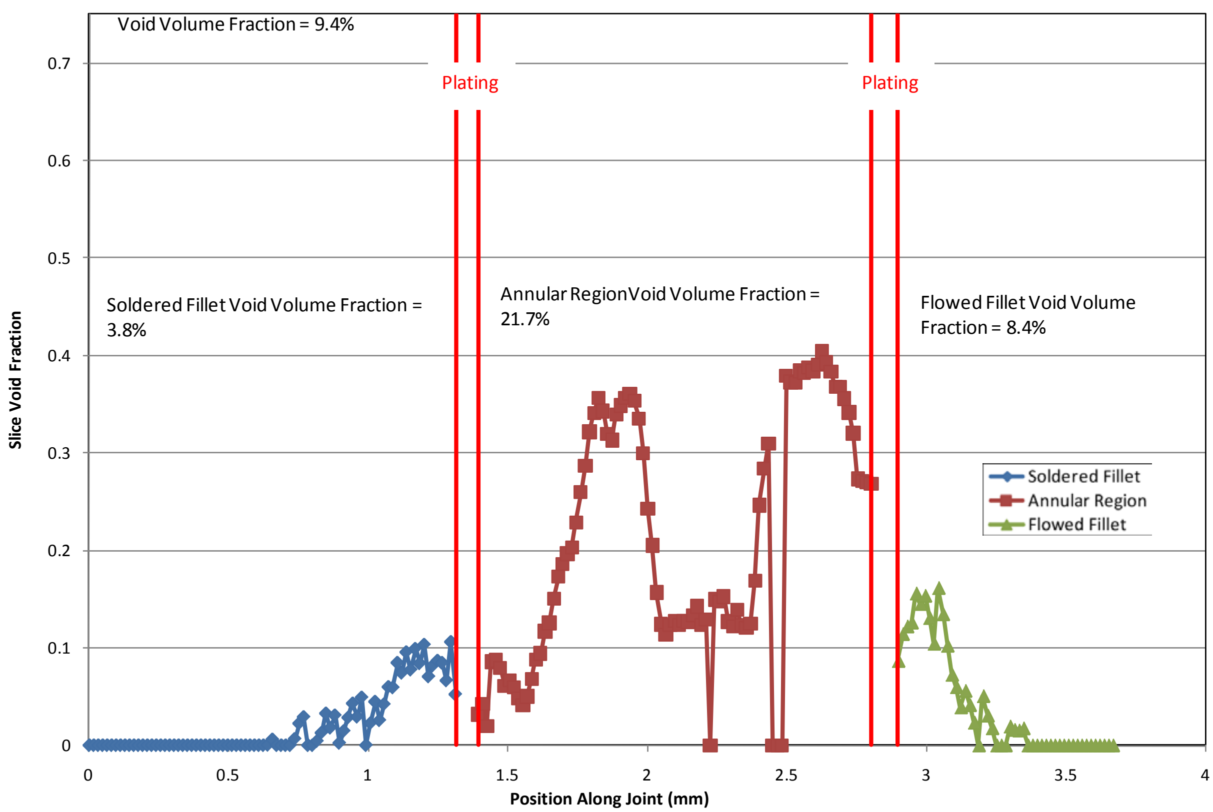

Figure 30.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (B8).

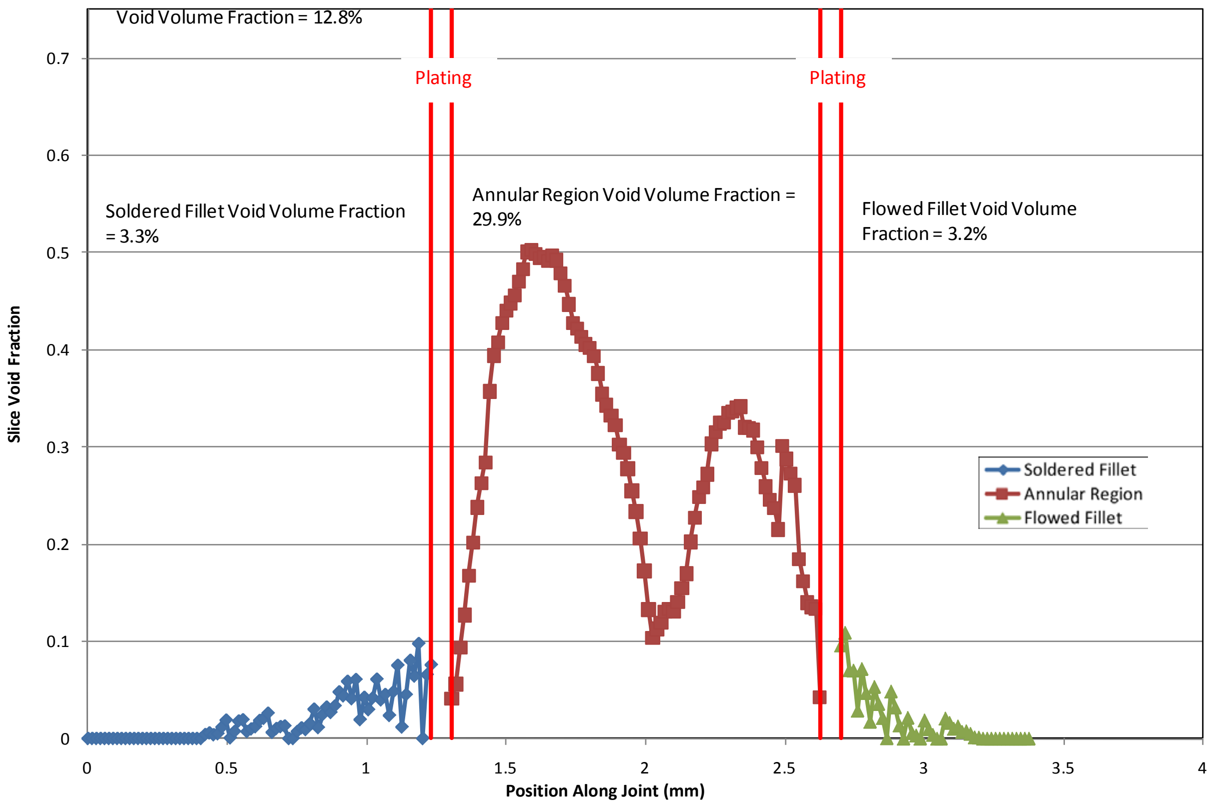

Figure 31.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (B13).

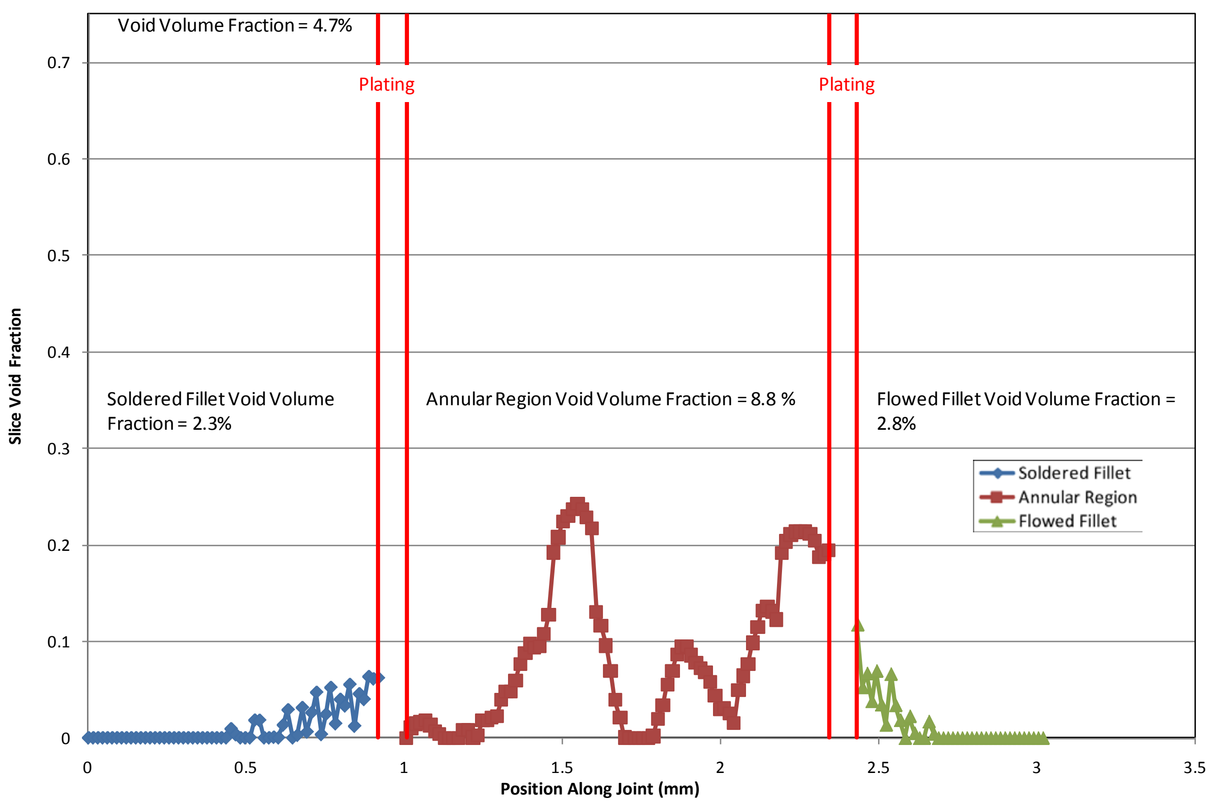

Figure 32.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (B21).

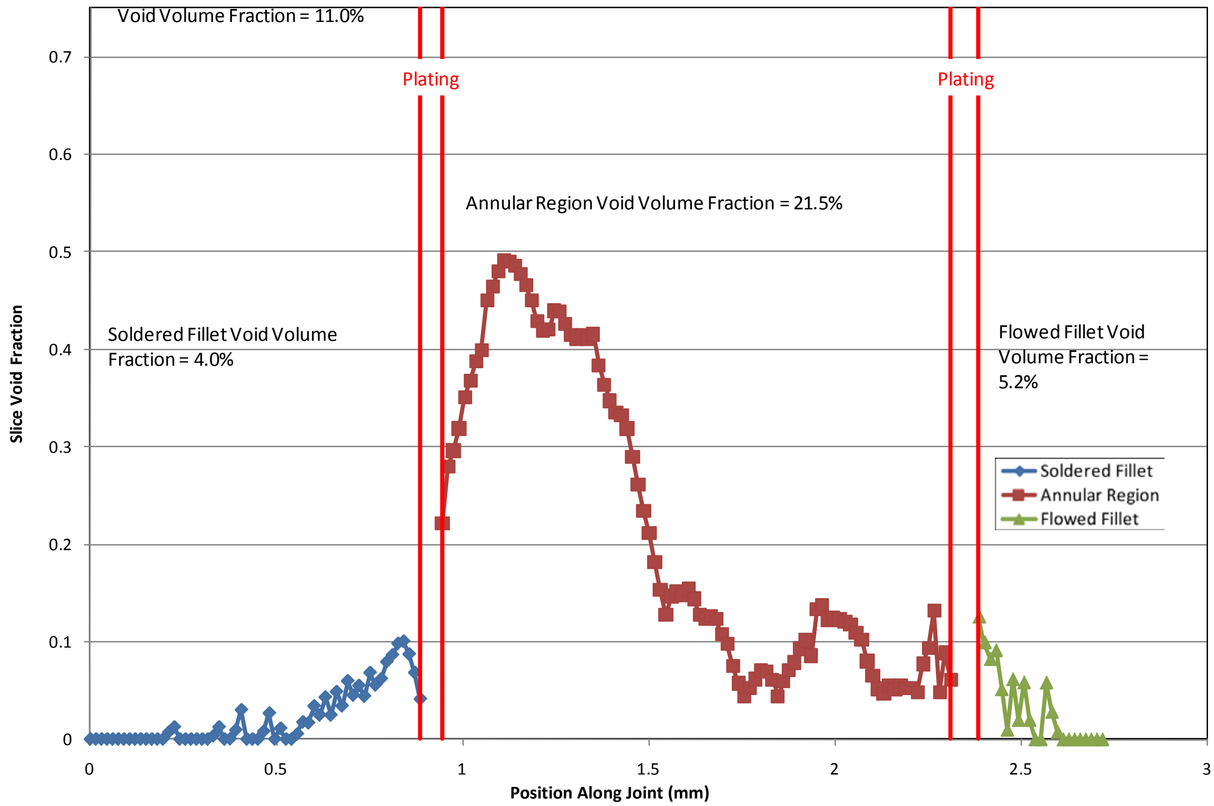

Figure 33.—Slice Void Fraction for a 60% tin-40% lead flux cored, reduced gravity, solder joint (B29).

