

Boiling Experiment Facility (BXF): Post Flight Assessment Anomaly Investigation Report

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1.0 Introduction

The Boiling eXperiment Facility (BXF) is an experiment package designed for the Microgravity Science Glovebox (MSG) located on the International Space Station (ISS). Two experiments operate in this facility, the Microheater Array Boiling Experiment (MABE) and the Nucleate Pool Boiling Experiment (NPBX). The working fluid used by the facility is perfluoro-n-hexane.

MABE utilizes two arrays of microheaters along with measurement circuitry to record the local heat transfer characteristics on the surface of the heaters during boiling in a microgravity environment. Each heater is individually controlled to operate at a constant temperature.

NPBX consists of an array of five microcavities, or nucleation sites, on the surface of a polished aluminum wafer. The heat applied to each nucleation site is individually controlled, and the data obtained will be used to further the understanding of the heat transfer associated with nucleate boiling heat flux.

1.1 Background

BXF was turned over to NASA and packaged for launch aboard space shuttle flight ULF-5 in October 2010. After a lengthy delay, ULF-5 launched on February 24, 2011. BXF was installed into MSG and began Flight operations on March 22, 2011 (GMT 2011/081). BXF operated successfully for the next 3 weeks with the exception of five problems. The High Speed Camera image of the 7 mm MABE Array was out of alignment such that one row and one column of the array could not be seen in the image. During Week 2, the dissolved gas concentration was measured at 299 ppm, which exceeded the requirement of < 100 ppm. The Space Acceleration Measurement System (SAMS) unit that was to provide acceleration data for BXF was inoperable. Data from another unit was used instead. The connector from MSG video recorder 4 to the downlinking system was disconnected for a short period, and there were problems with the MSG laptop computer (MLC) that prevented file transfer from BXF during the calibration activities.

On April 11, 2011 (GMT 2011/101), the dissolved gas concentration was measured at 712 ppm, and on that day a major anomaly occurred. The voltage on 24 Vdc Bus 1 dropped unexpectedly to about 6 V, and an off-nominal current was drawn from MSG. This condition went unnoticed for approximately 8 min at which point a fluid loop pressure warning occurred. The BXF system entered into safe mode and tripped the safety circuit to remove power from the heaters and motors. It was observed that all pressure readings and some temperature readings were off-nominal. Attempts were made to recover by resetting the embedded controllers (ECs), restarting the BXF software, and cycling power to BXF. All attempts failed. The system was shutdown.

Over the next couple of weeks, multiple meetings and an Engineering Review Board (ERB) were held to study the data collected, propose possible root causes, determine methods for troubleshooting on-orbit, and put together a plan and procedure for carrying out troubleshooting on-orbit. Reference the Anomaly Troubleshooting ERB Presentation slides in Appendix E of the Mission Summary Report, 60081-RPT-0404. On April 27, 2011 (GMT 2011/117), the on-orbit troubleshooting was performed. The results of the troubleshooting indicated a possible electrical short on 24 Vdc Bus 1. It was also determined that with the 24 Vdc Bus 1 circuit breaker open, some NPBX science could still be obtained. One more week of operations with modified procedures was performed to obtain some limited NPBX science.

BXF was returned on space shuttle flight ULF-7, and Post-Flight troubleshooting activities were performed in accordance with the BXF Post-Flight Assessment Anomaly Investigation Plan, 60081-PLAN-0383.

1.2 Purpose

This document serves as the report for presenting the results and conclusions of investigation activities that were performed to determine the root causes of the anomaly, camera misalignment, and dissolved gas concentration issues and to verify the calibration and accuracy of the pressure and temperature measurements.

1.3 Scope

This report covers the results of Post-Flight Assessment (PFA) investigation activities that were performed on the BXF Flight hardware per 60081-PLAN-0383.

2.0 Documents

The following documents are applicable to this report.

Document Number	Document Title
60081-PLAN-0383	Post-Flight Assessment Anomaly Investigation Plan
60081-PROC-0390	Post-Flight Assessment Hardware Visual Inspection at KSC
60081-PROC-0368	Packing and Shipping Procedure
60081-PROC-0384	Voltage Bus Resistance Check for Anomaly Investigation
60081-PROC-0378	Flight Operations Anomaly Troubleshooting Procedure
60081-PROC-0379	NPBX Background Heaters Only Flight Operations Procedure
MGUEMSGBXFN001	BXF Setup Crew Procedure
60081-PROC-0391	Containment Vessel Gas Sampling Procedure
60081-PROC-0304	Containment Vessel Assembly Procedure, 60081M01A205
60081-PROC-0385	24Vdc Bus 1 Component Resistance Check for Anomaly Investigation
60081-PROC-0392	Pre-Drain Fluid Sampling and Analysis Procedure
60081-PROC-0397	Fluid Vapor Pressure Determination, FOD Collection, and Fluid Transfer Procedure
60081-RPT-0399	Post-Flight Pressure Measurement Verification Report
60081-RPT-0400	Post-Flight Temperature Measurement Verification Report
60081-PROC-0300	Fluids System Leak Test Procedure
60081-PROC-0393	Fluids System Leak Test at Elevated Temperature
60081-RPT-0401	Post-Flight Assessment BXF EC Engineering Checkout Report
60081-PROC-0075	Avionics Box Test Procedure
60081-PLAN-0394	Post-Flight Assessment Cartridge Heater Inspection Plan
60081-PROC-0395	Cartridge Heater Post-Extraction Resistance Check
60081-PROC-0396	Cartridge Heater Wiring Dissection
60081-PROC-0389	Post-Flight FOD Collection Procedure

3.0 Investigation Results

The following subsections give brief summaries of the results for each investigation activity that was conducted on the BXF Flight hardware. Only brief summaries are given. Detailed results are documented in individual reports, as-run procedures, attachments to the as-run plans, or appendices of this report as

specified in each subsection. Only results of activities are presented. For detailed information on each activity itself, reference 60081–PLAN–0383.

3.1 Exterior Visual Inspection and Packing at KSC

At the beginning of the visual inspection at Kennedy Space Center (KSC), it was observed that the BXF Flight hardware components were positioned and oriented in a disorganized manner. The Containment Vessel (CV) was located on a cart, and the remaining components were located on a table in the center of the lab. A few Non-BXF Flight components were mixed in with those of BXF.

In general, there were no findings that could be readily associated with the anomaly during the KSC visual inspection. All components were in their packings. Some packings were open, and some had minor tears and punctures. Some components were observed to have minor marks and scratches. Notable observations were as follows.

- Minor damage found on connector P108 of cable W301
- Dirt and minor damage found on the HSC Mirror
- Missing protective CCD cap of HSC S/N 001
- Fingerprints and damaged thermal pad on AB Mounting Plate
- HSC Processor S/N 001 appeared to be unused—ramification being that HSC Processor S/N 002 was the one used on orbit.

Details for the visual inspection and packing of the hardware are documented in the as-run procedures 60081–PROC–0390 and 60081–PROC–0368, respectively. Both are located in manufacturing work order (MWO) 60081M01L123–01.

3.2 Unpacking and Exterior Visual Inspection at ZIN

Additional observations were made by the technicians during unpacking of the hardware after arrival at ZIN.

- Pin E of connector P302 was found to be slightly bent
- Connector P8 of Cable W205 was not capped
- Minor damage found on CV Mounting Plate
- Debris found on outside of 2.5 mm MABE Lens
- RTV was missing from a screw located on top of the Avionics Box near connector J1

None of the additional observations made could be readily associated with the on-orbit anomaly.

Details are documented in the as-run procedure 60081–PROC–0368 located in MWO 60081M01L123–01.

3.3 Voltage Bus Resistance Check

The Voltage Bus Resistance Check found a short between the 24Vdc Bus 1 voltage line and the J101 connector shell (CV structure). The resistance measured was 5.43 Ω . A bonding measurement between connector J101 and the CV structure also failed. The bond resistance was 43 m Ω . These results showed that there was a problem located somewhere within the CV.

Details are documented in the as-run procedure 60081–PROC–0384 located in MWO 60081M01L123–01.

3.4 Functional Check

The Functional Check successfully demonstrated that the BXF Flight hardware functional capability was the same as it was just prior to being disassembled and stowed on orbit.

Some details are documented in the as-run procedure 60081–PROC–0378 located in MWO 60081M01L123–01. Remaining details are in electronic form located in Appendix B of this report.

3.5 Dissolved Gas Concentration Measurement

The Dissolved Gas Concentration, measured August 18, 2011, after return to ZIN, was found to be 603 ppm at a fluid temperature of 21.5°C and a fluid pressure of 0.36 atm. For comparison, the following table shows a list of Dissolved Gas Concentration values over time during Flight operations.

Date	Gas concentration, ppm	Fluid temperature, °C	Fluid pressure, atm
March 21, 2011 (GMT Day 081)	–46	30.3	0.35
March 31, 2011 (GMT Day 091)	299	33.1	0.46
April 3, 2011 (GMT Day 094)	261	23.1	0.31
April 10, 2011 (GMT Day 101)	712	24.8	0.42
April 26, 2011 (GMT Day 117)	737	23.6	0.41
May 8, 2011 (GMT Day 129)	589	23.1	0.37
May 11, 2011 (GMT Day 132)	543	30.1	0.46

Based on the measurements made Post-Flight and throughout operations, the gas contamination leakage appears to have stopped when on-orbit testing ended in May 2011.

The PFA Dissolved Gas Concentration Measurement is documented in the as-run procedure 60081–PROC–0379 located in MWO 60081M01L123–01.

3.6 High Speed Camera Alignment Check

Assembly of the BXF Flight hardware per MGUEMSGBXFN001 did not result in an HSC Camera misalignment on the ground as severe as that observed on orbit. Troubleshooting found that a misalignment more similar to that observed on orbit could be induced by unloading the HSC Mounting Bracket and not fully seating the MABE lens against the HSC Alignment Bracket set screws.

These observations suggest that minor compliance in the camera mounting hardware, incomplete seating of the lens on the set screws, or a combination of both of these factors could have caused the image misalignment observed on-orbit. The one attempt that was made to correct the alignment during Flight operations was unsuccessful. It is possible, with further opportunities to iterate, that proper alignment could have been achieved during Flight operations. The potential for success, however, would have been hindered by the following factors: crew time constraints; the inability to have the system powered during alignment for image viewing; and the lack of a high fidelity Engineering Model to utilize for guidance and assistance. These factors would have likely made future attempts similarly unsuccessful. Details are documented in an attachment to the as-run BXF PFA plan, 60081–PLAN–0383, located in MWO 60081M01L123–01. The HSC images acquired during the alignment check can be found in Appendix C of this report.

3.7 24 Vdc Bus 1 Anomaly Check

In accordance with the BXF PFA plan, the 24 Vdc Bus 1 Anomaly Check was not performed, because the BXF Flight hardware failed the Voltage Bus Resistance Check of section 3.3 of the plan.

3.8 Containment Vessel Gas Sampling

This activity was not originally part of the BXF PFA plan but was added due to growing concern that a Bulk Fluid Heater may have overheated and generated perfluoroisobutene (PFIB) from the BXF Fluid. PFIB is a hazardous gas and has an acceptable exposure limit of only 10 parts per billion. The intent of the CV Gas Sampling was to determine whether any fluid, and possibly PFIB, might be present in the CV interior space.

Two samples of gas were taken from the interior space of the CV, and both samples were analyzed for hydrogen fluoride (HF), fluorine (F₂), and perfluoro-n-hexane (PFnH). No HF or F₂ were detected. This greatly increased the confidence that no PFIB was present in the CV interior space. Some PFnH was detected at very low levels, 334 and 437 ppm. This low level of PFnH was attributed to low diffusion leakage through the BXF Test Chamber soft seals. If there had been a major leak of PFnH into the CV interior space, the concentration would have been several orders of magnitude greater. It was, therefore, concluded that the BXF Test Chamber was intact (first level of containment still in place) and that it was okay to proceed with disassembly of the CV.

In addition to the results discussed above, the analysis also showed the presence of carbon byproducts in the gas samples, suggesting that a combustion event may have taken place within the CV interior space.

Details are documented in the as-run procedure 60081–PROC–0391 located in MWO 60081M01A205–03.

3.9 Containment Vessel Disassembly: Inspect Interior and Install CV Legs

This activity was modified slightly to include monitoring of the short found on 24 Vdc Bus 1. The intent was to determine the nature of the short, whether it was intermittent or stable, and isolate its location.

Disassembly of the CV revealed the presence of burnt/melted wiring. The wiring leading to Cartridge Heater Assembly S/N 010, utilized for Bulk Fluid Heater 1, exhibited a dark black and brown discoloration in and around connector J215. Some of the discoloration was observed on nearby wires. The overall internal insulation sleeving of the cartridge heater wiring appeared to have melted and protruded through the shield braid near connector J215. A red tie wrap that held the cartridge heater wiring in place was damaged, melted, and fused to the shield braid.

There is clearly a problem associated with Bulk Fluid Heater 1.

Details of disassembly are documented in the as-run procedure 60081–PROC–0304 located in MWO 60081M01A205–03. Observations are noted in an attachment to the as-run BXF PFA plan, 60081–PLAN–0383, located in MWO 60081M01L123–01.