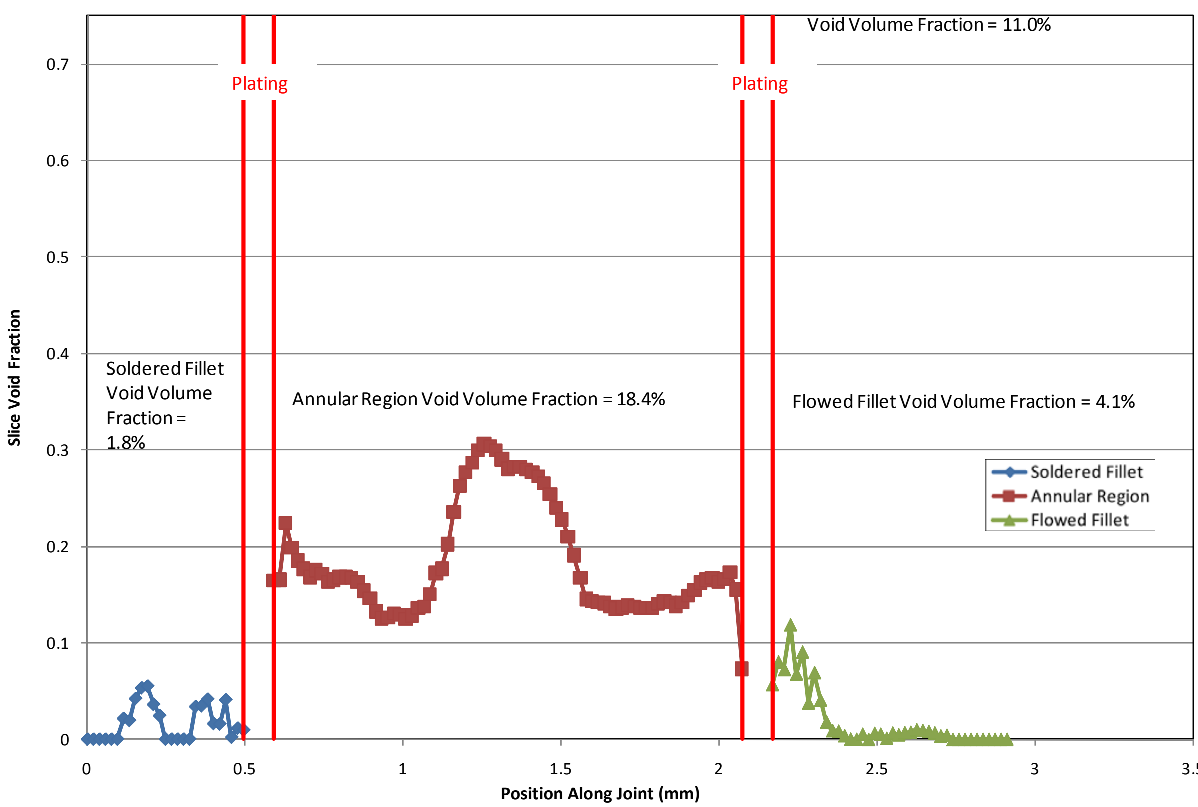

Figure 34.—Slice Void Fraction for a 60% tin-40% lead flux cored, normal gravity, solder joint (GA1).

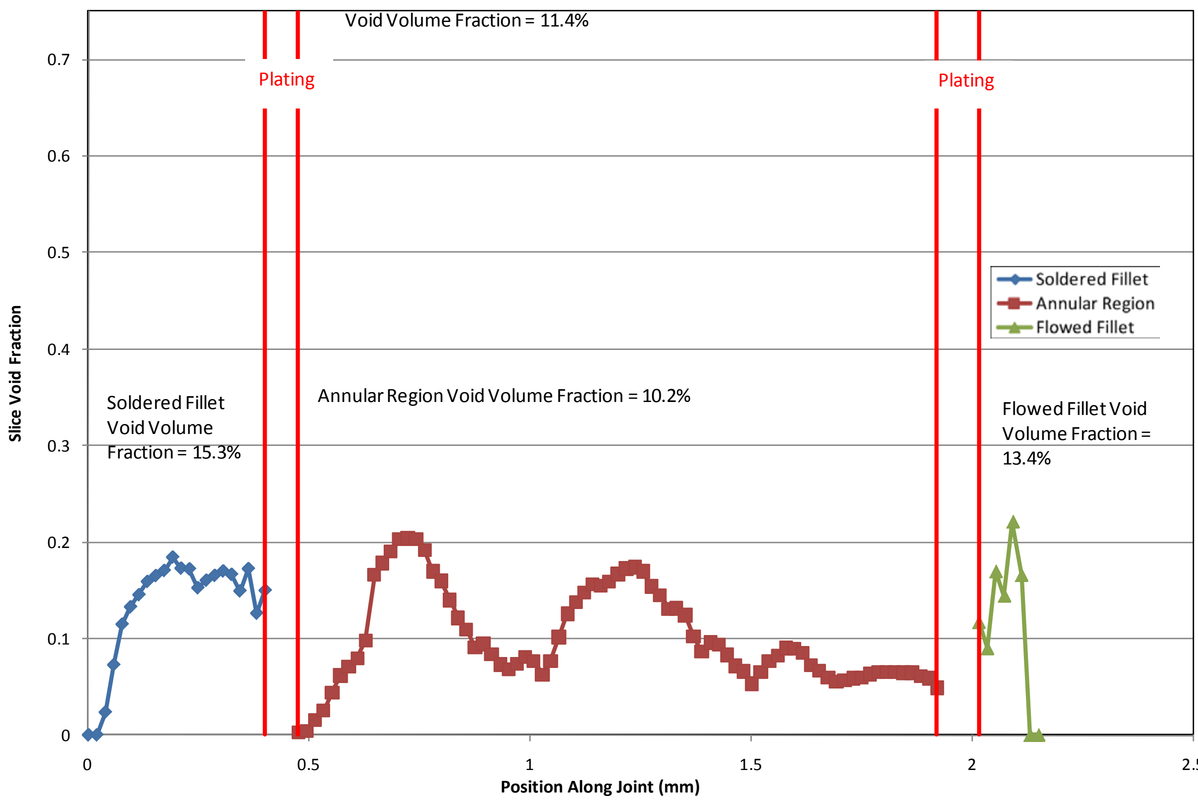

Figure 35.—Slice Void Fraction for a 60% tin-40% lead flux cored, normal gravity, solder joint (GA4).

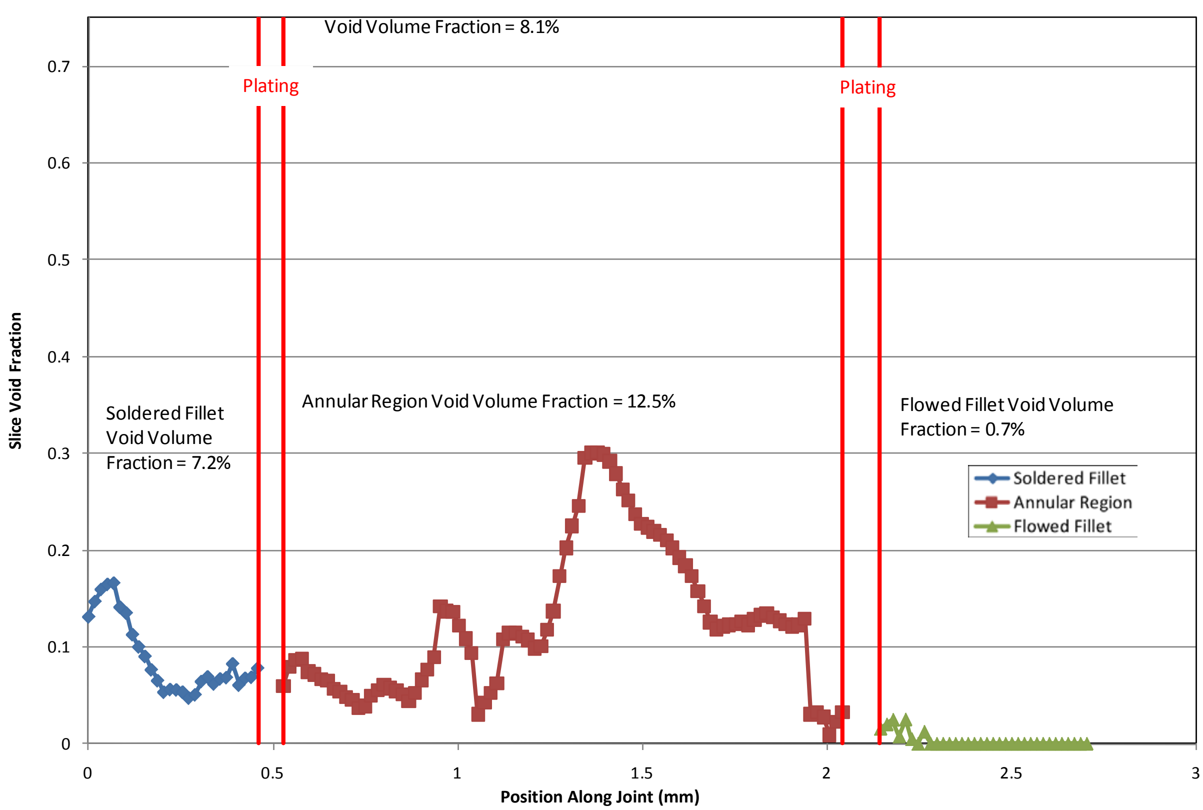

Figure 36.—Slice Void Fraction for a 60% tin-40% lead flux cored, normal gravity, solder joint (GA5).

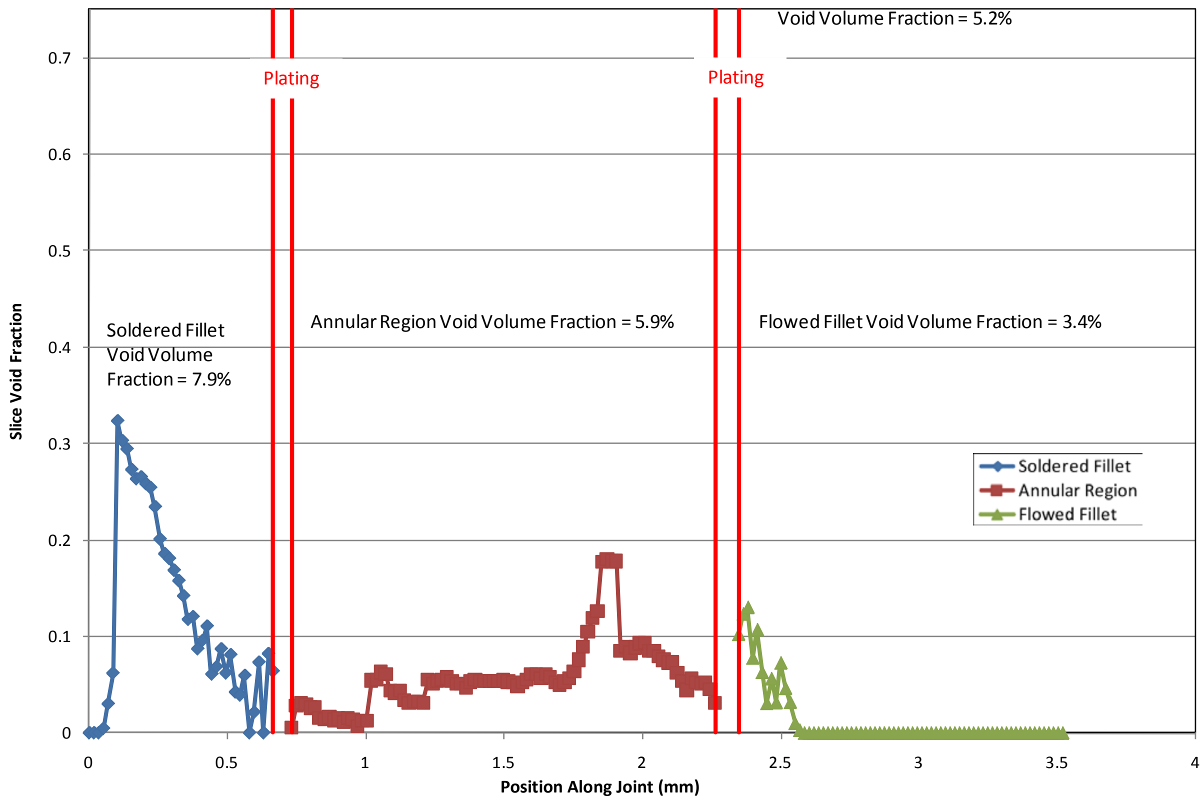

Figure 37.—Slice Void Fraction for a 60% tin-40% lead flux cored, normal gravity, solder joint (GA6).

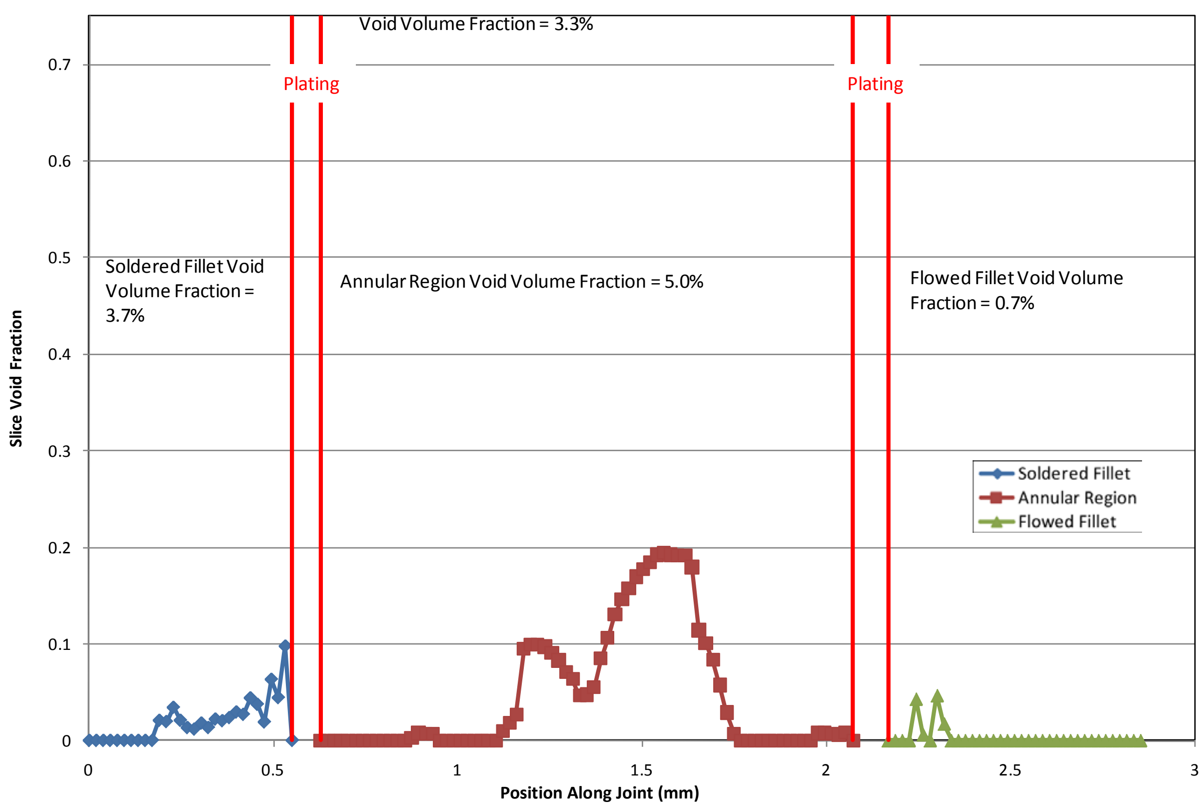

Figure 38.—Slice Void Fraction for a 60% tin-40% lead flux cored, normal gravity, solder joint (GA7).

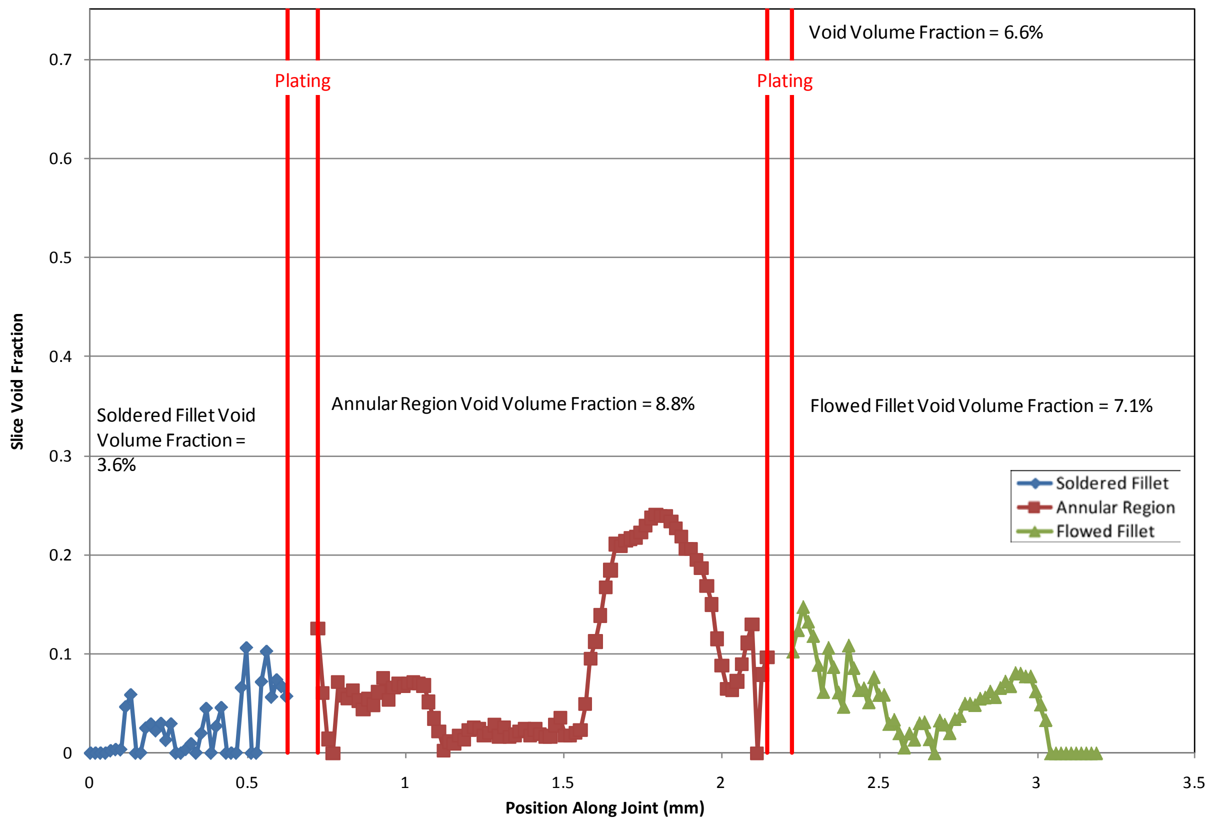

Figure 39.—Slice Void Fraction for a eutectic lead flux cored, reduced gravity, solder joint (E26).

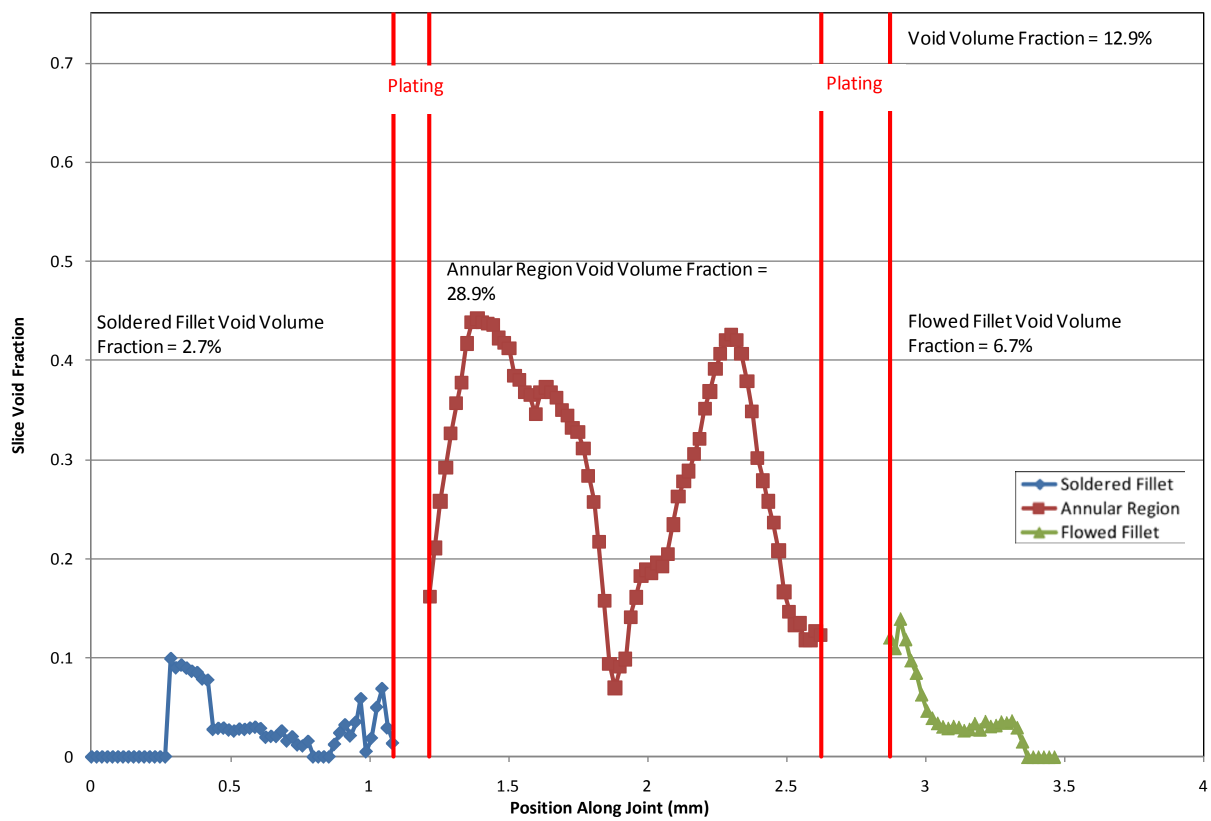

Figure 40.—Slice Void Fraction for a eutectic lead flux cored, reduced gravity, solder joint (F6).

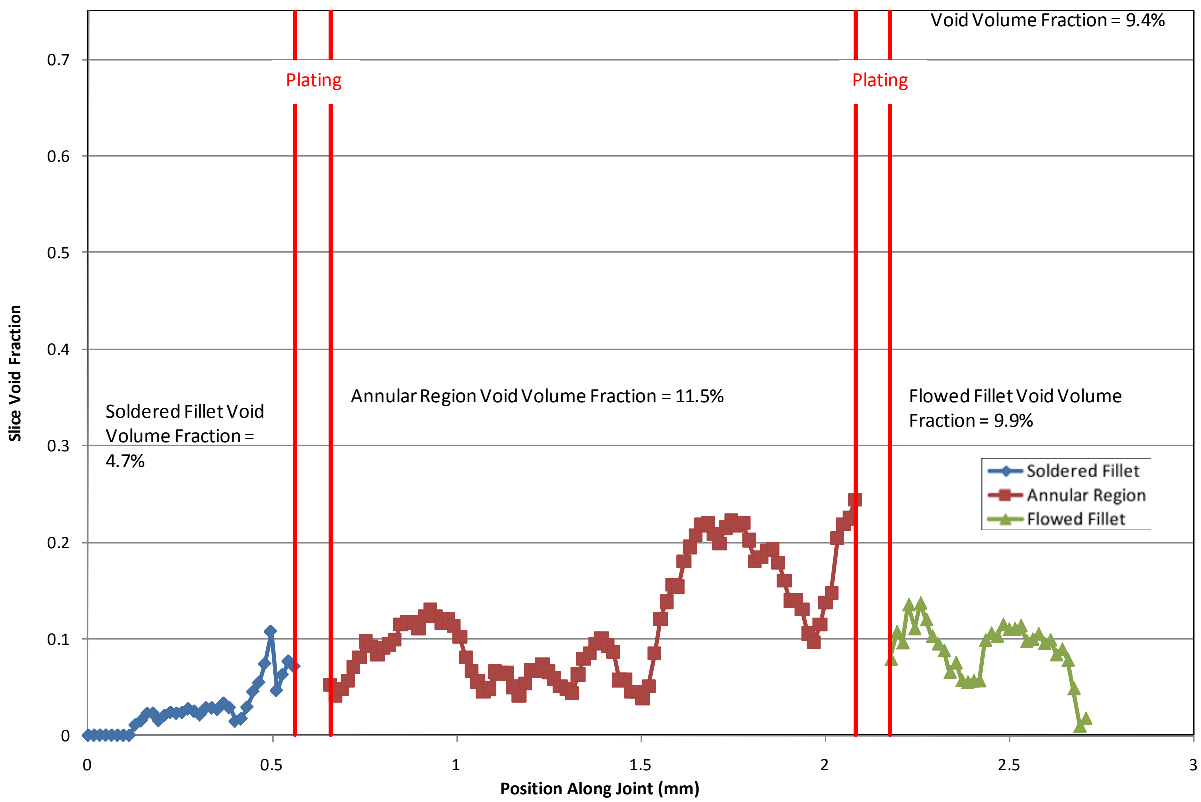

Figure 41.—Slice Void Fraction for a eutectic lead flux cored, reduced gravity, solder joint (F9).