3.10 24 Vdc Bus 1 Component Resistance Check

Cartridge Heater Assembly S/N 010 (Bulk Fluid Heater 1) failed the 24Vdc Bus 1 Component Resistance Check. Heater 1 had multiple shorts as follows.

Cartridge Heater S/N 010 (Bulk Fluid Heater 1)		
Location	Resistance, Ω	Pass criteria
Between power and return	2.4	> 8 Ω
Between power and structure	6.26	> 1 M Ω
Between return and structure	5.97	> 1 M Ω

Additional failures were found on Cartridge Heater Assembly S/N 012 (Bulk Fluid Heater 2) as follows.

Cartridge Heater S/N 012 (Bulk Fluid Heater 2)		
Location	Resistance, Ω	Pass criteria
Between power and structure	35.6	> 1 M Ω
Between return and structure	34.1	> 1 M Ω

Cartridge Heater Assembly S/N 009 (Bulk Fluid Heater 3) passed the resistance check along with all other components on 24 Vdc Bus 1.

These results confirmed a problem with Bulk Fluid Heater 1 and revealed a possible hidden degradation of Bulk Fluid Heater 2.

Details are documented in the as-run procedure 60081–PROC–0385 located in MWO 60081M01A205–03.

3.11 Pre-Drain Fluid Sampling and Analysis

This activity was not originally part of the BXF PFA plan but was added due to stronger evidence that one or more Bulk Fluid Heaters overheated, increasing concerns that PFIB was produced.

As a consequence of determining that Bulk Fluid Heaters 1 and 2 were shorted, two samples of the BXF fluid were taken. One sample was sent out for analysis to determine whether PFIB was present or not. The second sample was stored for possible analysis in-house. The analysis results confirmed the presence of PFIB in the BXF Fluid at 90 parts per *million*. The acceptable exposure level (AEL) of PFIB is 10 parts per *billion*.

Upon notification of this result, the BXF CV was reassembled back into the CV Housing to reestablish three levels of containment. All BXF PFA activities were placed on hold until it was determined how to proceed.

Details are documented in the as-run procedure 60081–PROC–0392 located in MWO 60081M01A205–03.

3.12 Flight Hardware Drain/Fluid Disposal

This activity was not originally part of the BXF PFA plan but was added due to the discovery of the presence of hazardous PFIB in the BXF Fluid.

After weighing the pros and cons of several courses of action, it was finally determined that the BXF Fluid would be removed from the BXF hardware and disposed of by the NASA Hazardous Waste Management organization. The fluid was transferred into two disposal cylinders, and NASA Hazardous Waste Management arranged for a disposal vendor to pick them up.

Just prior to the transfer process, a series of temperature and pressure measurements were taken to determine the Dissolved Gas Concentration of the fluid, and during the transfer, the fluid was passed through a filter to collect any foreign object debris (FOD) present in the fluid. The filter containing the collected FOD was stored for future analysis.

The resulting Dissolved Gas Concentration value was 870 ppm at 20.7 °C and 0.40 atm. The temperature and pressure measurements, however, were taken in a manner that differed greatly from the method used for prior Dissolved Gas Concentration calculations. At the time these measurements were taken, a GSE pressure transducer was used instead of the transducers of the BXF system, an external fluids system was attached to the BXF hardware, and there was no bellows control of BXF Fluid pressure. While it is possible that there was an increase in gas contamination at this time, due to the differences in how the measurements were taken, the value of 870 ppm is likely not very meaningful.

Details are documented in the as-run procedure 60081–PROC–0397 located in MWO 60081M01A205–03.

3.13 Pressure and Temperature Measurement Accuracy Check

A comparison between the Pre and Post-Flight results of pressure measurement testing found that there was little to no deviation in data that could not be explained by the combined uncertainty of the BXF system and the pressure calibrator used for testing. This suggested that the state of the BXF electrical system, post-anomaly, had no effect on the output of the pressure transducers. Post-Flight temperature measurement verifications were performed on the BXF Bulk Fluid, Cavity, Surround, Background and Insulation (Rake) Thermistors with the BXF avionics in the post-anomaly flight-like configuration. Unlike the pressure measurement verification, a complete end-to-end calibration of the temperature measurement system could not be performed since the locations and configurations of the thermistor elements made it impossible to do so without complete disassembly and possible damage to the system and components of interest. Instead, the thermistors were disconnected from the rest of the system as close to the element as possible and replaced with a variable load. The load on each temperature circuit was varied to simulate each element's output based on the Pre-Flight thermistor calibration results and the temperature ranges of interest. Ambient temperature checks of the thermistor elements were also performed to support the system verification results. All thermistor elements, except the known non-conformance of Cavity Thermistor 5, showed good agreement with Pre-Flight calibration results indicating that the elements themselves and associated cabling were in good working order.

In general, all of the random variation observed in the temperature measurement verification data showed reasonable agreement with the Pre-Flight uncertainty analyses conducted. There were a number of instances where data outliers were observed in the Post-Flight results, and these may be attributed to experimental errors as identified and discussed in 60081–RPT–0400. Since the outliers generally occurred only at the extremes of the temperature ranges tested (suggesting saturation of the measurement channel) and the rest of the data followed expected trends, there appears to be no significant impact to the BXF temperature measurements in the post-anomaly configuration of the system.

Details for the pressure and temperature measurement accuracy checks are documented in 60081–RPT–0399 and 60081–RPT–0400, respectively.

3.14 Containment Vessel Disassembly: Uninstall CV Top Plate/CV Fan Visual Inspection and Touch Test

This activity was modified to include a CV Fan Inspection and Touch Test to determine whether “smoke” may have been generated that could have adversely affected the pressure sensors.

The Top Plate was uninstalled from the CV to prepare for subsequent PFA activities. After the Top Plate was uninstalled, the fans located on it underwent a visual inspection and “white glove” touch test. Reddish-brown FOD was found present on the leading edge of the fan blades and the inner surface of the housing on both CV Fans. The material had a slight reddish appearance when adhered to the fans, but took on more of a brownish appearance when transferred to the white cloth used for the touch test. The substantial amount of FOD present on the CV Fans suggests that “smoke” may have been generated within the CV interior space during the anomaly on-orbit.

Details for the disassembly are documented in the as-run procedure 60081–PROC–0304 located in MWO 60081M01A205–03. Details for the CV Fan visual inspection and touch test are documented in an attachment to the BXF PFA plan, 60081–PLAN–0383, located in MWO 60081M01L123–01.

3.15 Room Temperature Leak Test

An overall instantaneous vacuum leak rate of 0.9×10^{-8} sccs helium (He) was measured, and a permeation leak rate of 4.1×10^{-6} sccs He was measured over 2.7 hr. For pressure, a leak rate of 1.1×10^{-7} sccs He was measured over 1.5 hr, which was also the background rate.

During Pre-Flight leak testing, the results were as follows:

- Vacuum Instantaneous Leak Rate: 7.0×10^{-7} sccs He
- Vacuum Permeation Leak Rate: 5.4×10^{-6} sccs He, over 4.8 hr
- Permeation Leak Rate: 1.3×10^{-7} sccs He, over 15 min (background rate)

As can be seen above, the Post-Flight leak rates are comparable to the Pre-Flight leak rates, which suggests that there have been no new leaks since that time.

It should be noted that during individual component sniffing while under pressure, two Cartridge Heater Assemblies, S/Ns 012 and 009 (Bulk Fluid Heaters 2 and 3, respectively) were found to have a slightly higher localized leak rate of 1.7×10^{-7} sccs He. No leaks were found on any other components, including the Cartridge Heater Assembly S/N 010 (Bulk Fluid Heater 1).

Details are documented in the as-run procedure 60081-PROC-0300 located in MWO 60081M01A206-02.

3.16 Elevated Temperature Leak Test

This activity was not originally part of the BXF PFA plan but was added to determine the credibility of the presence of temperature-dependent leaks that may have been induced by the elevated temperatures experienced by the BXF hardware on-orbit.

The Elevated Temperature Leak Test, which used the CV Housing and a thermal chamber set at 50 °C, produced an overall instantaneous vacuum leak rate of 1.0×10^{-7} sccs He and a permeation leak rate of 1.7×10^{-5} sccs He over 2.8 hr. The test was repeated at room temperature, again using the CV Housing, to produce an instantaneous leak rate of 1.1×10^{-8} sccs He and a permeation leak rate of 7.5×10^{-6} sccs He over 4.3 hr. The room temperature results were comparable to those generated during the “bagged” Room Temperature Leak Test (Section 3.15) and are an order of magnitude lower than the leak rates observed at an elevated temperature of 50 °C.

Individual component spraying at elevated temperature inside the thermal chamber without the CV Housing did not reveal any specific leak sources. In general, all components and seals appeared to share in the increased leak rate at higher temperatures.

Details are documented in the as-run procedure 60081-PROC-0393 located in MWO 60081M01A206-02.

3.17 BXF Embedded Controller Inspection and Bench Test

Visual inspection of the BXF Embedded Controller (EC) found the same FOD that was found during the CV Fan Visual Inspection. The reddish-brown FOD was located in areas of the board that were exposed to the air flow of the fans.

The BXF EC passed bench testing with the exception of two failures. The Flow Meter Input failed, because the worst case error of +15 counts exceeded the success criterion of ± 10 counts. The control relays for Bulk Fluid Heaters 2 and 3 failed, because their on-state resistances of $\approx 2 \Omega$ each exceeded the success criterion of $< 1 \Omega$.

It should be noted that the control relay for Bulk Fluid Heater 1 passed the success criterion.

The Flow Meter Input was not specified as a requirement for BXF. The success criterion was, therefore, arbitrarily selected based on actual results achieved during development. The current worst case

error of +15 counts is equivalent to a fluid flow measurement error of +0.006 L/min. This failure is likely not related to the on-orbit anomaly.

The higher on-state resistance of each failing control relay reduced the amount of power delivered to Bulk Fluid Heaters 2 and 3 resulting in less than nominal heating of the BXF Fluid with Bulk Fluid Heater 1 carrying more of the burden. Consequently, the time required to achieve desired fluid temperatures may have been longer than normal.

Details of the visual inspection are documented in the as-run process plan PP60081E01A520–3 located in MWO 60081M01A205–03. Details of the bench test are documented in 60081–RPT–0401.

4.0 Conditional/Optional Investigation

The following subsections give brief summaries of the results for each conditional/optional investigation activity that was conducted on the BXF Flight hardware. The activities in this section were either conditional or optional, being performed only when certain conditions were met, or at the discretion of ZIN and NASA project management. Only brief summaries are given. Detailed results are documented in individual reports, as-run procedures, attachments to the as-run plans, or appendices of this report as specified in each subsection. Only the results of activities are presented. For detailed information on each activity itself, reference 60081–PLAN–0383.

4.1 2.7 mm MABE Embedded Controller Inspection

The original BXF PFA plan specified this activity be an inspection *and* bench test, but the project determined that a bench test was not necessary since the investigation results were pointing towards the Bulk Fluid Heaters as the source of the failure. This activity was reduced in scope to a visual inspection only.

The visual inspection of the 2.7 mm MABE EC found the same FOD that was found during the CV Fan Visual Inspection. The reddish-brown FOD was located in areas of the board that were exposed to the air flow of the fans. All other observations were nominal.

It is unlikely that the 2.7 mm MABE EC contributed to the on-orbit anomaly.

This visual inspection is documented in the as-run process plan PP60081E01A501–3 located in MWO 60081M01A205–03.

4.2 7.0 mm MABE Embedded Controller Inspection

The original BXF PFA plan specified this activity be an inspection *and* bench test, but the project determined that a bench test was not necessary since the investigation results were pointing towards the Bulk Fluid Heaters as the source of the failure. This activity was reduced in scope to a visual inspection only with extra attention paid to the circuit components for microheater 27.

The visual inspection of the 7.0 mm MABE EC found the same FOD that was found during the CV Fan Visual Inspection. The reddish-brown FOD was located in areas of the board that were exposed to the air flow of the fans. Additionally, attention was focused on the board components associated with control of microheater 27, because it was noted during operations that this microheater had stopped functioning. All components involved with microheater 27 appeared nominal. All other observations also appeared nominal.

It is unlikely that the 7.0 mm MABE EC contributed to the on-orbit anomaly.

This visual inspection is documented in the as-run process plan PP60081E01A519–3 located in MWO 60081M01A205–03.

4.3 Avionics Box Output Voltage Test

The original BXF PFA plan specified this activity be a *full-fledged* bench test, but the project determined that a *full-fledged* bench test was not necessary since the investigation results were pointing towards the Bulk Fluid Heaters as the source of the failure. This activity was reduced in scope to an output voltage test only.

All output voltages of the BXF Avionics Box (AB) passed the success criterion of $\pm 10\%$ of nominal. The resulting voltages are listed below.

Voltage Bus	Voltage, V
12 Vdc Bus	11.952
24 Vdc Bus 1	23.971
24 Vdc Bus 2	23.943

It is unlikely that the BXF AB contributed to the on-orbit anomaly.

Details are documented in the as-run procedure 60081-PROC-0075 located in MWO 60081M01A438-04.