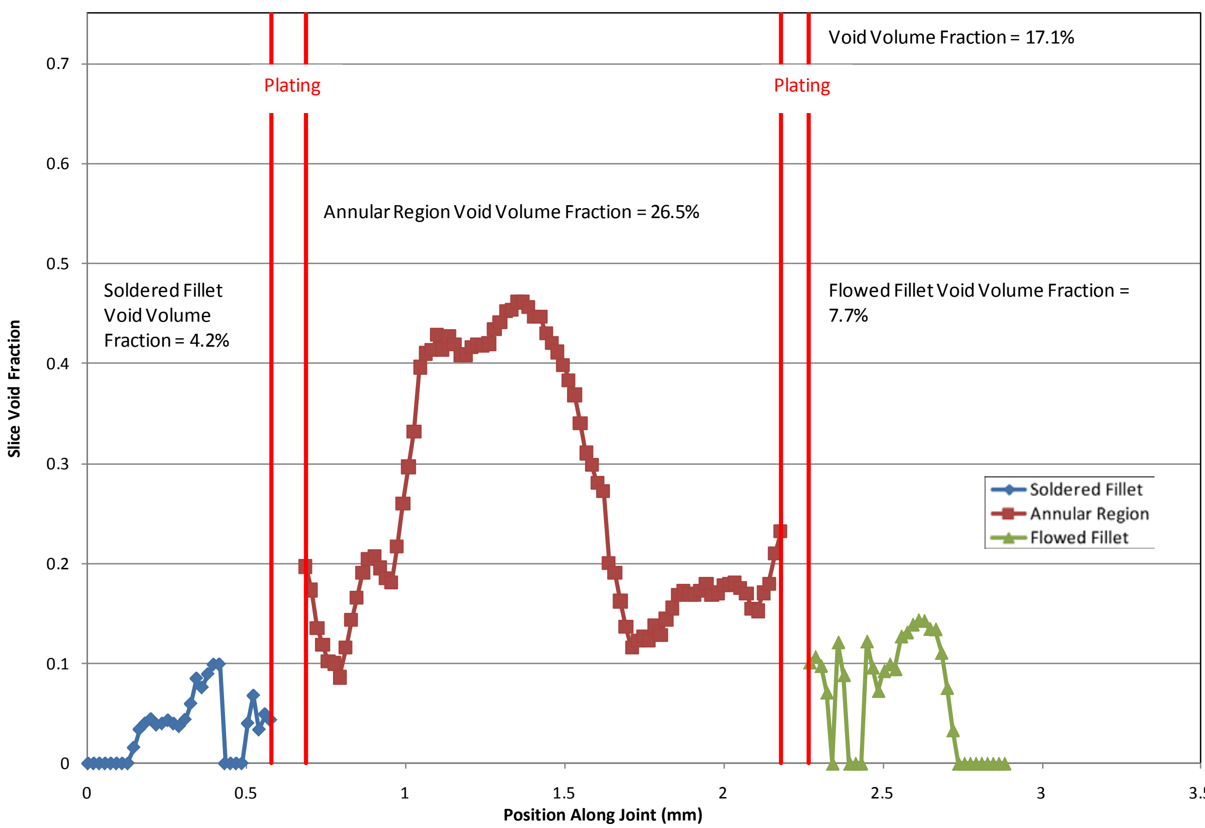

Figure 42.—Slice Void Fraction for a eutectic lead flux cored, reduced gravity, solder joint (F11).

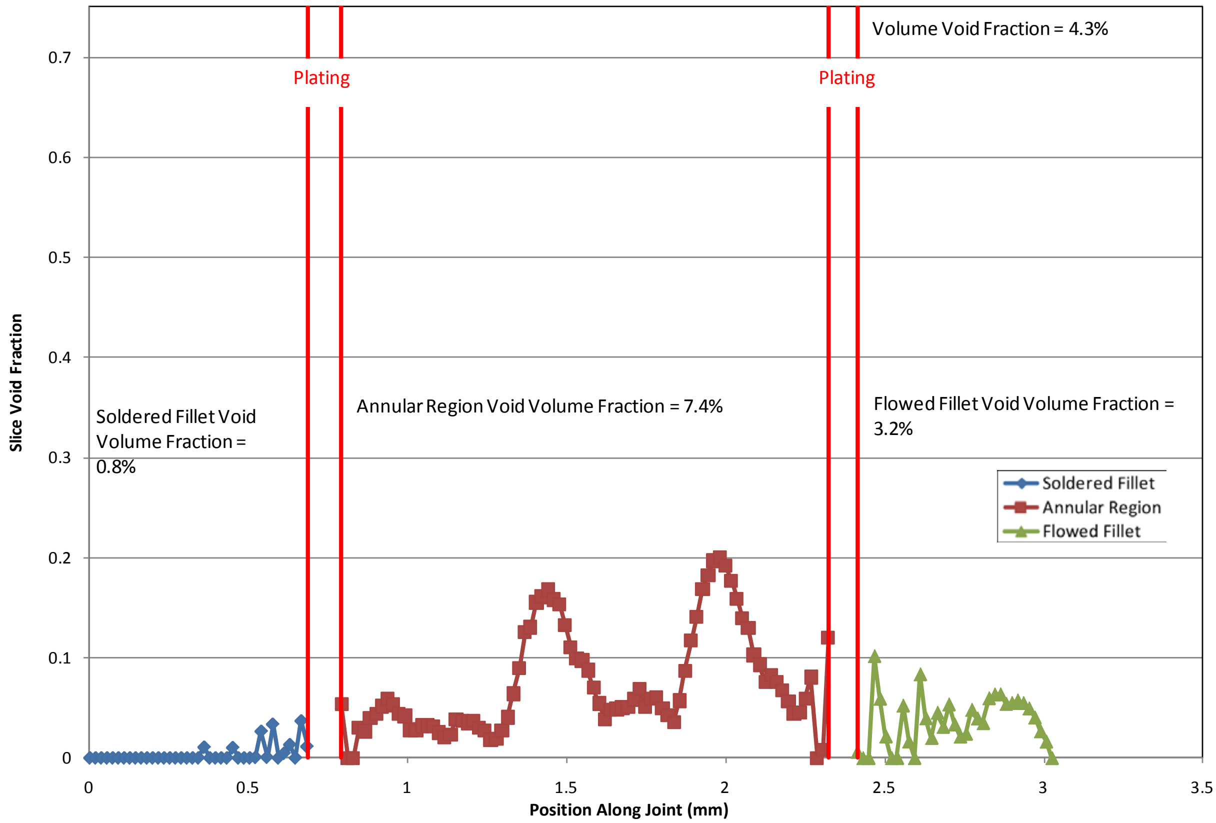

Figure 43.—Slice Void Fraction for a eutectic lead flux cored, reduced gravity, solder joint (F13).

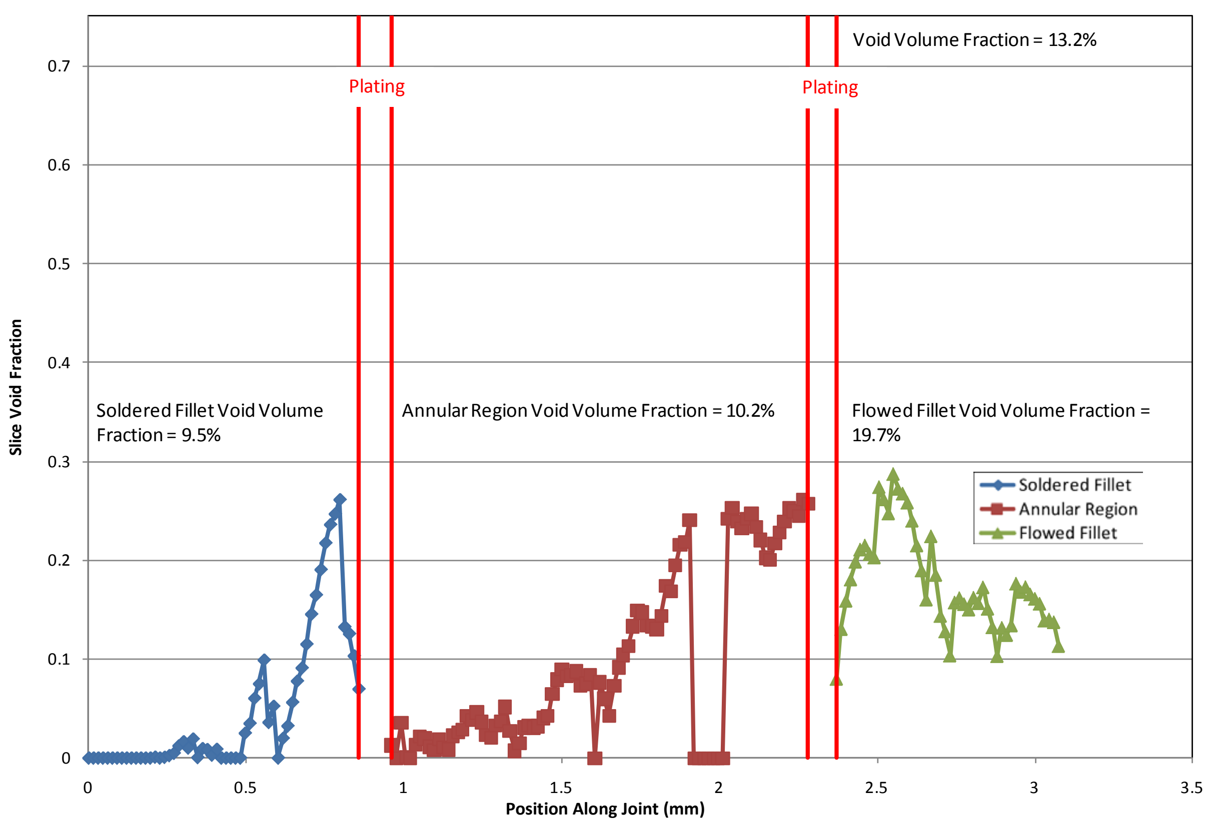

Figure 44.—Slice Void Fraction for a eutectic lead flux cored, reduced gravity, solder joint (F31).

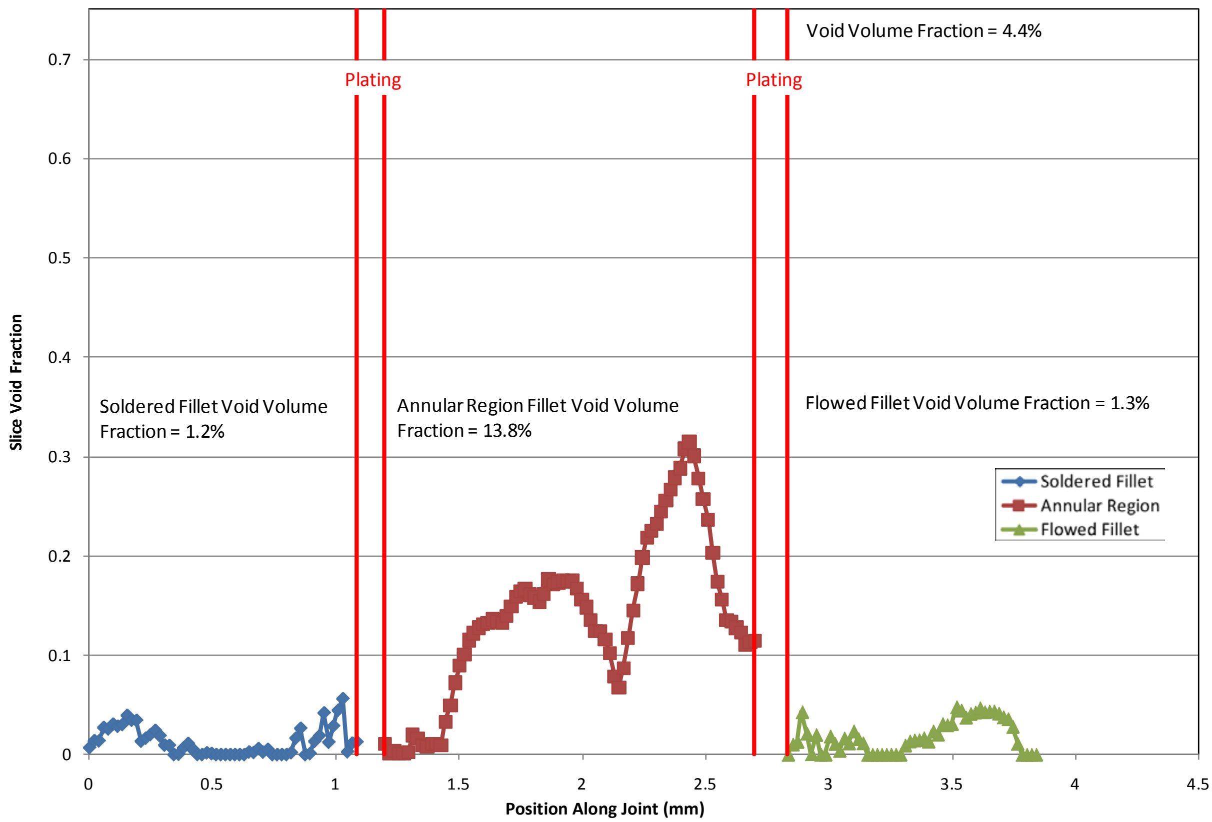

Figure 45.—Slice Void Fraction for a eutectic lead flux cored, reduced gravity, solder joint (F32).