4.4 Avionics Box Interior Visual Inspection

Visual Inspection of the interior space of the BXF AB found everything to be nominal.

This inspection is documented in the as-run process plan PP60081M01A438-3 located in MWO 60081M01A438-04.

4.5 Bulk Fluid Heater Extraction and Inspection

The extraction and inspection investigation activities for the Bulk Fluid Heaters were conducted in accordance with the Post-Flight Assessment Cartridge Heater Inspection Plan, 60081-PLAN-0394. The following subsections discuss the results of each activity.

4.5.1 Extraction and Visual Inspection (Section 3.1 of PLAN-0394)

All three Cartridge Heaters Assemblies were removed from the BXF Test Chamber and visually inspected. The metal sheaths of Cartridge Heaters S/Ns 012 and 009 (Bulk Fluid Heaters 2 and 3, respectively) appeared discolored and blackened. Heater 2 appeared more blackened than Heater 3. Other than the discoloration, however, no additional damage was observed.

Cartridge Heater S/N 010 (Bulk Fluid Heater 1) could not be extracted from its port fitting on the Test Chamber. So, the entire fitting was removed from the chamber and left in place on the heater. Heater 1 showed extreme damage at two locations along the sheath. Melting of the Incoloy 800 is evident in both locations. The brownish magnesium oxide (MgO) insulating material and greenish remains of the nickel chromium (NiCr) wiring inside are also visible. Melting points of the various materials are listed below.

Material	Melting Point, °C
Incoloy 800	1385
Magnesium oxide	2800
Nickel chromium	1400

The damage observed on Bulk Fluid Heater 1 proves that temperatures in excess of 1400 °C were achieved on-orbit.

Details are documented in an attachment to the as-run PFA Cartridge Heater Inspection Plan, 60081-PLAN-0394, located in MWO 60081M01A206-02. Photos taken during the inspection can be found in Appendix D of this report.

4.5.2 Post-Extraction Resistance Check (Section 3.2 of PLAN-0394)

The Post-Extraction Resistance Check yielded similar results for Bulk Fluid Heaters 2 and 3 as those obtained during the 24 Vdc Bus 1 Component Resistance Check. Heater 2 had partial shorts to the heater sheath, but not the wiring shield. Heater 3 passed the check.

The results of Bulk Fluid Heater 1 were erratic. A few of the results technically passed, but the resistance value was not stable. It was still evident in the recorded data that Heater 1 suffered a major failure.

Details are documented in the as-run procedure 60081-PROC-0395 located in MWO 60081M01A206-02.

4.5.3 X-Ray Inspection (Section 3.3 of PLAN-0394)

X-rays of the Flight Cartridge Heater Assemblies showed the obvious damage of S/N 010 (Bulk Fluid Heater 1). The two damaged areas are easily seen. When S/Ns 012 and 009 (Bulk Fluid Heaters 2 and 3, respectively) are compared, there appears to be a subtle difference between them. The internal heater coil of S/N 012 appears to be slightly unwound and irregular, but these observations are subjective.

Details are documented in an attachment to the as-run PFA Cartridge Heater Inspection Plan, 60081-PLAN-0394, located in MWO 60081M01A206-02. Photos of the Cartridge Heater x-ray images can be found in Appendix E of this report.

4.5.4 Heater Wiring Dissection (Section 3.4 of PLAN-0394)

Two heaters were dissected. Cartridge Heater S/N 012 (Bulk Fluid Heater 2) was dissected first followed by Cartridge Heater S/N 010 (Bulk Fluid Heater 1).

Throughout all stages of dissection for Heater 2, observations were nominal, and the heater resistance was stable at $\approx 9.63 \Omega$. The Post-Dissection Resistance Check of Heater 2 found two partial shorts, each $\approx 40 \Omega$, between the heater sheath and both the power and return lines going into the sheath. This is in agreement with prior investigation results.

Difficulties were encountered during the dissection of Heater 1. The wiring shield braid could not be pulled back from the connector, because the shield was fused with the internal insulation sleeving. Cutting open the shield braid proved to be a slow process, as it was found that the shield had been hardened. After the shield was cut open, it was observed that the internal insulation sleeving was carbonized near the connector. The sleeving crumbled apart easily as the dissection proceeded. The insulation of the internal wiring appeared blackened overall, but whitened over the crimped area. The wire insulation near the connector was melted away leaving bare exposed wire. When the insulation sleeving was finally removed from around the connector, it was observed that the connector was melted and completely encasing the internal contacts. The contacts could not be extracted. During the dissection, the wiring separated from the heater sheath on its own without the need for cutting it, and the heater sheath became bent at one of the damaged portions of the sheath. The heater resistance was unstable and varied greatly as the assembly was handled. A stable value of 7.08Ω was finally measured during the Post-Dissection Resistance Check. Shorts of $\approx 8 \Omega$ each were found between the heater sheath and both power and return lines. The wiring that separated from the heater sheath failed continuity testing.

Details are documented in two copies, one for each heater, of the as-run procedure 60081-PROC-0396 located in MWO 60081M01A206-02.

4.6 FOD Analysis

The original BXF PFA plan included FOD collection along with the analysis, however, this was before the discovery of PFIB in the BXF Fluid. When the Fluid was disposed of, the opportunity was taken at that time to collect any FOD present. This activity was reduced in scope to an analysis only.

Also, originally this activity was for Fluid FOD only. When the CV Fan FOD was discovered, this activity was expanded to include collection and analysis of the CV Fan FOD.

The filter containing FOD collected during the Flight Hardware Drain/Fluid Disposal activity was analyzed by NASA GRC using a Field Emission Scanning Electron Microscope (FESEM). The analysis found the presence of fluorine, magnesium, aluminum, silicon, chromium, and in some cases, iron and nickel. Magnesium was consistently found in many of the particles analyzed. The following table lists the most likely sources of the elements detected in the Fluid FOD.

Element(s)	Source(s)
Magnesium	MgO Insulation of Bulk Fluid Heater 1
Oxygen	
Nickel	Incoloy 800 and NiCr Resistance Wiring of Bulk Fluid Heater 1, Stainless Steel (SS) Tubing of BXF Fluids System
Chromium	
Iron	
Aluminum	BXF Test Chamber
Fluorine	Soft Goods and Insulating Materials throughout BXF System
Silicon	

A sample of the CV Fan FOD was collected and also sent for analysis by NASA GRC using a FESEM. The analysis consistently found the presence of carbon, fluorine, silicon, and oxygen. Tin, sodium, calcium, aluminum, and sulfur were also detected. Some of these elements, especially fluorine, carbon, and oxygen, are likely the result of decomposition of materials making up the burned/melted wiring of Bulk Fluid Heater 1. Some of these materials are Halar (tie wrap), Viton (insulation sleeving), Teflon (wire insulation), and nylon (connector).

Collection of the CV Fan FOD is documented in the as-run procedure 60081–PROC–0389 located in MWO 60081M01A205–03. The Fluid and CV Fan FOD analyses are documented in reports generated by NASA GRC, and these reports are available in files maintained by the NASA Project Manager.

5.0 Conclusions

5.1 High Speed Camera Misalignment

Based on the results outlined in Section 3.6, it can be concluded that the high speed camera (HSC) misalignment was due to compliance in the HSC hardware. It is possible that correct alignment could have been achieved with more time and iteration.

5.2 Dissolved Gas Concentration

The results of Sections 3.5, 3.15, and 3.16 suggest that the overall leak rate of the BXF hardware increased when the hardware was exposed to higher operating temperatures on-orbit. This was not anticipated, and the hardware was leak tested only at room temperatures before Flight.

5.3 On-Orbit Anomaly

It can be concluded from the investigation results that Cartridge Heater S/N 010 (Bulk Fluid Heater 1) overheated. The heater temperature had to have reached at least 1400 °C in order to melt the Incoloy 800 and NiCr materials of the heater. The heat that was generated probably transferred via thermal conduction down the cartridge heater wiring causing the burn and melt damage observed near the connector. The

burning and melting of the heater and its wiring led to the creation of an electrical short on 24 Vdc Bus 1. This short would have caused the 24 Vdc Bus 1 DC/DC converter to go into current limiting mode, reducing voltage output, while at the same time, causing higher than nominal current draw from MSG.

The investigation results also suggest that Cartridge Heater S/Ns 012 and 009 (Bulk Fluid Heaters 2 and 3, respectively) may have also overheated, or came close to doing so.

The manufacturers of the cartridge heaters and BXF Fluid (PFnH) were consulted to determine the possible reasons why the heaters overheated. The following is a list of the most likely causes:

- Lack of direct heater temperature monitoring and control allowed overheating to occur.
- The dissipation heat flux of the cartridge heaters was within the range required for the onset of boiling (4 W/cm^2 versus 6 to 10 W/cm^2) in normal gravity (Ref. 1).
- Fluid flow rate may have been too low to carry heat away from the heaters.
- Microgravity may have inhibited convective removal of heat from the heaters.

One or more of the factors above contributed to a scenario in which nucleation boiling of the fluid may have been induced around the heaters. In the case of Heater 1, this nucleation boiling may have progressed to film boiling, causing the heater to become completely enveloped in vapor. The vapor, in turn, would have acted as a thermal insulator and significantly reduced heat transfer from the heater to the fluid. This would have caused the heater to enter into a “runaway” condition in which the heater temperature increases extremely rapidly. The Bulk Fluid temperature sensors throughout the Test Chamber would not have detected this local temperature rise at the heater.

Appendix A.—Acronyms and Abbreviations

AB	Avionics Box
AEL	Acceptable Exposure Limit
atm	atmospheres
BXF	Boiling eXperiment Facility
CCD	Charged Coupled Device
CV	Containment Vessel
dc or DC	direct current
EC	Embedded Controller
ERB	Engineering Review Board
F ₂	fluorine
FESEM	Field Emission Scanning Electron Microscope
FOD	Foreign Object Debris
GMT	Greenwich Mean Time
GRC	NASA Glenn Research Center
GSE	Ground Support Equipment
He	helium
HF	hydrogen fluoride
HSC	high speed camera
ISS	International Space Station
KSC	NASA Kennedy Space Center
L/min	liters per minute
MABE	Microheater Array Boiling Experiment
MgO	magnesium oxide
MSG	Microgravity Science Glovebox
MWO	Manufacturing Work Order
NASA	National Aeronautics and Space Administration
NiCr	nickel chromium
NPBX	Nucleate Pool Boiling eXperiment
PFA	Post-Flight Assessment
PFIB	perfluoroisobutene
PFnH	perfluoro-n-hexane
ppm	parts per million
RTV	Room Temperature Volatile
S/N	serial number
sccs	standard cubic centimeters per second
ULF	Utilization and Logistics Flight
ZIN	ZIN Technologies

Appendix B.—Functional Check Details

This appendix contains the BXF Ops Display screenshots, acquired HSC images, Command Log file, and Housekeeping Data files generated during the Functional Check. See Section 3.4.

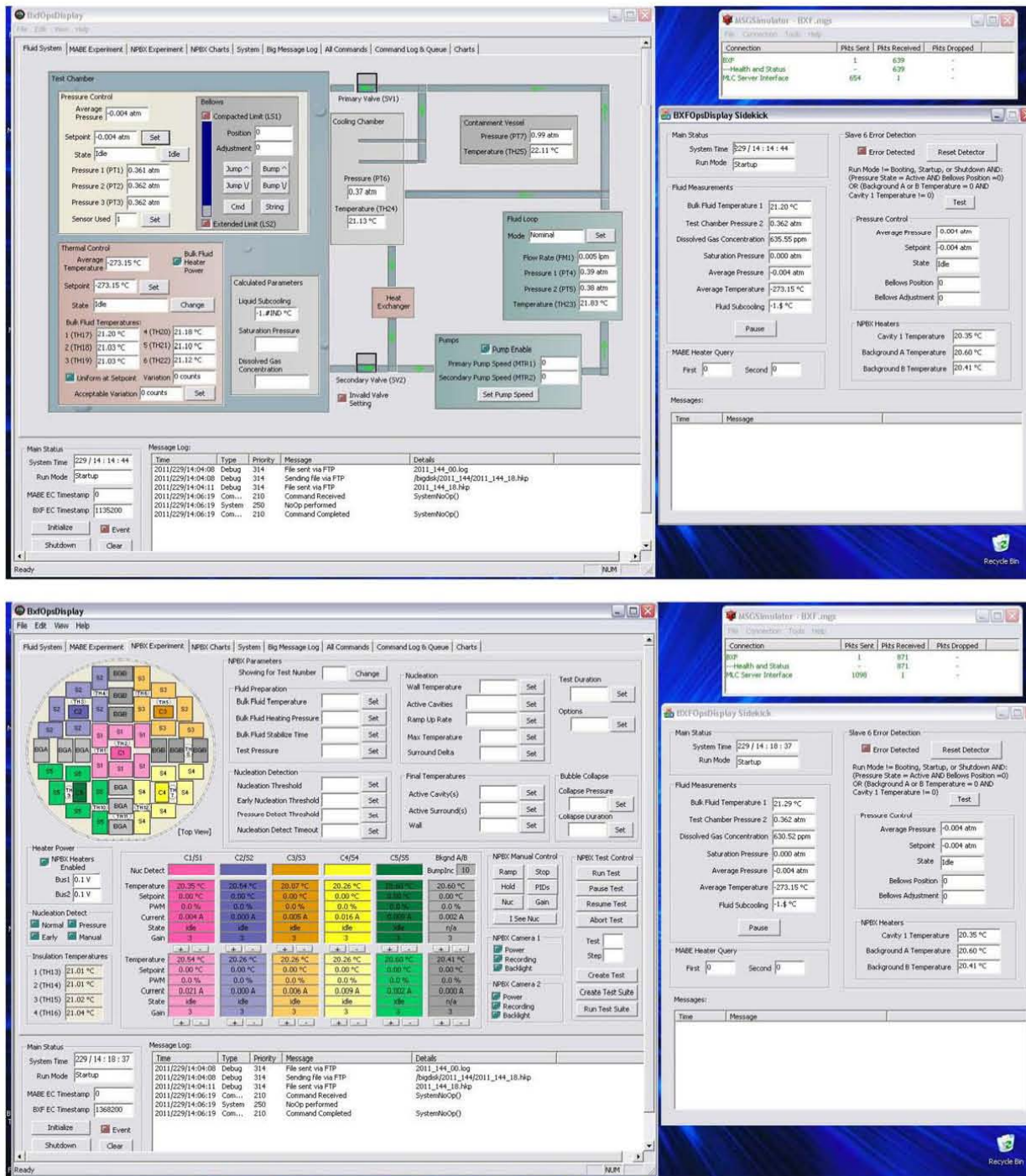


Figure B.1.—Screen displays for RS-422 Communication test: Fluid System Tab for BXFOPSDisplay (top left) and for Sidekick (top right), NPBX Experiment Tab for BXFOPSDisplay (bottom left) and for Sidekick (bottom right).