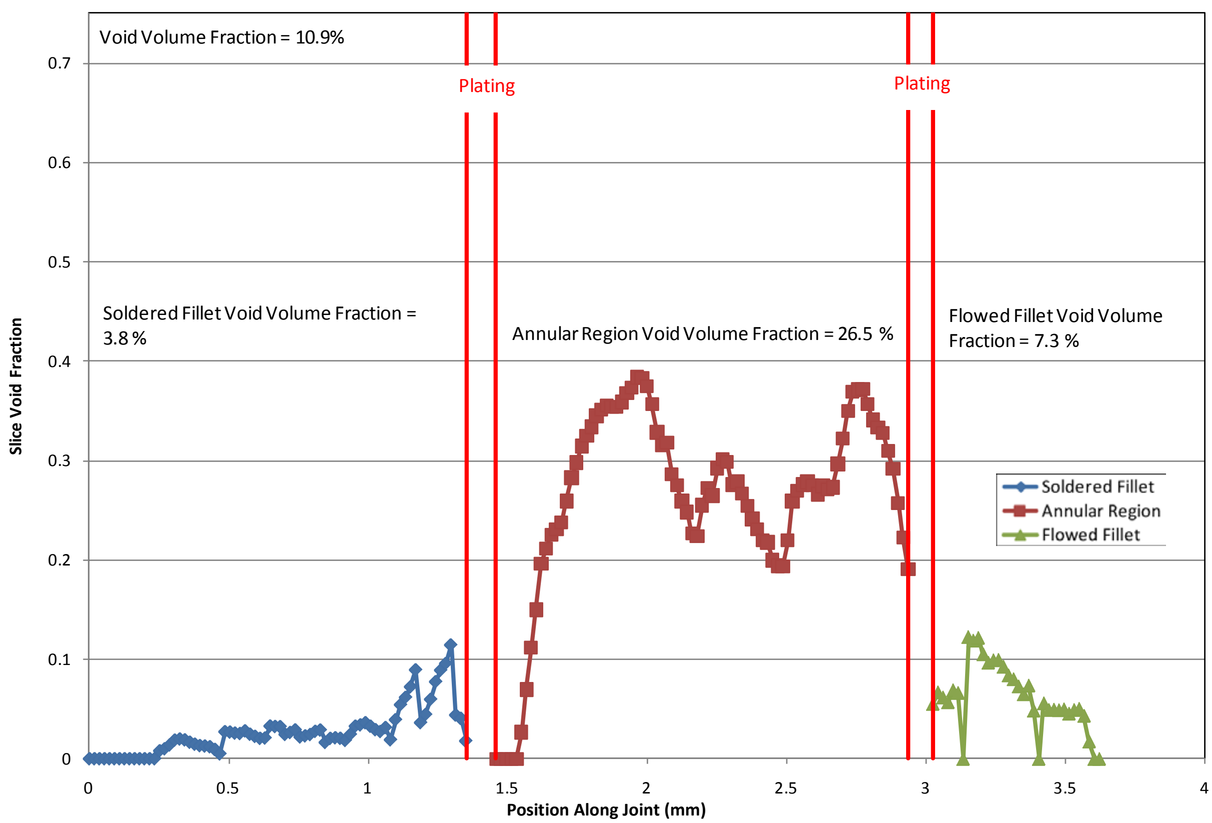

Figure 46.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (J19).

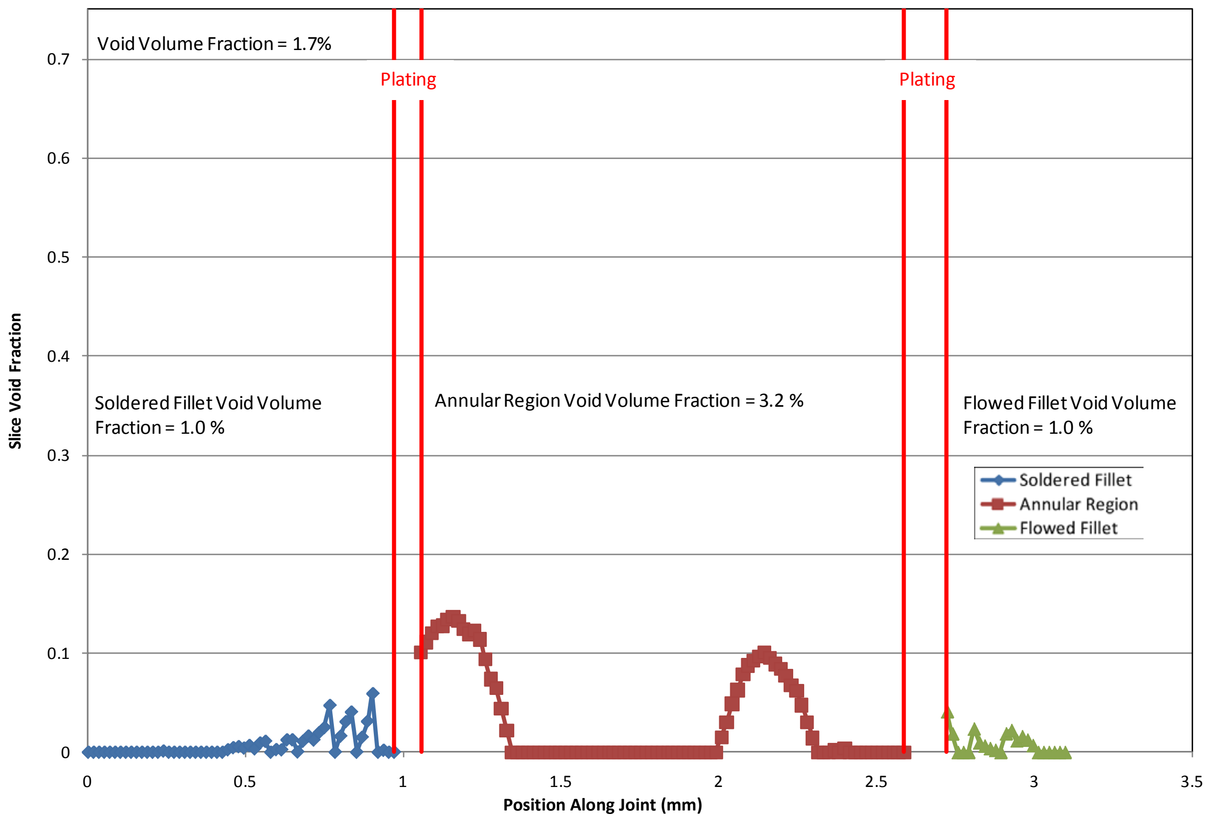

Figure 47.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (J20).

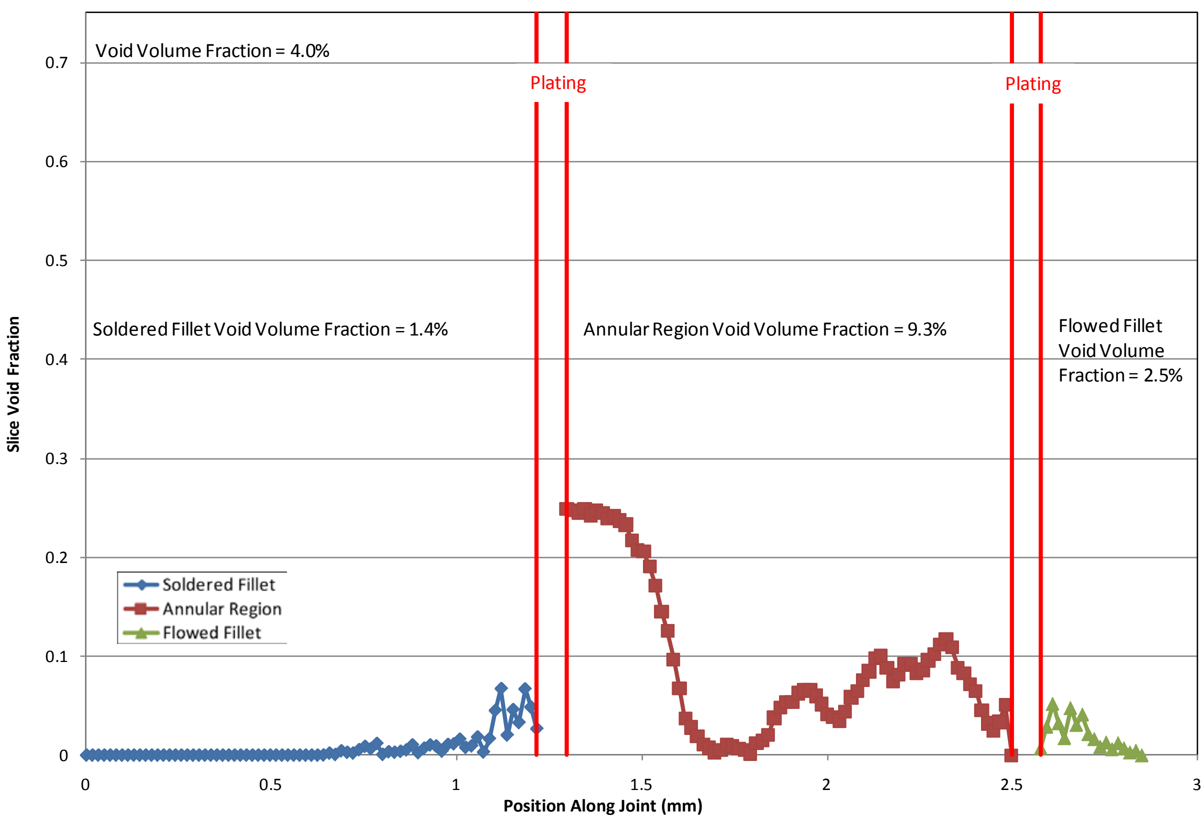

Figure 48.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (J22).

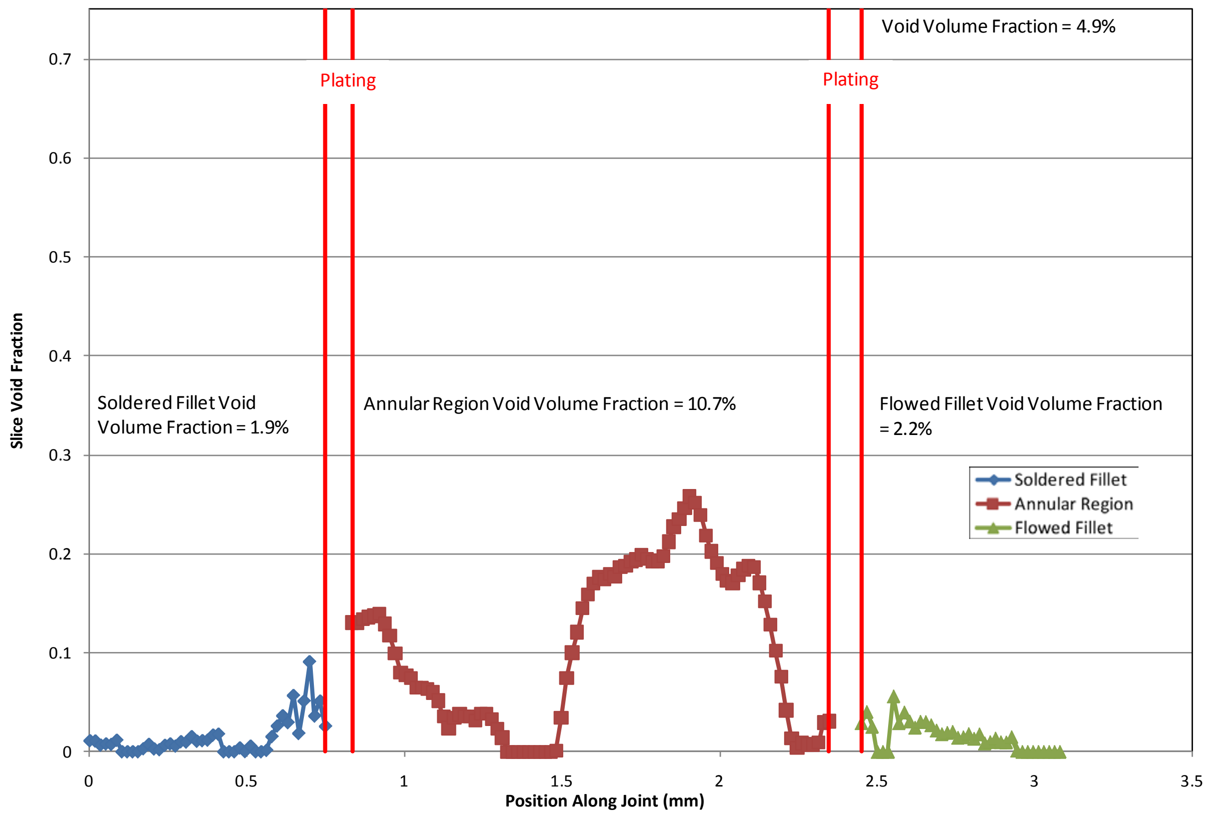

Figure 49.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (J28).

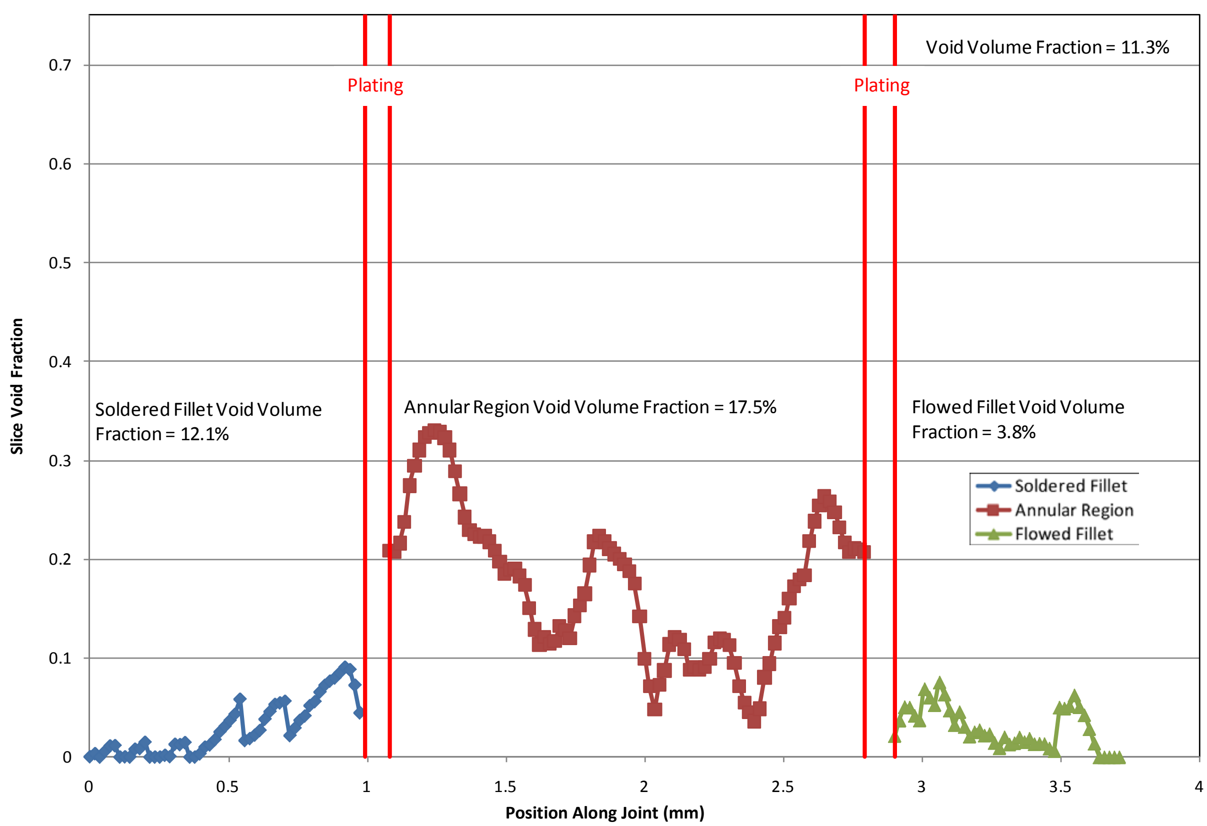

Figure 50.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (J29).

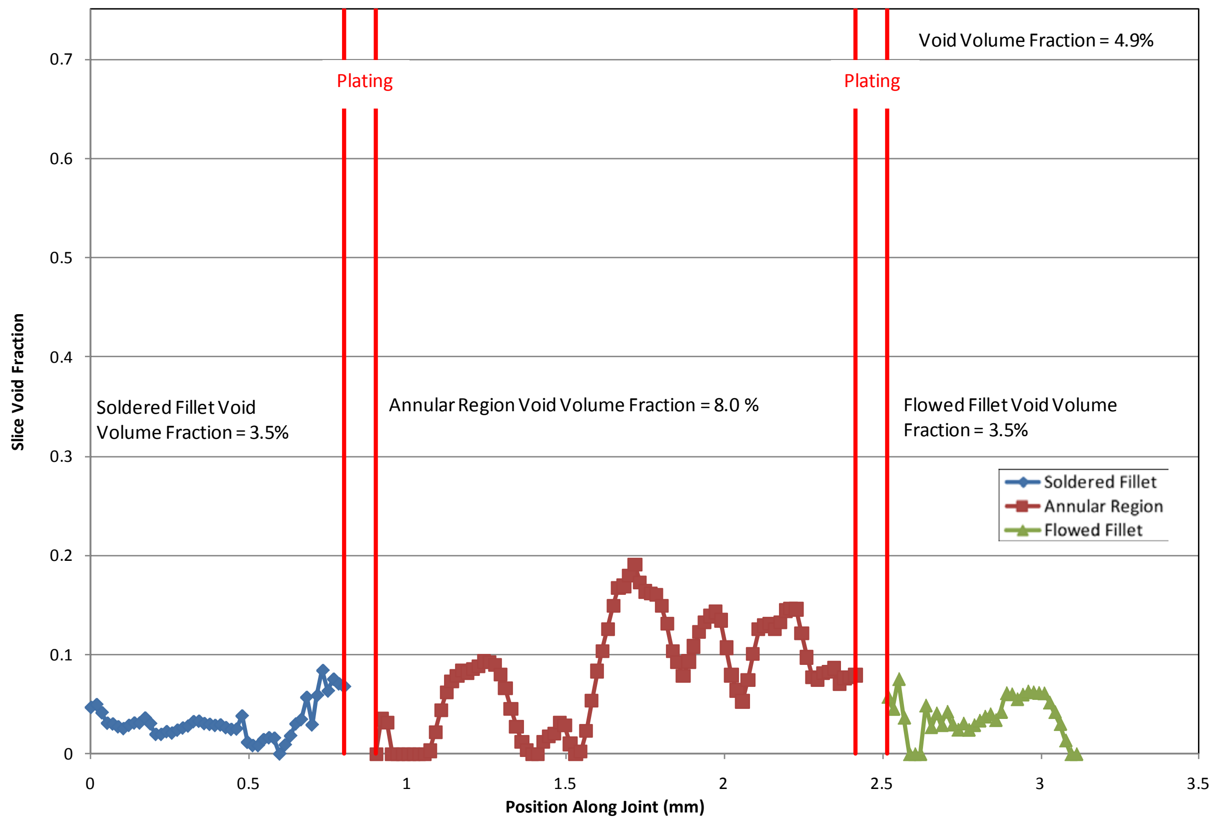

Figure 51.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (K7).

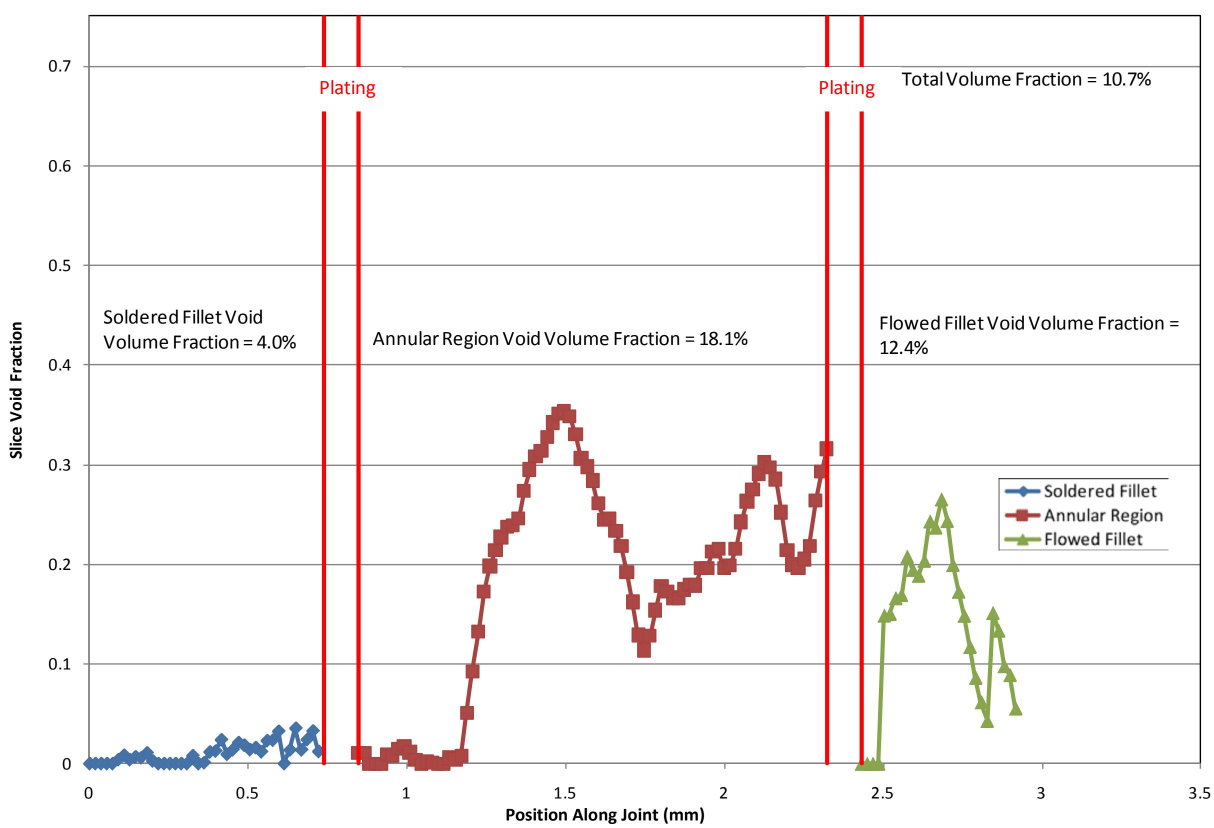

Figure 52.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (K14).