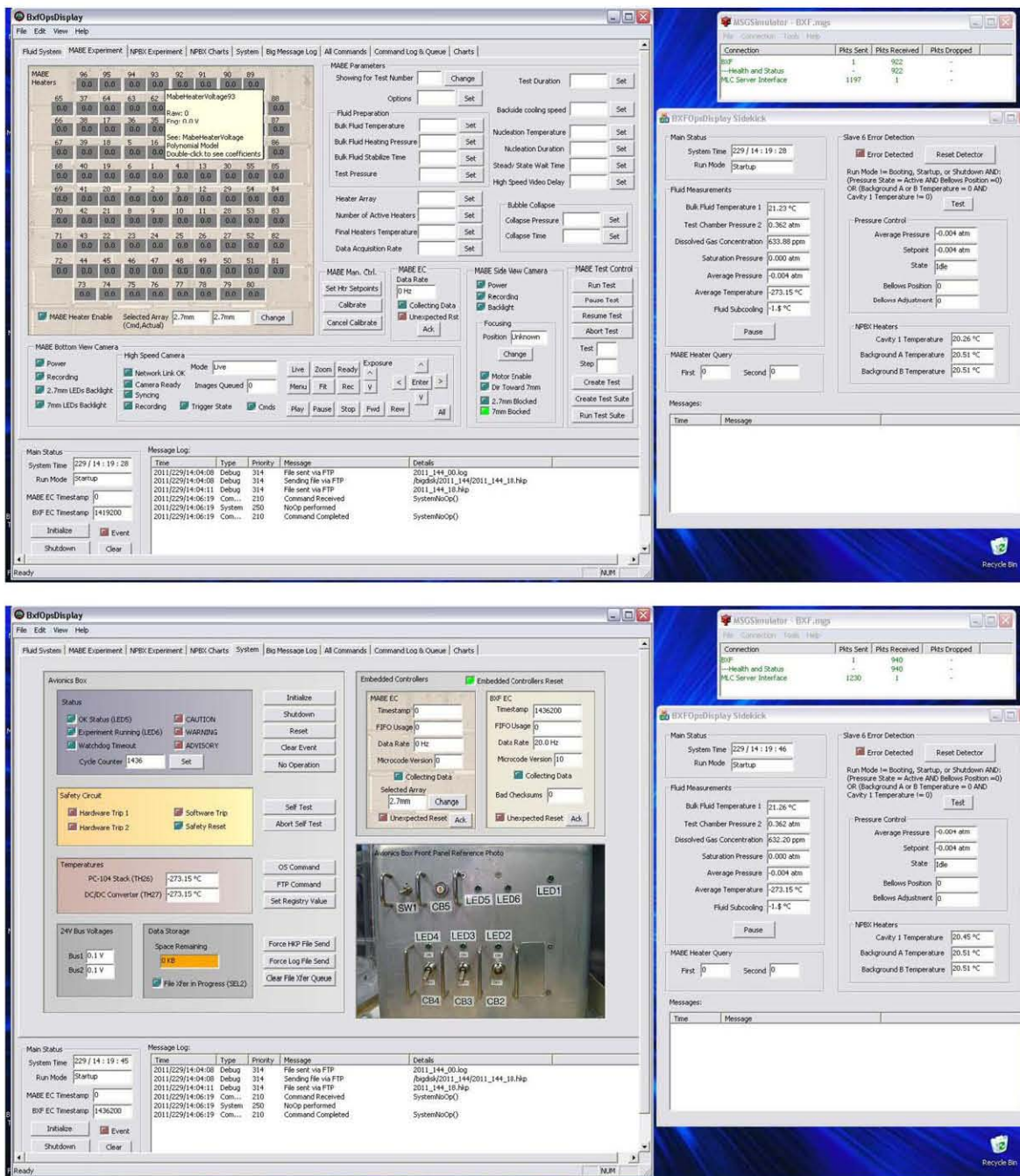


Figure B.2.—Screen displays for RS-422 Communication test: MABE Experiment TAB for BXFOPSDisplay (top left) and for Sidekick (top right), System Tab for BXFOPSDisplay (bottom left) and for Sidekick (bottom right).

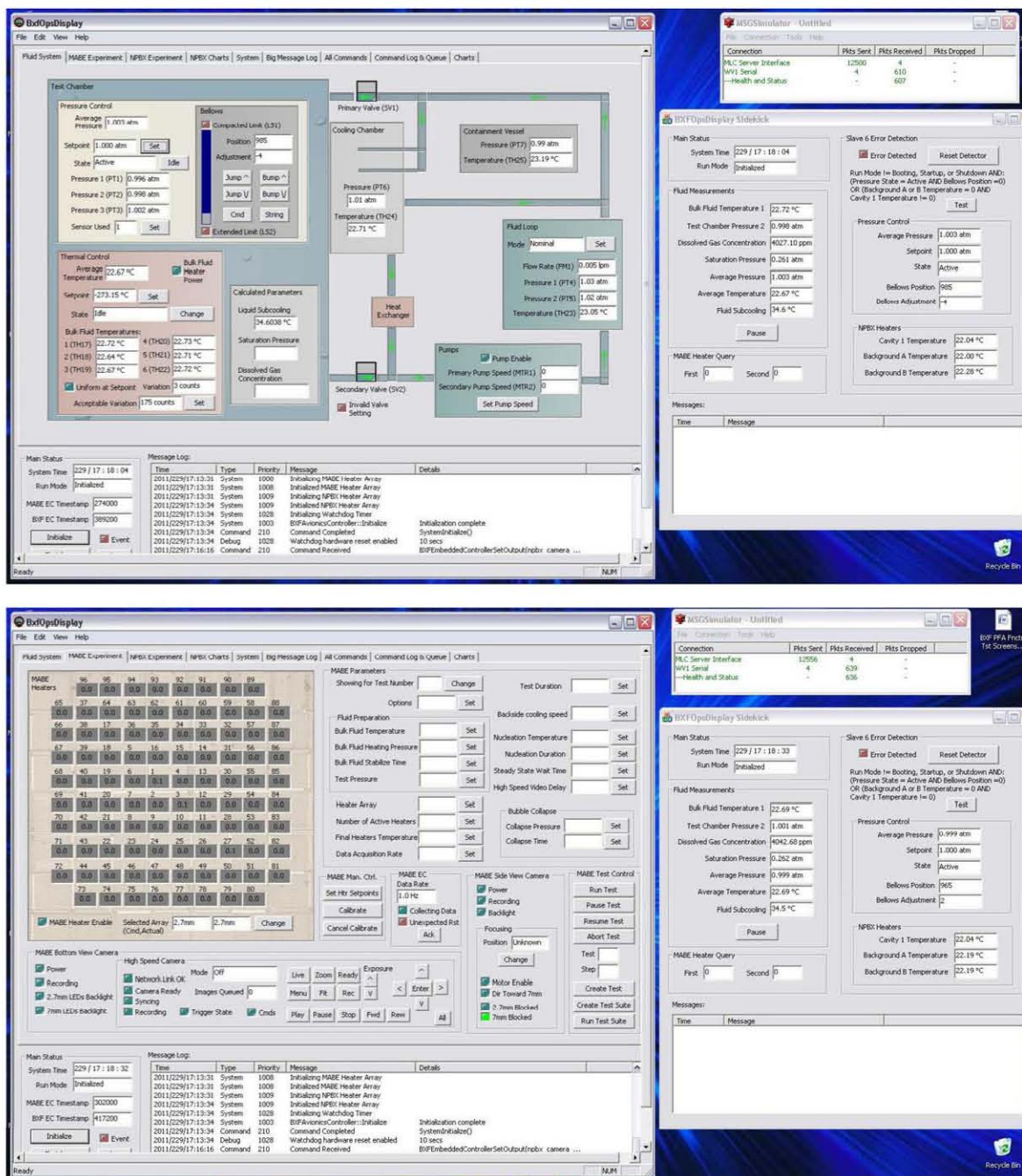


Figure B.3.—Screen displays for Systems Initialization Test: Fluid System Tab for BXFOPSDisplay (top left) and for Sidekick (top right), MABE Experiment Tab for BXFOPSDisplay (bottom left) and for Sidekick (bottom right).

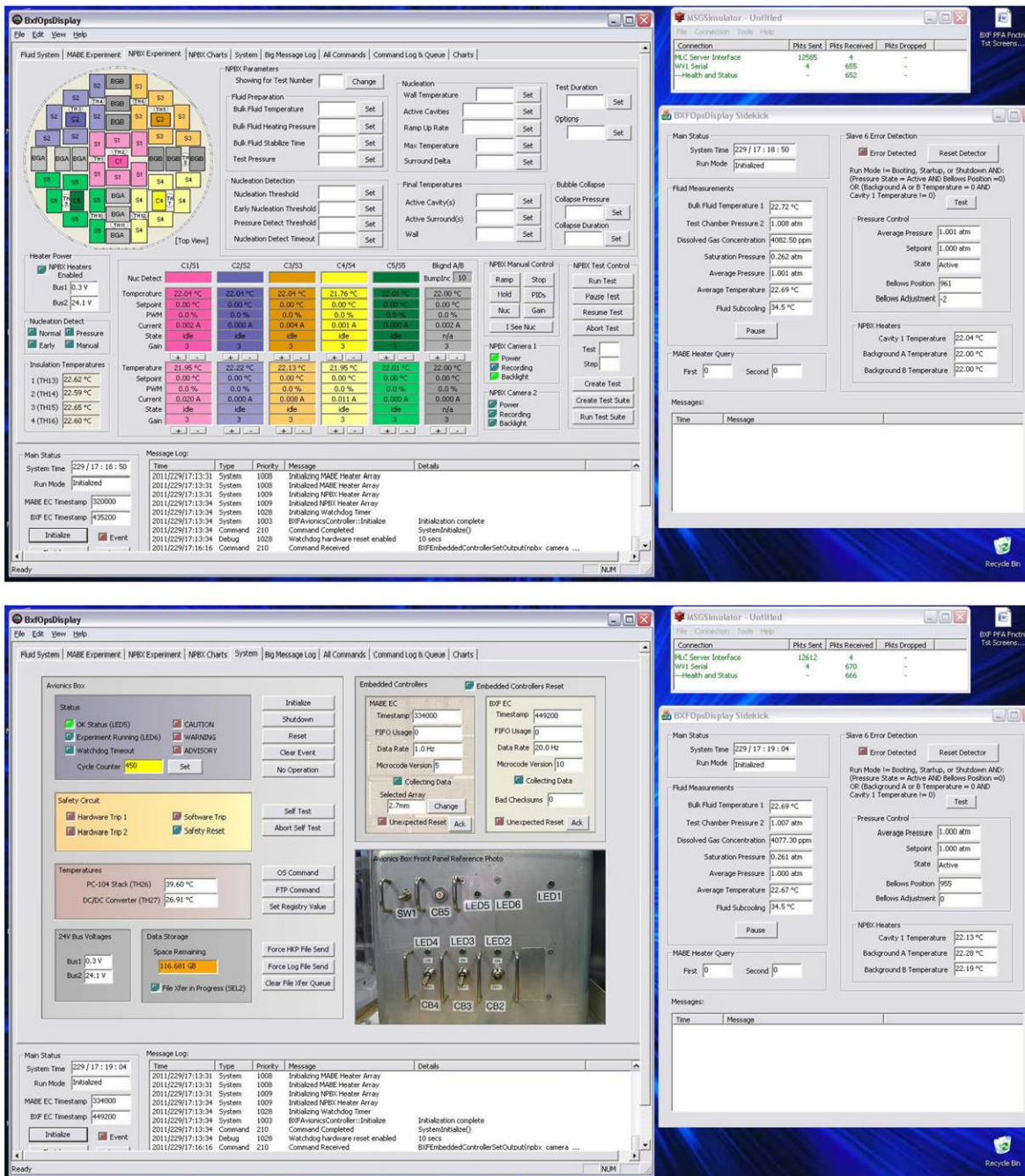


Figure B.4.—Screen displays for Systems Initialization Test: NPBX Experiment Tab for BXFOPSDisplay (top left) and for Sidekick (top right), System Tab for BXFOPSDisplay (bottom left) and for Sidekick (bottom right).