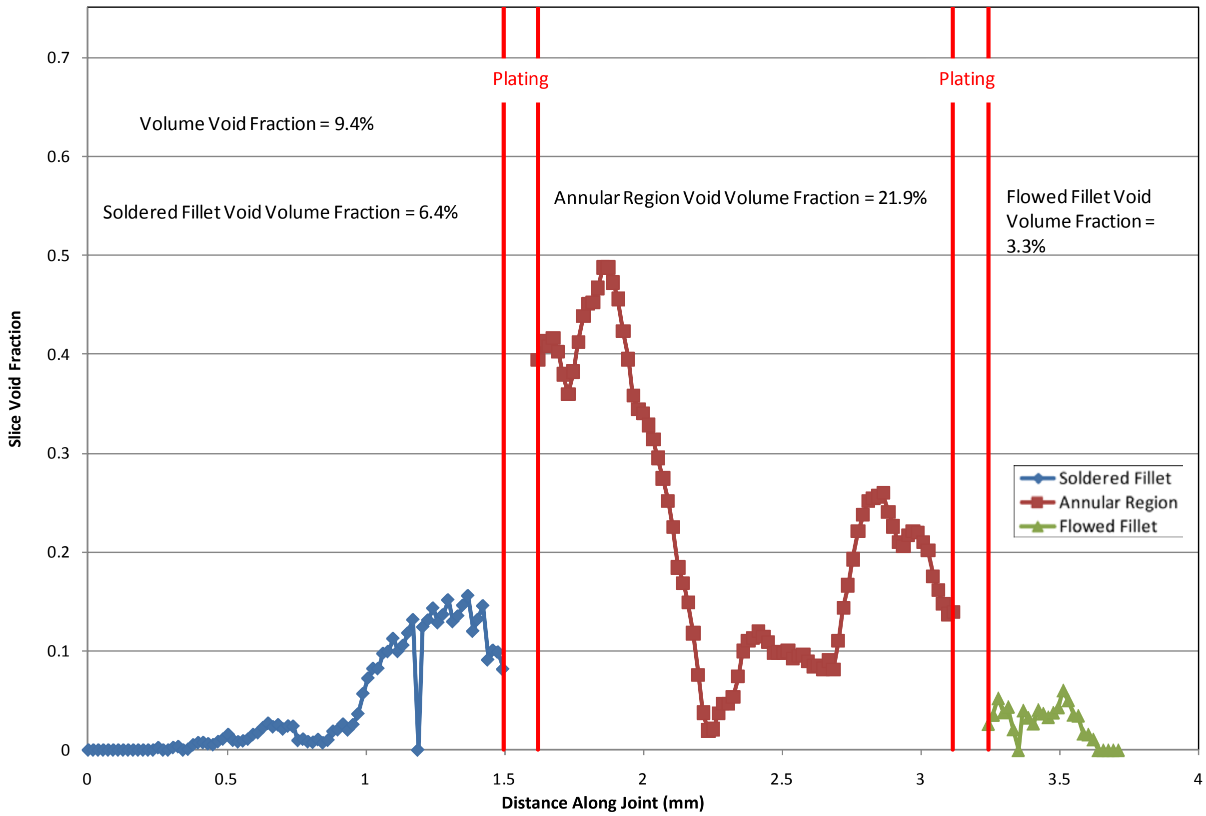

Figure 53.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (K22).

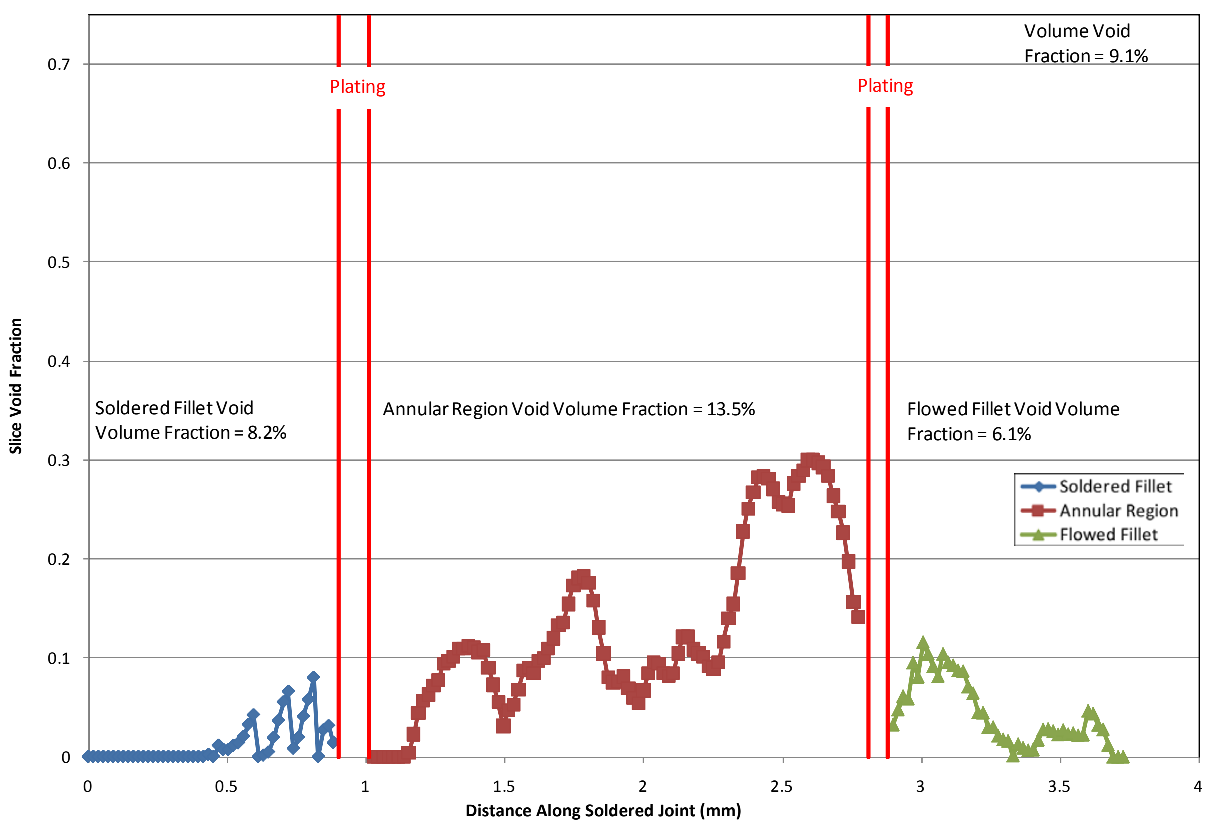

Figure 54.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (K23).

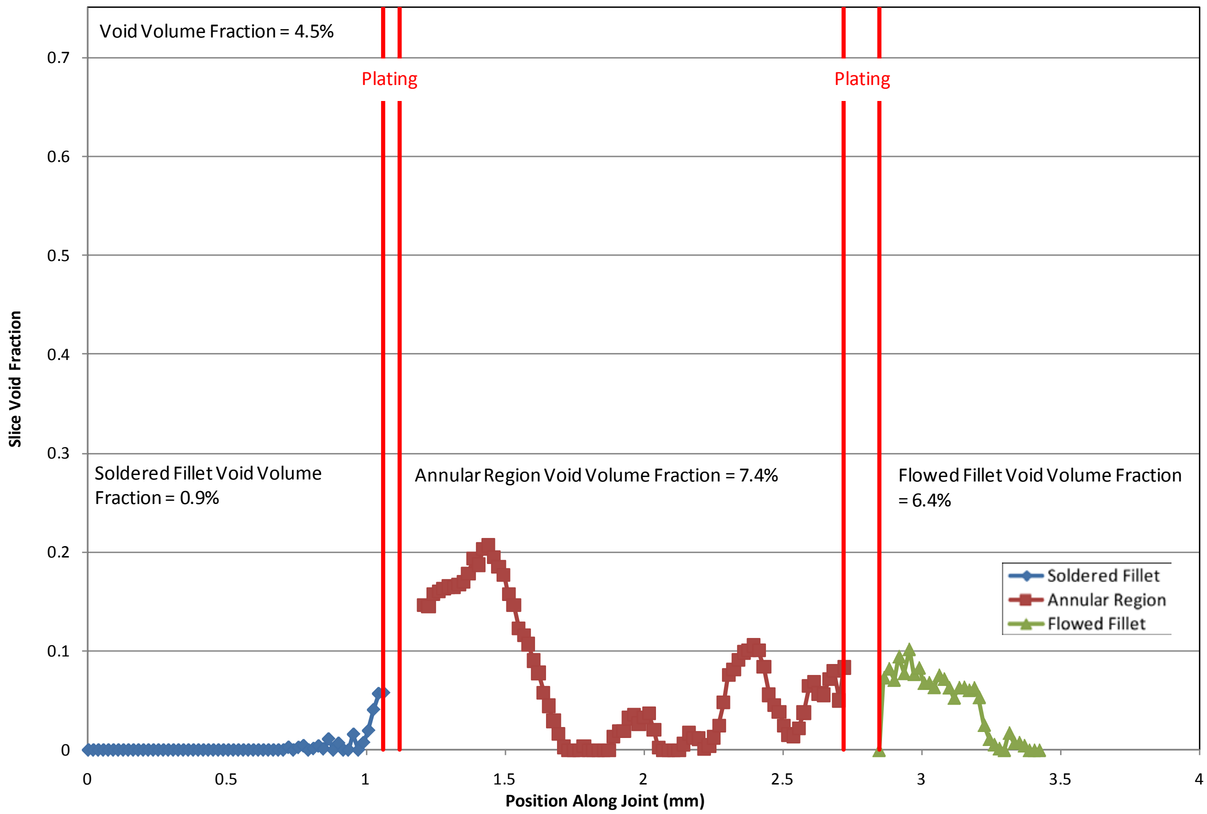

Figure 55.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, reduced gravity, solder joint (K25).

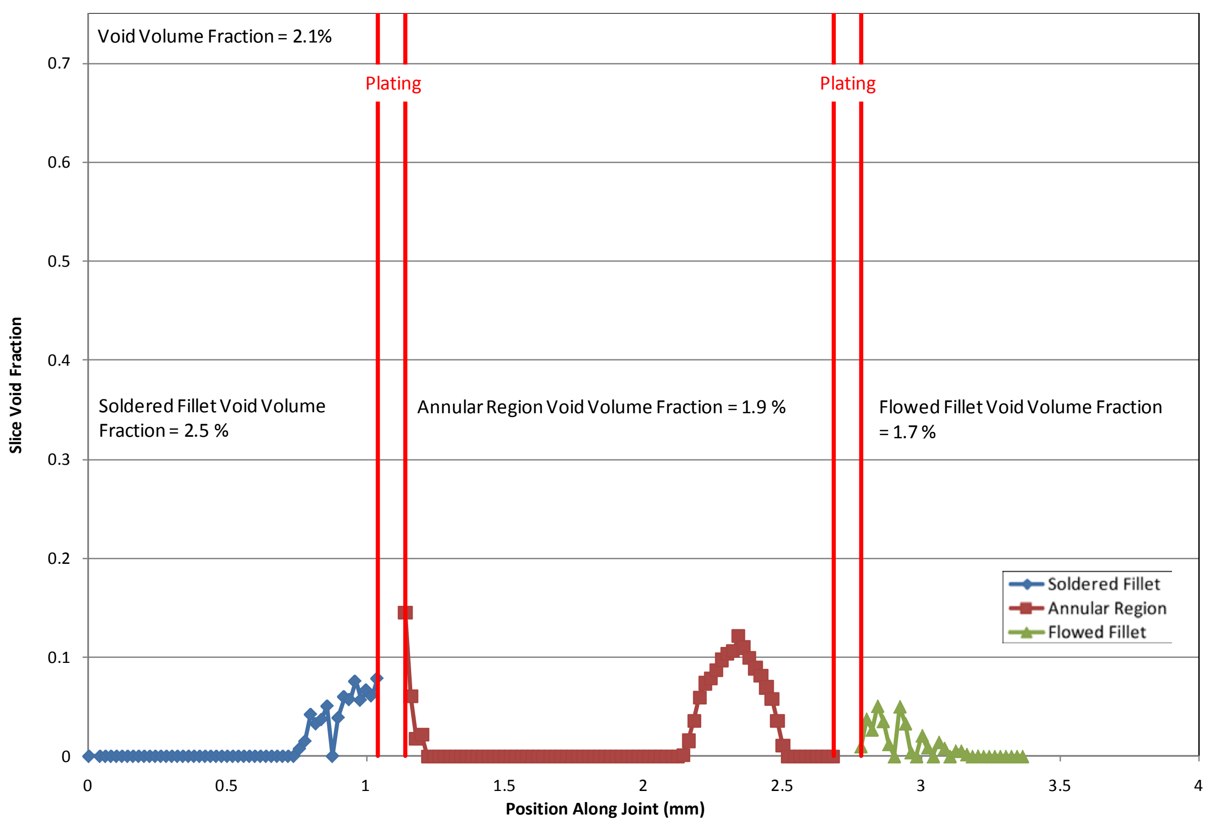

Figure 56.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, normal gravity, solder joint (GC3).

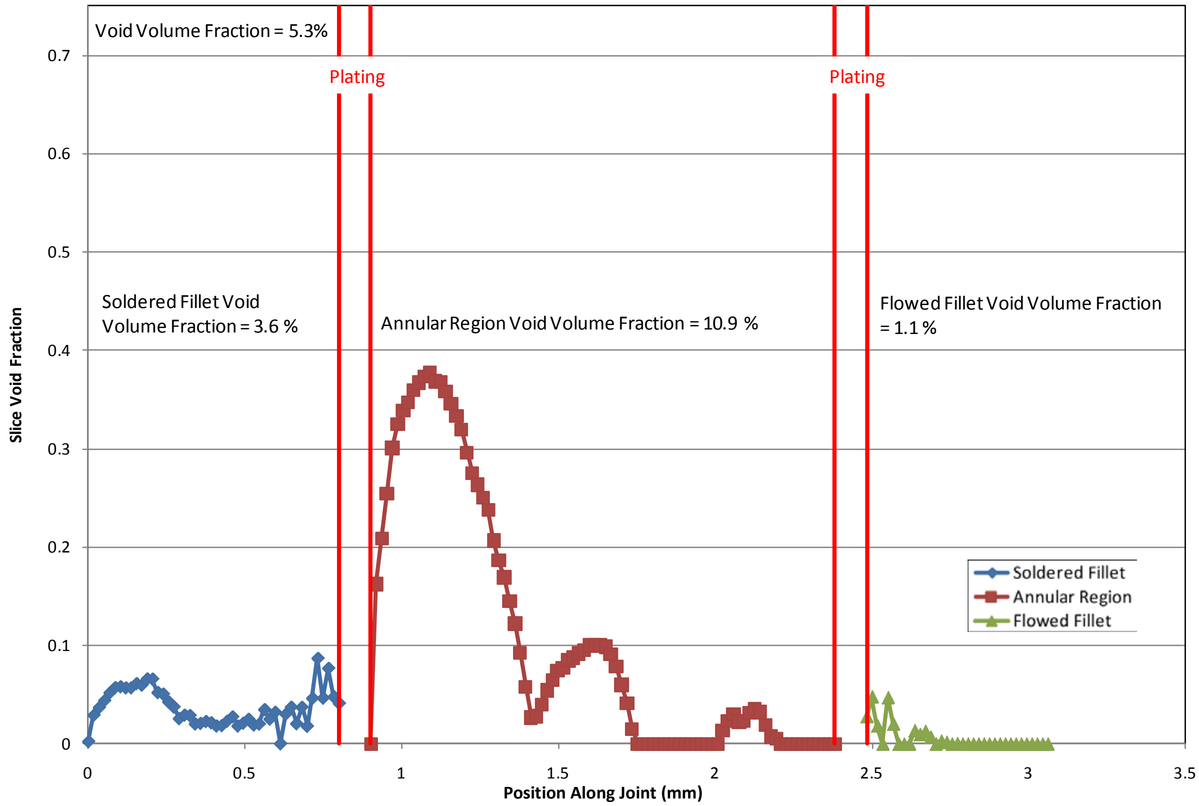

Figure 57.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, normal gravity, solder joint (GC6).

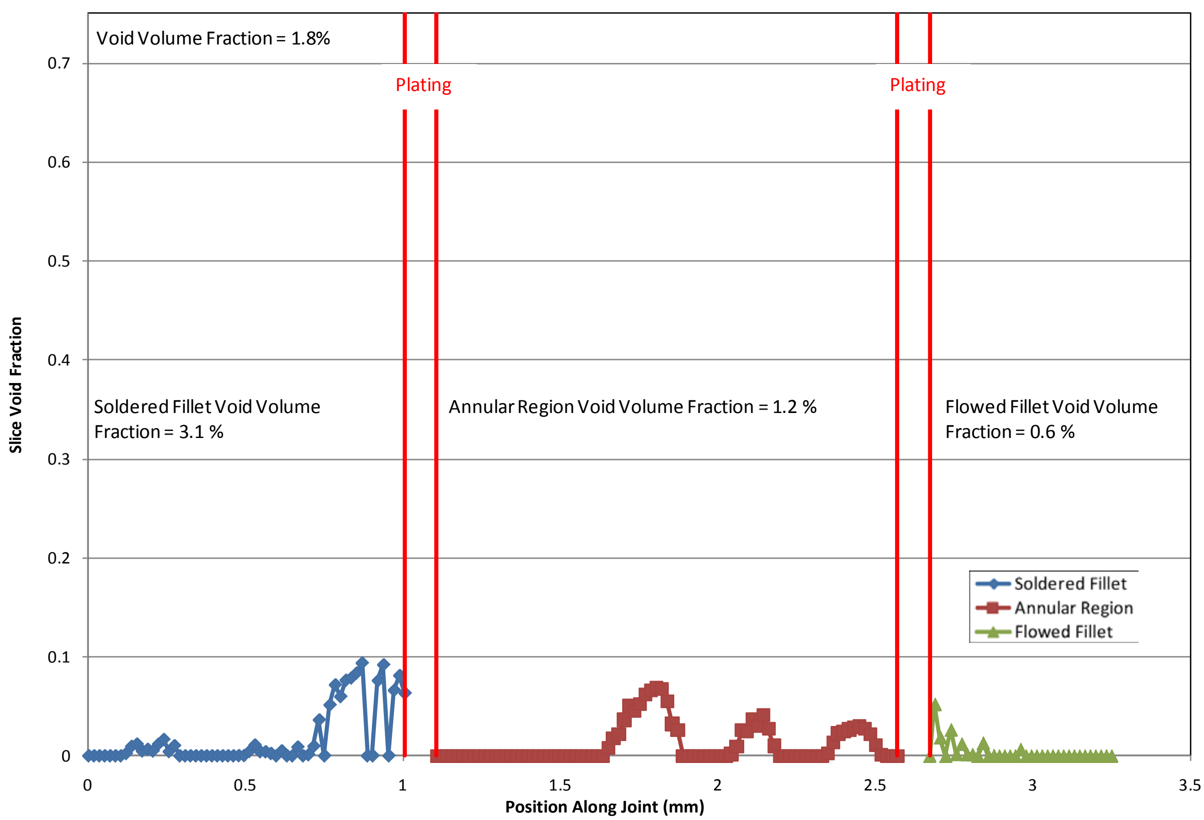

Figure 58.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, normal gravity, solder joint (GC7).

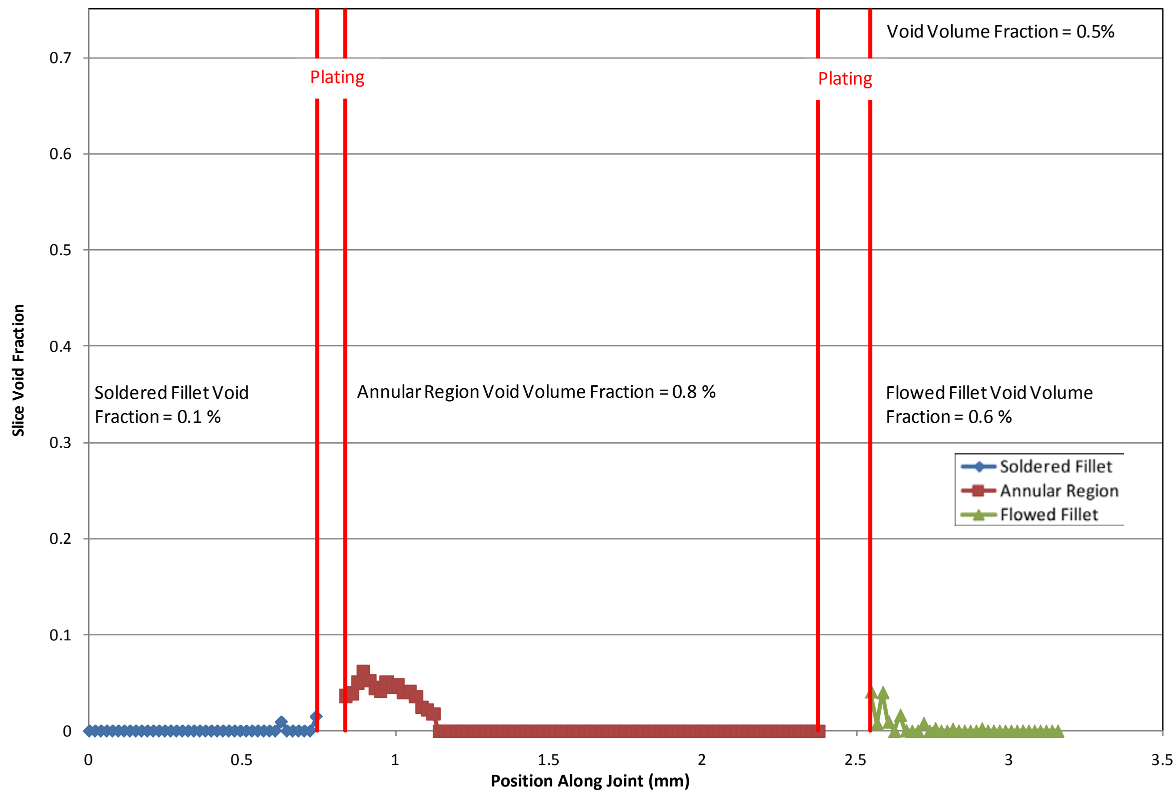

Figure 59.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, normal gravity, solder joint (GC8).

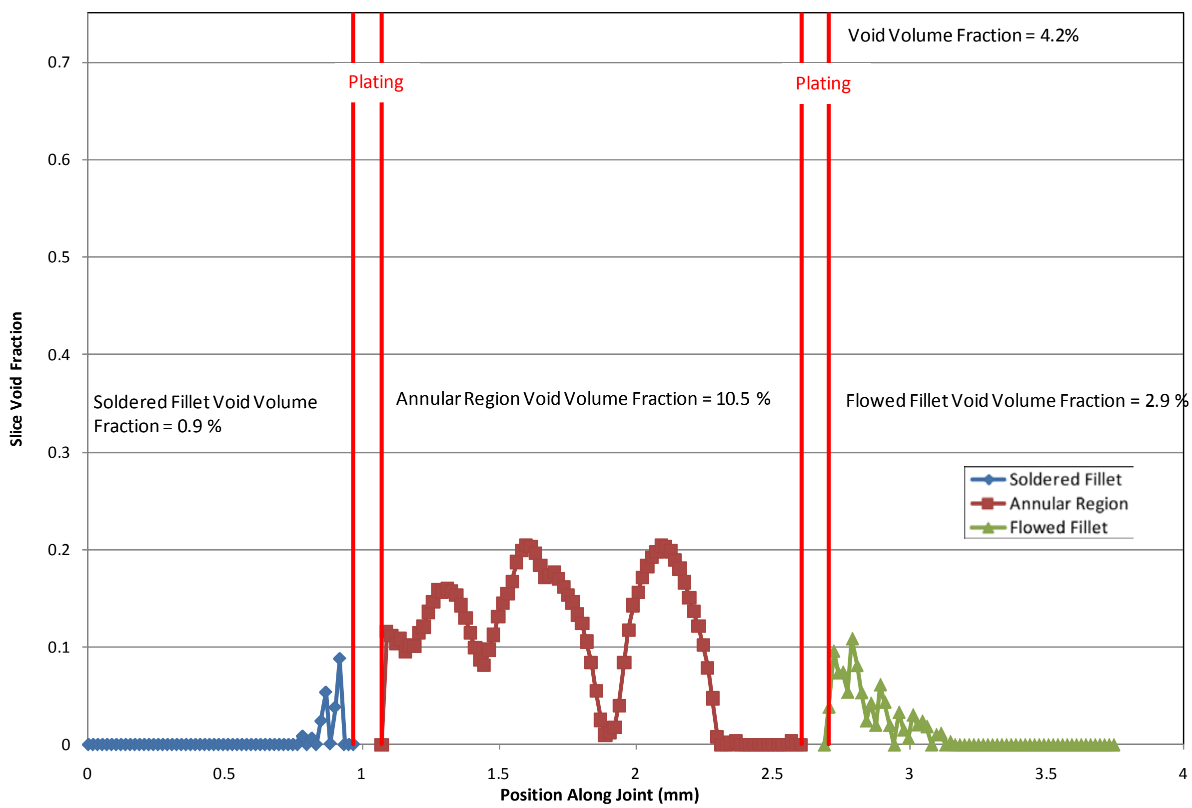

Figure 60.—Slice Void Fraction for a 60% tin-40% lead, external liquid flux, normal gravity, solder joint (GC10).

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-01-2012

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Soldering in a Reduced Gravity Environment (SoRGE)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Easton, John, W.; Struk, Peter, M.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 431767.04.01.03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17133

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2012-217119

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 33, 38, and 12
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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. Currently, crew members on the International Space Station (ISS) recover from faults by removing and replacing, using backup systems, or living without the function of Orbital Replacement Units (ORUs). These ORUs are returned to a depot where the root cause of the failure is determined and the ORU is repaired. The crew has some limited repair capability with the Modulation/DeModulation (MDM) ORU, where circuit cards are removed and replace in faulty units. 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 future spaceflight operations. To this end, the Soldering in a Reduced Gravity Environment (SoRGE) experiment studied the effect of gravity on the formation of solder joints on electronic circuit boards. This document describes the SoRGE experiment, the analysis methods, and results to date. This document will also contain comments from the crew regarding their experience conducting the SoRGE experiment as well as recommendations for future improvements. Finally, this document will discuss the plans for the SoRGE samples which remain on ISS.

15. SUBJECT TERMS
Soldering; Space maintenance; Astronaut training; Circuit boards; Microgravity; International Space Station; Solders; Space missions

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email:help@sti.nasa.gov)
U	U	U	UU	70	19b. TELEPHONE NUMBER *(include area code)* 443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18