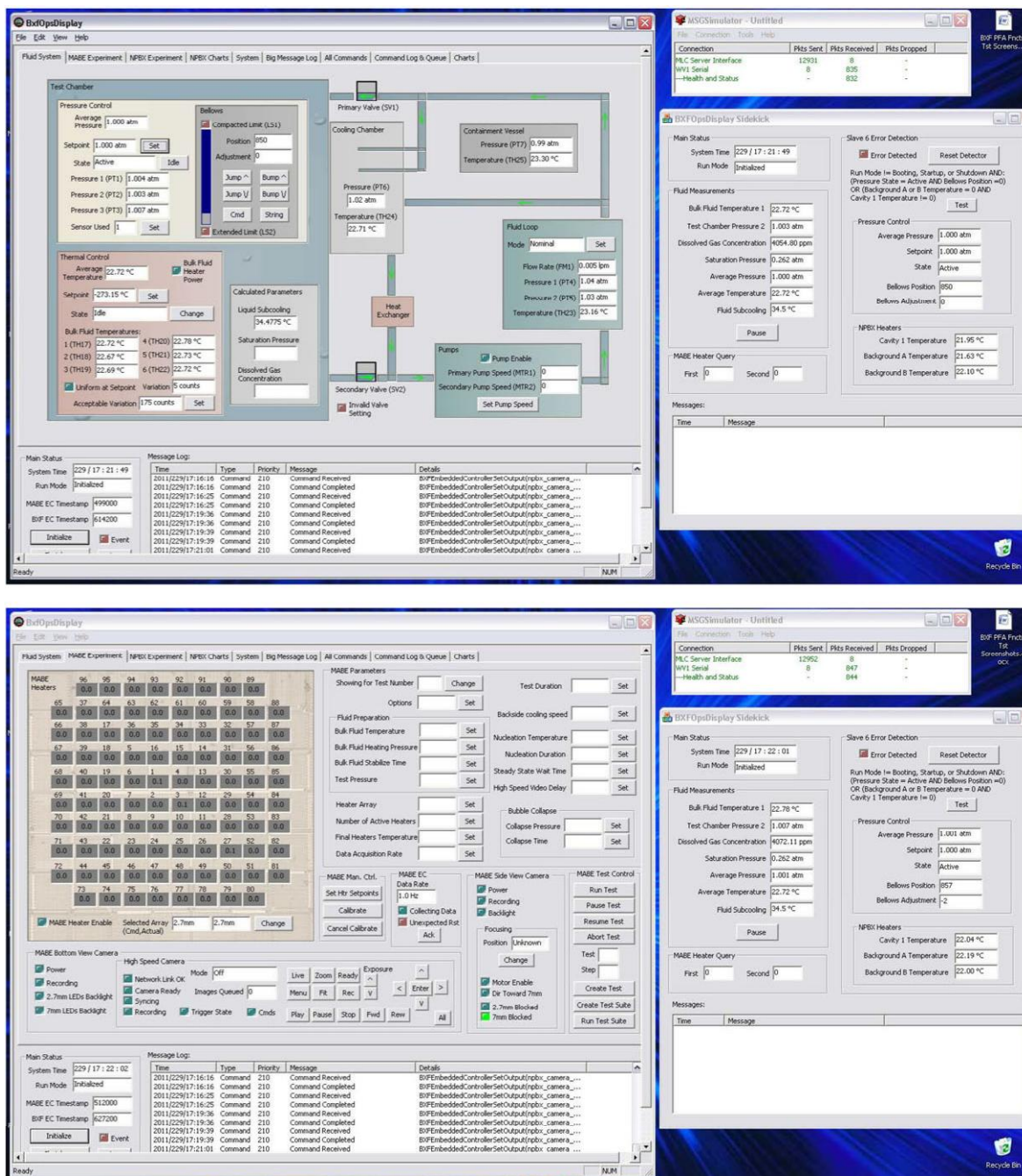
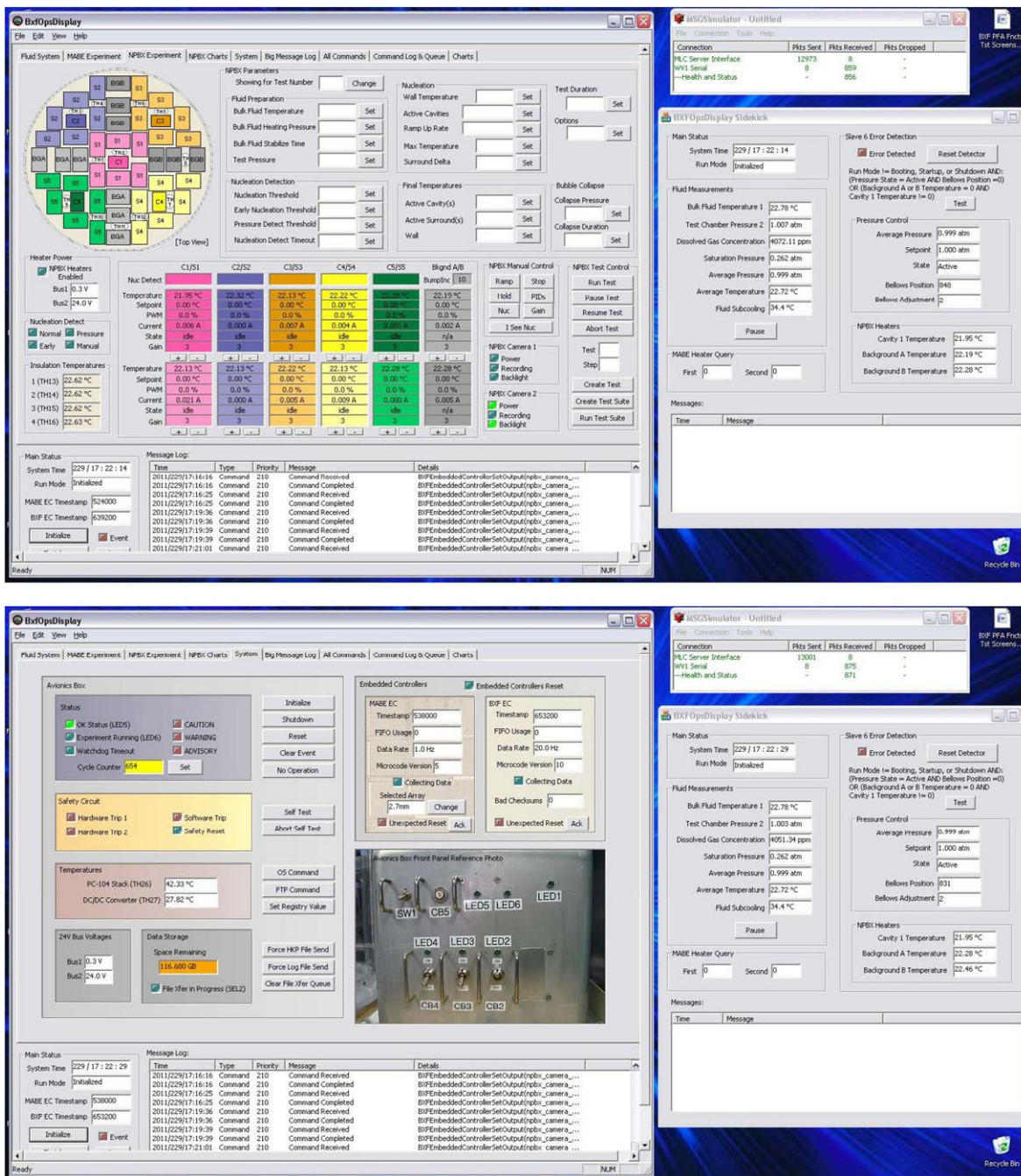


Figure B.5.—Screen displays for BxFOpsDisplay Fluid System Tab for BxFOpsDisplay (top left) and for Sidekick (top right), MABE Experiment Tab for BxFOpsDisplay (bottom left) and for Sidekick (bottom right).



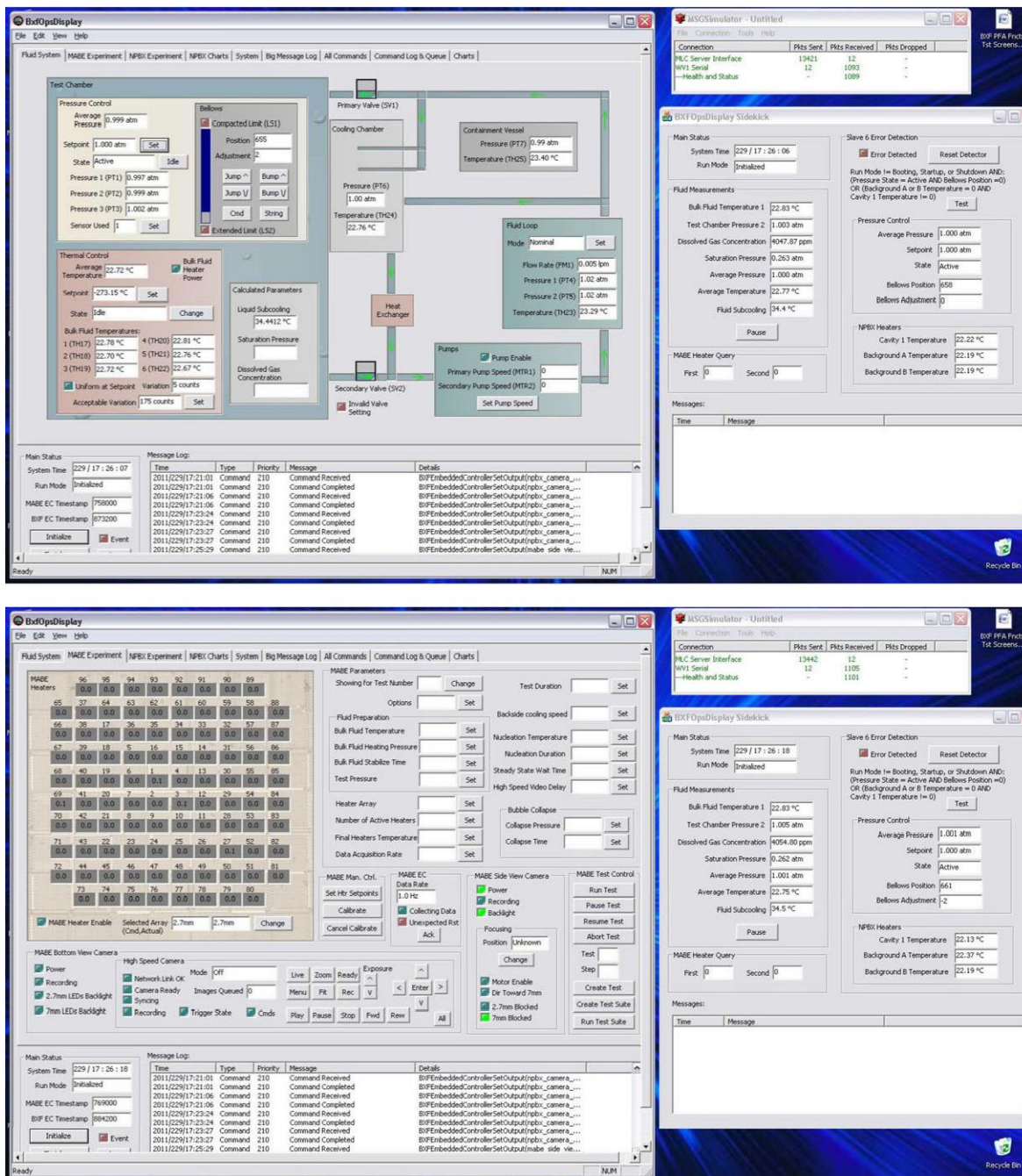


Figure B.7.—Screen displays for BxFOpsDisplay and Sidekick. Fluid System Tab for BxFOpsDisplay (top left) and for Sidekick (top right), MABE Experiment Tab for BxFOpsDisplay (bottom left) and for Sidekick (bottom right).

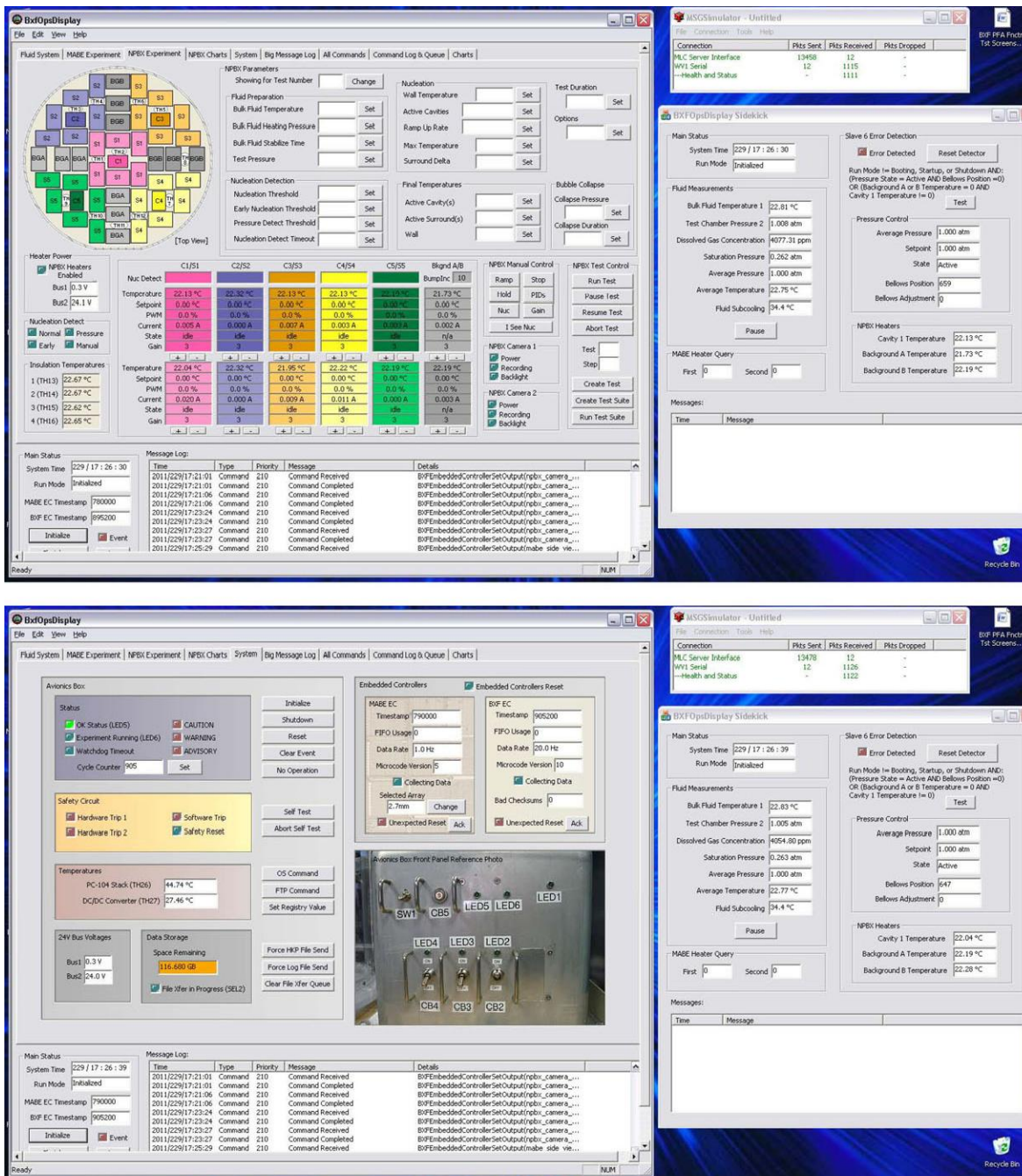


Figure B.8.—Screen displays for BXP EC I/O Test, NPBX Camera 2 Test: NPBX Experiment Tab for BXPSPDisplay (top left) and for Sidekick (top right), System Tab for BXPSPDisplay (bottom left) and for Sidekick (bottom right).

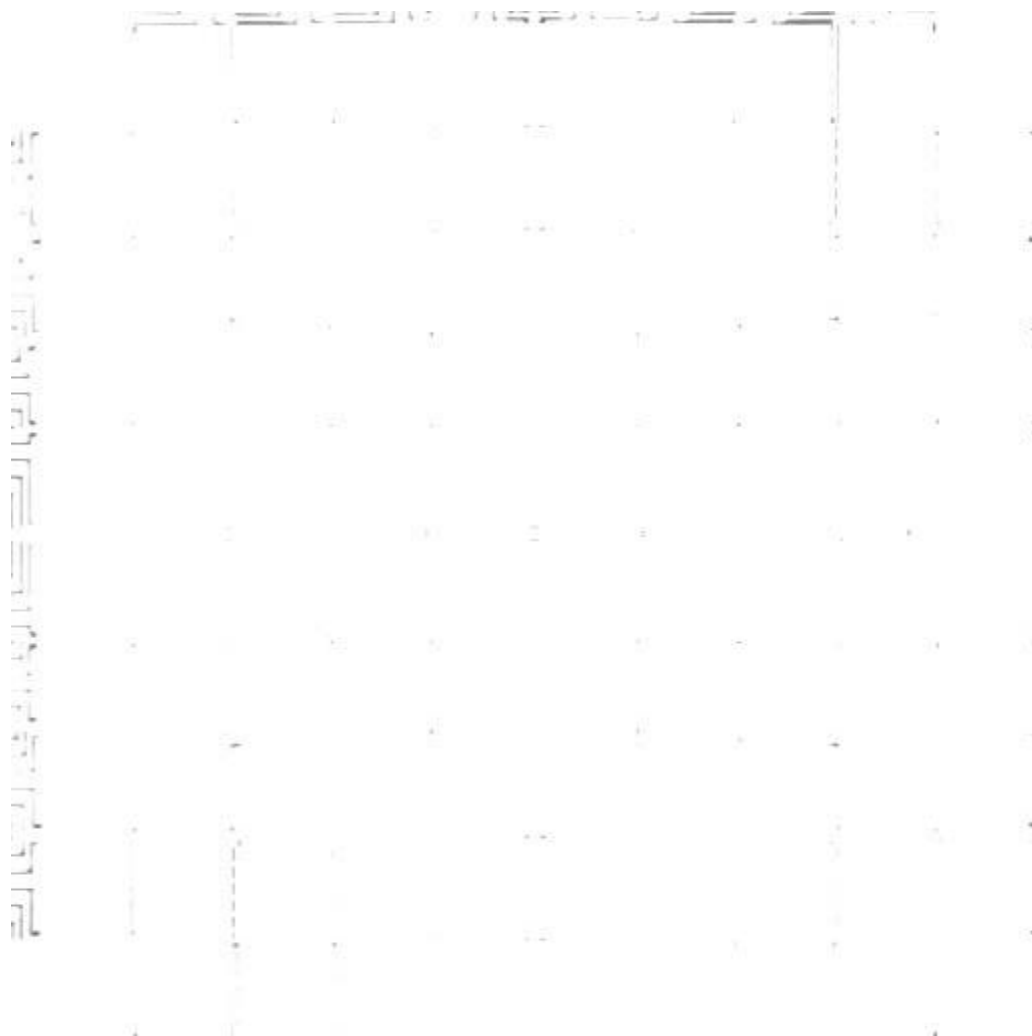


Figure B.9.—Captured image of MABE 7.0 mm array with default exposure.

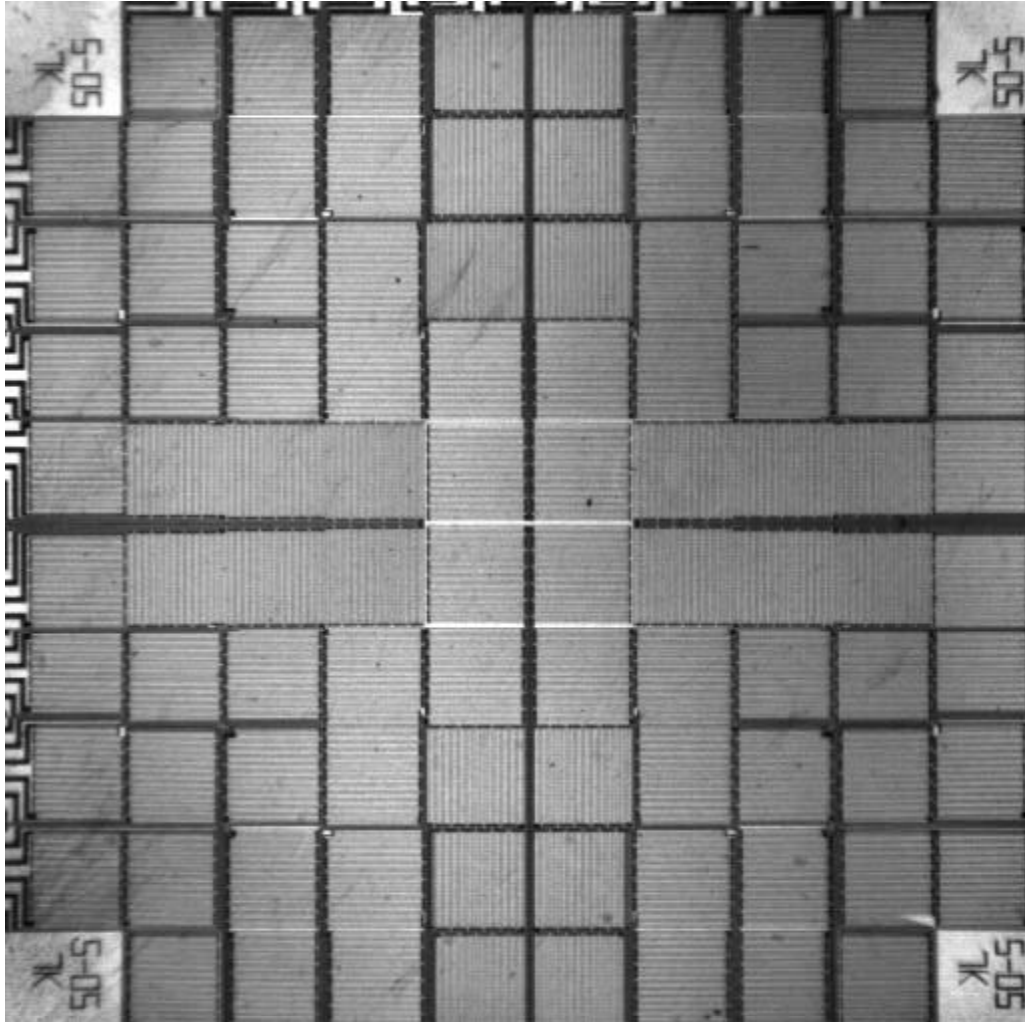


Figure B.10.—Captured image of MABE 7.0 mm array with 1/13000 s exposure.

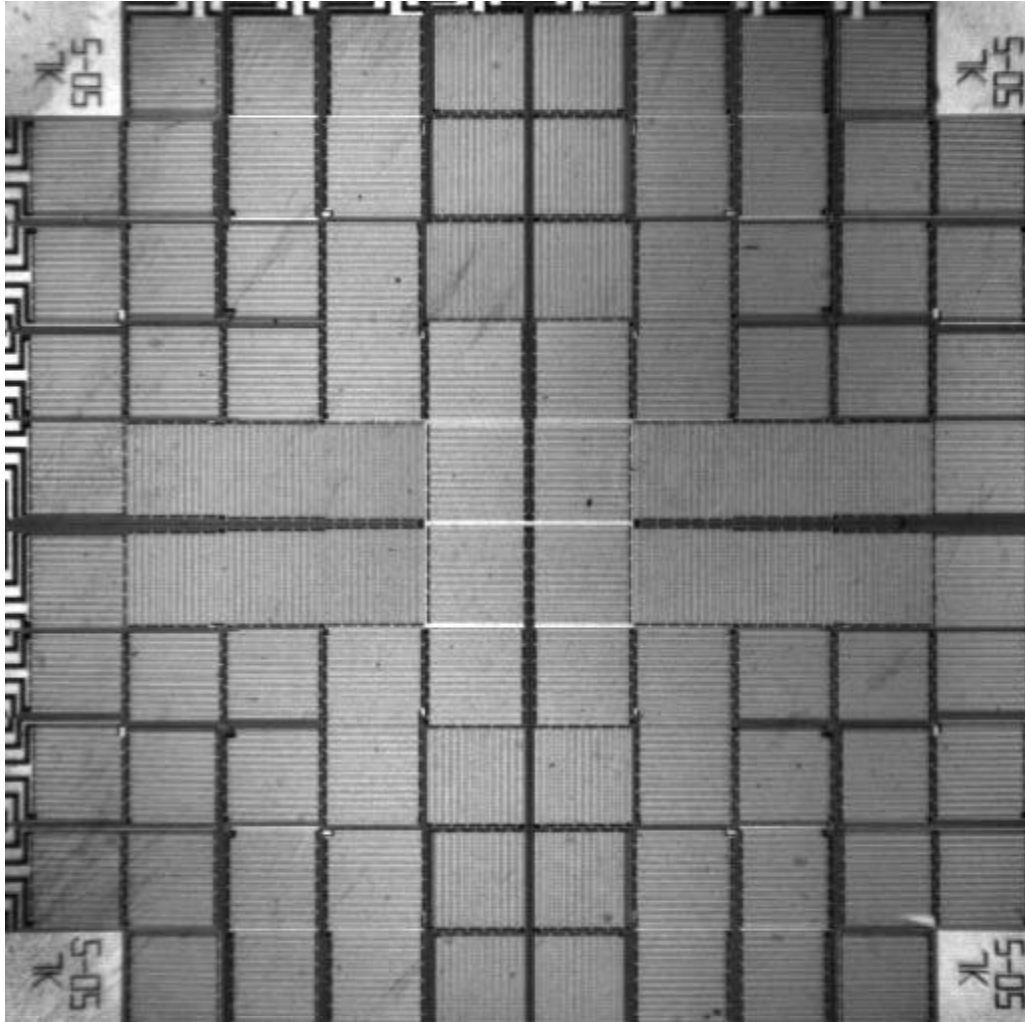


Figure B.11.—Captured image of MABE 7.0 mm array with 1/13000 s exposure.

Log Files During BXF Function Check:

2011_229_00.log

RS422 Communication Test

```
"2011/229/14: 04: 08", "System", "280", "Changed system time", "2011/229/14: 04: 08"
"2011/229/14: 04: 08", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_144/2011_144_00.log"
"2011/229/14: 04: 08", "Debug", "314", "File sent via FTP", "2011_144_00.log"
"2011/229/14: 04: 08", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_144/2011_144_18.hkp"
"2011/229/14: 04: 11", "Debug", "314", "File sent via FTP", "2011_144_18.hkp"
"2011/229/14: 06: 19", "Command", "210", "Command Received", "SystemNoOp()"
"2011/229/14: 06: 19", "System", "250", "NoOp performed", ""
"2011/229/14: 06: 19", "Command", "210", "Command Completed", "SystemNoOp()"
```

Safety Circuit Test

```
"2011/229/14: 21: 24", "Command", "210", "Command
Received", "BXFEmbeddedControlIerSetOutput(safety_reset, On)"
"2011/229/14: 21: 24", "Command", "210", "Command
Completed", "BXFEmbeddedControlIerSetOutput(safety_reset, On)"
"2011/229/14: 21: 27", "Command", "210", "Command
Received", "BXFEmbeddedControlIerSetOutput(safety_reset, Off)"
"2011/229/14: 21: 27", "Command", "210", "Command
Completed", "BXFEmbeddedControlIerSetOutput(safety_reset, Off)"
```

System Initialize

```
"2011/229/14: 27: 50", "Command", "210", "Command Received", "SystemInitialize()"
"2011/229/14: 27: 50", "System", "1003", "BXFAvi oni csControlIer: : Ini ti al i ze", "Ini ti al i zi ng.
."
"2011/229/14: 27: 54", "System", "1013", "Ini ti al i zi ng CrewI nterfacePanel", ""
"2011/229/14: 27: 54", "System", "1012", "Ini ti al i zi ng Vi deo Recordi ng System", ""
"2011/229/14: 27: 54", "System", "1012", "NOT Homi ng MABE Si de Vi ew Camera focus", ""
"2011/229/14: 27: 54", "System", "1012", "Ini ti al i zed Vi deo Recordi ng System", ""
"2011/229/14: 27: 54", "System", "1014", "Ini ti al i zi ng Contai nment Vessel", ""
"2011/229/14: 27: 54", "System", "1010", "Ini ti al i zi ng Pressure Control System", ""
"2011/229/14: 27: 54", "Debug", "1010", "... Reloading pressure control system
parameters", "P=2.000, I=0.000, D=0.000"
"2011/229/14: 27: 54", "Debug", "1010", "... Reloading pressure control system
parameters", "Sensor=1(1-3), Pol l Peri od=1000, InRange=25, Max Bel lows Correct="
"2011/229/14: 27: 55", "Debug", "1010", "Going to safe pressure 793=1.000 atm", ""
"2011/229/14: 27: 55", "System", "1010", "Ini ti al i zed Pressure Control System", ""
"2011/229/14: 27: 55", "System", "1011", "Ini ti al i zi ng Thermal Control System", ""
"2011/229/14: 27: 55", "Debug", "1011", "TCS parameters loaded", "MABE Test Pump
Setpoi nt=600, Bul k Heating Pump Setpoi nt=600, Update peri od =2000 msec"
"2011/229/14: 27: 55", "Debug", "1011", "TCS parameters loaded", "Bul k Stabi l i ty
Vari ation=175, Val id Sensor Vari ation=800, Bul k Tempera ture In Range Li mi t=25"
"2011/229/14: 27: 55", "System", "1011", "Ini ti al i zed Thermal Control System", ""
"2011/229/14: 27: 55", "System", "1007", "Ini ti al i zi ng High Speed Vi deo System", ""
"2011/229/14: 27: 55", "System", "1008", "Ini ti al i zi ng MABE Heater Array", ""
"2011/229/14: 27: 55", "System", "1008", "Ini ti al i zed MABE Heater Array", ""
"2011/229/14: 27: 55", "System", "1009", "Ini ti al i zi ng NPBX Heater Array", ""
"2011/229/14: 27: 57", "System", "1009", "Ini ti al i zed NPBX Heater Array", ""
"2011/229/14: 27: 57", "System", "1028", "Ini ti al i zi ng Watchdog Ti mer", ""
"2011/229/14: 27: 57", "System", "1003", "BXFAvi oni csControlIer: : Ini ti al i ze", "Ini ti al i zati o
n complete"
"2011/229/14: 27: 57", "Command", "210", "Command Completed", "SystemIni ti al i ze()"
"2011/229/14: 27: 57", "Debug", "1028", "Watchdog hardware reset enabled", "10 secs"
"2011/229/15: 00: 00", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/2011_229_14.hkp"
"2011/229/15: 00: 28", "Debug", "314", "File sent via FTP", "2011_229_14.hkp"
"2011/229/15: 35: 40", "Command", "210", "Command Received", "SystemShutdown(Shutdown)"
"2011/229/15: 35: 52", "Command", "210", "Command Completed", "SystemShutdown(Shutdown)"
"2011/229/15: 35: 54", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/2011_229_15.hkp"
"2011/229/17: 11: 37", "System", "1001", "Getti ng Versi on and Checksum...", ""
"2011/229/17: 11: 37", "System", "1001", "BXFAvi oni csControlIer", "VER: 60081-SW-F001-
1.10CS: : Check Di sabl ed"
"2011/229/17: 11: 37", "System", "1002", "BXFAvi oni csControlIer", "BXFAvi oni cs ControlIer
started."
```

"2011/229/17: 11: 36", "System", "280", "Changed system time", "2011/229/17: 11: 36"
 "2011/229/17: 13: 30", "Command", "210", "Command Received", "SystemInitialize()
 "2011/229/17: 13: 30", "System", "1003", "BXFAvionicsController: Initialize", "Initializing
 "2011/229/17: 13: 31", "System", "1013", "Initializing CrewInterfacePanel", ""
 "2011/229/17: 13: 31", "System", "1012", "Initializing Video Recording System", ""
 "2011/229/17: 13: 31", "System", "1012", "NOT Homing MABE Side View Camera focus", ""
 "2011/229/17: 13: 31", "System", "1012", "Initialized Video Recording System", ""
 "2011/229/17: 13: 31", "System", "1014", "Initializing Containment Vessel", ""
 "2011/229/17: 13: 31", "System", "1010", "Initializing Pressure Control System", ""
 "2011/229/17: 13: 31", "Debug", "1010", "...Reloading pressure control system
 parameters", "P=2.000, I=0.000, D=0.000"
 "2011/229/17: 13: 31", "Debug", "1010", "...Reloading pressure control system
 parameters", "Sensor=1(1-3), Poll Period=1000, InRange=25, Max Bellows Correct=
 "2011/229/17: 13: 31", "Debug", "1010", "Going to safe pressure 793=1.000 atm", ""
 "2011/229/17: 13: 31", "System", "1010", "Initialized Pressure Control System", ""
 "2011/229/17: 13: 31", "System", "1011", "Initializing Thermal Control System", ""
 "2011/229/17: 13: 31", "Debug", "1011", "TCS parameters loaded", "MABE Test Pump
 Setpoint=600, Bulk Heating Pump Setpoint=600, Update period =2000 msec"
 "2011/229/17: 13: 31", "Debug", "1011", "TCS parameters loaded", "Bulk Stability
 Variation=175, Valid Sensor Variation=800, Bulk Temperature In Range Limit=25"
 "2011/229/17: 13: 31", "System", "1011", "Initialized Thermal Control System", ""
 "2011/229/17: 13: 31", "System", "1007", "Initializing High Speed Video System", ""
 "2011/229/17: 13: 31", "System", "1008", "Initializing MABE Heater Array", ""
 "2011/229/17: 13: 31", "System", "1008", "Initialized MABE Heater Array", ""
 "2011/229/17: 13: 31", "System", "1009", "Initializing NPBX Heater Array", ""
 "2011/229/17: 13: 34", "System", "1009", "Initialized NPBX Heater Array", ""
 "2011/229/17: 13: 34", "System", "1028", "Initializing Watchdog Timer", ""
 "2011/229/17: 13: 34", "System", "1003", "BXFAvionicsController: Initialize", "Initialization
 complete"
 "2011/229/17: 13: 34", "Command", "210", "Command Completed", "SystemInitialize()
 "2011/229/17: 13: 34", "Debug", "1028", "Watchdog hardware reset enabled", "10 secs"

NPBX Camera 1 Test

"2011/229/17: 16: 16", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_1_power, On)"
 "2011/229/17: 16: 16", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_1_power, On)"
 "2011/229/17: 16: 25", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_1_backlight, On)"
 "2011/229/17: 16: 25", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_1_backlight, On)"
 "2011/229/17: 19: 36", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_1_backlight, Off)"
 "2011/229/17: 19: 36", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_1_backlight, Off)"
 "2011/229/17: 19: 39", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_1_power, Off)"
 "2011/229/17: 19: 39", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_1_power, Off)"

NPBX Camera 2 Test

"2011/229/17: 21: 01", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_2_power, On)"
 "2011/229/17: 21: 01", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_2_power, On)"
 "2011/229/17: 21: 06", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_2_backlight, On)"
 "2011/229/17: 21: 06", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_2_backlight, On)"
 "2011/229/17: 23: 24", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_2_backlight, Off)"
 "2011/229/17: 23: 24", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_2_backlight, Off)"
 "2011/229/17: 23: 27", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_2_power, Off)"
 "2011/229/17: 23: 27", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_2_power, Off)"

MABE Side View Camera Test

"2011/229/17: 25: 29", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_power, On)"
"2011/229/17: 25: 29", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_power, On)"
"2011/229/17: 25: 32", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_backl ight, On)"
"2011/229/17: 25: 32", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_backl ight, On)"
"2011/229/17: 28: 28", "Command", "210", "Command"
Received", "SetMabeSi deVi ewCameraFocusPosi ti onCommand(2. 7mm)"
"2011/229/17: 28: 37", "Command", "210", "Command"
Completed", "SetMabeSi deVi ewCameraFocusPosi ti onCommand(2. 7mm)"
"2011/229/17: 29: 05", "Command", "210", "Command"
Received", "SetMabeSi deVi ewCameraFocusPosi ti onCommand(7mm)"
"2011/229/17: 29: 14", "Command", "210", "Command"
Completed", "SetMabeSi deVi ewCameraFocusPosi ti onCommand(7mm)"
"2011/229/17: 29: 37", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_backl ight, Off)"
"2011/229/17: 29: 37", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_backl ight, Off)"
"2011/229/17: 29: 41", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_power, Off)"
"2011/229/17: 29: 41", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(mabe_si de_vi ew_camera_power, Off)"
"2011/229/17: 33: 56", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(mabe_7mm_l eds, On)"
"2011/229/17: 33: 56", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(mabe_7mm_l eds, On)"
"2011/229/17: 35: 23", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(mabe_7mm_l eds, Off)"
"2011/229/17: 35: 23", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(mabe_7mm_l eds, Off)"

Fluid Loop Test

"2011/229/17: 37: 08", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerCool ingPumpSpeed(1, 600)"
"2011/229/17: 37: 08", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerCool ingPumpSpeed(1, 600)"
"2011/229/17: 37: 28", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(pump_enabl e, On)"
"2011/229/17: 37: 28", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(pump_enabl e, On)"
"2011/229/17: 38: 38", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(pump_enabl e, Off)"
"2011/229/17: 38: 38", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(pump_enabl e, Off)"
"2011/229/17: 39: 19", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerCool ingPumpSpeed(2, 600)"
"2011/229/17: 39: 19", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerCool ingPumpSpeed(2, 600)"
"2011/229/17: 39: 32", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(pump_enabl e, On)"
"2011/229/17: 39: 32", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(pump_enabl e, On)"
"2011/229/17: 40: 39", "Command", "210", "Command"
Received", "BXFEmbeddedControlIerSetOutput(pump_enabl e, Off)"
"2011/229/17: 40: 39", "Command", "210", "Command"
Completed", "BXFEmbeddedControlIerSetOutput(pump_enabl e, Off)"
"2011/229/17: 43: 25", "Command", "210", "Command"
Received", "SystemManual SetChamberPressure(0)"
"2011/229/17: 43: 25", "Command", "210", "Command"
Completed", "SystemManual SetChamberPressure(0)"
"2011/229/17: 47: 40", "Command", "210", "Command"
Received", "SystemManual SendMotorCommand(3, -300)"
"2011/229/17: 47: 40", "Command", "210", "Command"
Completed", "SystemManual SendMotorCommand(3, -300)"
"2011/229/17: 48: 49", "Command", "210", "Command"
Received", "SystemManual SetChamberPressure(793)"
"2011/229/17: 48: 49", "Command", "210", "Command"

Completed", "SystemManual SetChamberPressure(793)"
 "2011/229/17: 49: 36", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(primary_val ve, 0n)"
 "2011/229/17: 49: 36", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(primary_val ve, 0n)"
 "2011/229/17: 50: 42", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(primary_val ve, 0ff)"
 "2011/229/17: 50: 42", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(primary_val ve, 0ff)"
 "2011/229/17: 51: 18", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(secondary_val ve, 0n)"
 "2011/229/17: 51: 18", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(secondary_val ve, 0n)"
 "2011/229/17: 52: 23", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(secondary_val ve, 0ff)"
 "2011/229/17: 52: 23", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(secondary_val ve, 0ff)"
 "2011/229/17: 58: 27", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_1_backl ight, 0ff)"
 "2011/229/17: 58: 27", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_1_backl ight, 0ff)"
 "2011/229/17: 58: 31", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(npbx_camera_1_power, 0ff)"
 "2011/229/17: 58: 32", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(npbx_camera_1_power, 0ff)"
 "2011/229/18: 00: 00", "Debug", "314", "Sendi ng fi le vi a
 FTP", "/bi gdi sk/2011_229/2011_229_17. hkp"

MABE Bottom View Back Lights and Camera Test

"2011/229/18: 00: 19", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(mabe_2p7mm_l eds, 0n)"
 "2011/229/18: 00: 19", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(mabe_2p7mm_l eds, 0n)"
 "2011/229/18: 00: 23", "Debug", "314", "Fi le sent vi a FTP", "2011_229_17. hkp"
 "2011/229/18: 00: 29", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(mabe_2p7mm_l eds, 0ff)"
 "2011/229/18: 00: 30", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(mabe_2p7mm_l eds, 0ff)"
 "2011/229/18: 00: 35", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0n)"
 "2011/229/18: 00: 35", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0n)"
 "2011/229/18: 00: 41", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0ff)"
 "2011/229/18: 00: 41", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0ff)"
 "2011/229/18: 00: 47", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(mabe_2p7mm_l eds, 0n)"
 "2011/229/18: 00: 47", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(mabe_2p7mm_l eds, 0n)"
 "2011/229/18: 00: 49", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0n)"
 "2011/229/18: 00: 49", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0n)"
 "2011/229/18: 03: 49", "Command", "210", "Command
 Received", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0n)"
 "2011/229/18: 03: 49", "Command", "210", "Command
 Completed", "BXFEmbeddedControllerSetOutput(mabe_7mm_l eds, 0n)"
 "2011/229/18: 05: 39", "Command", "210", "Command Received", "Hi ghSpeedCameraPower(on)"
 "2011/229/18: 05: 39", "Command", "210", "Command Completed", "Hi ghSpeedCameraPower(on)"
 "2011/229/18: 05: 44", "System", "1007", "Ini ti al i z i ng Hi gh Speed Camera. . .", ""
 "2011/229/18: 05: 59", "System", "1007", "Hi gh Speed Camera number of Pixel Defects =
 0", ""
 "2011/229/18: 06: 03", "System", "1007", "Hi gh Speed Camera Ini ti al i z e d", ""
 "2011/229/18: 09: 05", "Command", "210", "Command
 Received", "Hi ghSpeedCameraCaptureI mage(500, 1, true)"
 "2011/229/18: 09: 18", "Command", "210", "Command
 Completed", "Hi ghSpeedCameraCaptureI mage(500, 1, true)"
 "2011/229/18: 09: 18", "Debug", "314", "Sendi ng fi le vi a

```

FTP", "/bi gdi sk/2011_229/MABEImages/0000_000/0000_000_00065345_0001.IMG"
"2011/229/18: 09: 23", "Debug", "314", "File sent via FTP", "0000_000_00065345_0001.IMG"
"2011/229/18: 11: 02", "Command", "210", "Command
Received", "HighSpeedCameraSetExposureTime(13000)"
"2011/229/18: 11: 03", "Command", "210", "Command
Completed", "HighSpeedCameraSetExposureTime(13000)"
"2011/229/18: 12: 41", "Command", "210", "Command
Received", "HighSpeedCameraCaptureImage(500, 1, true)"
"2011/229/18: 12: 50", "Command", "210", "Command
Completed", "HighSpeedCameraCaptureImage(500, 1, true)"
"2011/229/18: 12: 51", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/MABEImages/0000_000/0000_000_00065561_0001.IMG"
"2011/229/18: 12: 56", "Debug", "314", "File sent via
FTP", "0000_000_00065561_0001.IMG" "2011/229/18: 15: 33", "Command", "210", "Command
Received", "HighSpeedCameraConfigure(0, 500, 0, 0, 13000, 0)"
"2011/229/18: 15: 42", "Command", "210", "Command
Completed", "HighSpeedCameraConfigure(0, 500, 0, 0, 13000, 0)"
"2011/229/18: 15: 59", "Command", "210", "Command
Received", "HighSpeedCameraCaptureImage(500, 1, true)"
"2011/229/18: 16: 12", "Command", "210", "Command
Completed", "HighSpeedCameraCaptureImage(500, 1, true)"
"2011/229/18: 16: 12", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/MABEImages/0000_000/0000_000_00065759_0001.IMG"
"2011/229/18: 16: 25", "Debug", "314", "File sent via FTP", "0000_000_00065759_0001.IMG"
"2011/229/18: 17: 06", "Command", "210", "Command Received", "SystemSelfTest(4096, 1)"
"2011/229/18: 17: 07", "System", "1001", "BXFAvi onicsControl ler: : Sel fTest", "Setting mabe
sampling rate"
"2011/229/18: 17: 07", "System", "1004", "BXFAvi onicsControl ler: : Sel fTest", "Checkout
successful !"
"2011/229/18: 17: 07", "System", "1004", "BXFAvi onicsControl ler: : Sel fTest", "Checkout
successful !"
"2011/229/18: 17: 07", "Command", "210", "Command Complete", "SystemSelfTest(4096, 1)"
"2011/229/18: 17: 55", "Command", "210", "Command Received", "HighSpeedCameraPower(off)"
"2011/229/18: 17: 56", "Command", "210", "Command Completed", "HighSpeedCameraPower(off)"
"2011/229/18: 18: 17", "Command", "210", "Command Received", "HighSpeedCameraPower(on)"
"2011/229/18: 18: 17", "Command", "210", "Command Completed", "HighSpeedCameraPower(on)"
"2011/229/18: 18: 23", "System", "1007", "Ini ti al iz ing Hi gh Speed Camera...", ""
"2011/229/18: 18: 37", "System", "1007", "Hi gh Speed Camera number of Pixel Defects =
0", ""
"2011/229/18: 18: 42", "System", "1007", "Hi gh Speed Camera Ini ti al iz ed", ""
"2011/229/18: 19: 29", "Command", "210", "Command
Received", "BXFEmbeddedControl lerSetOutput(mabe_7mm_I eds, Off)"
"2011/229/18: 19: 29", "Command", "210", "Command
Completed", "BXFEmbeddedControl lerSetOutput(mabe_7mm_I eds, Off)"
"2011/229/18: 19: 37", "Command", "210", "Command Received", "HighSpeedCameraPower(off)"
"2011/229/18: 19: 38", "Command", "210", "Command Completed", "HighSpeedCameraPower(off)"
"2011/229/18: 25: 56", "Command", "210", "Command
Received", "SystemManual ForceLogFileSend()"

```

2011_229_01.log

Data Download

"2011/229/15: 36: 09", "System", "1001", "Forcing log file transfer", ""
"2011/229/15: 36: 11", "Debug", "314", "File sent via FTP", "2011_229_15.hkp"
"2011/229/15: 36: 11", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/2011_229_00.log"
"2011/229/15: 36: 11", "Debug", "314", "File sent via FTP", "2011_229_00.log"
"2011/229/18: 25: 56", "Command", "210", "Command
Completed", "SystemManual ForceLogFileSend()
"2011/229/18: 25: 56", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/2011_229_00.log"
"2011/229/18: 25: 57", "Debug", "314", "File sent via FTP", "2011_229_00.log"
"2011/229/18: 26: 04", "Command", "210", "Command
Received", "SystemManual ForceHousekeepingSend()
"2011/229/18: 26: 04", "Command", "210", "Command
Completed", "SystemManual ForceHousekeepingSend()
"2011/229/18: 26: 05", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/2011_229_18.hkp"
"2011/229/18: 26: 18", "Debug", "314", "File sent via FTP", "2011_229_18.hkp"
"2011/229/18: 26: 50", "Command", "210", "Command Received", "SystemShutdown(Shutdown)"
"2011/229/18: 27: 03", "Command", "210", "Command Completed", "SystemShutdown(Shutdown)"
"2011/229/18: 27: 05", "Debug", "314", "Sending file via
FTP", "/bi gdi sk/2011_229/2011_229_18_01.hkp"
"2011/229/18: 27: 06", "Debug", "314", "File sent via FTP", "2011_229_18_01.hkp"

Appendix C.—HSC Alignment Check Images

This appendix contains the images acquired during the High Speed Camera Alignment Check activity. See Section 3.6.

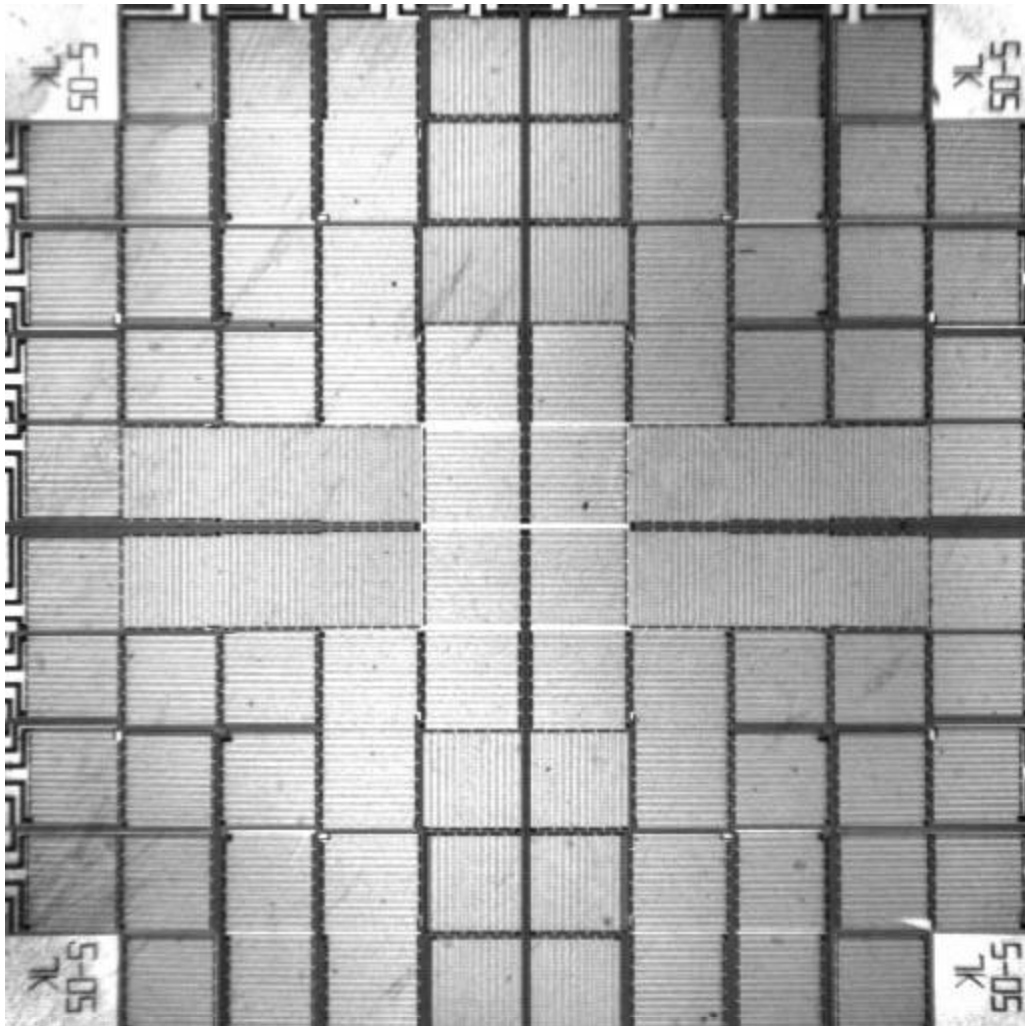


Figure C.1.—MABE 7.0 mm array imaged through HSC, lens correctly aligned.

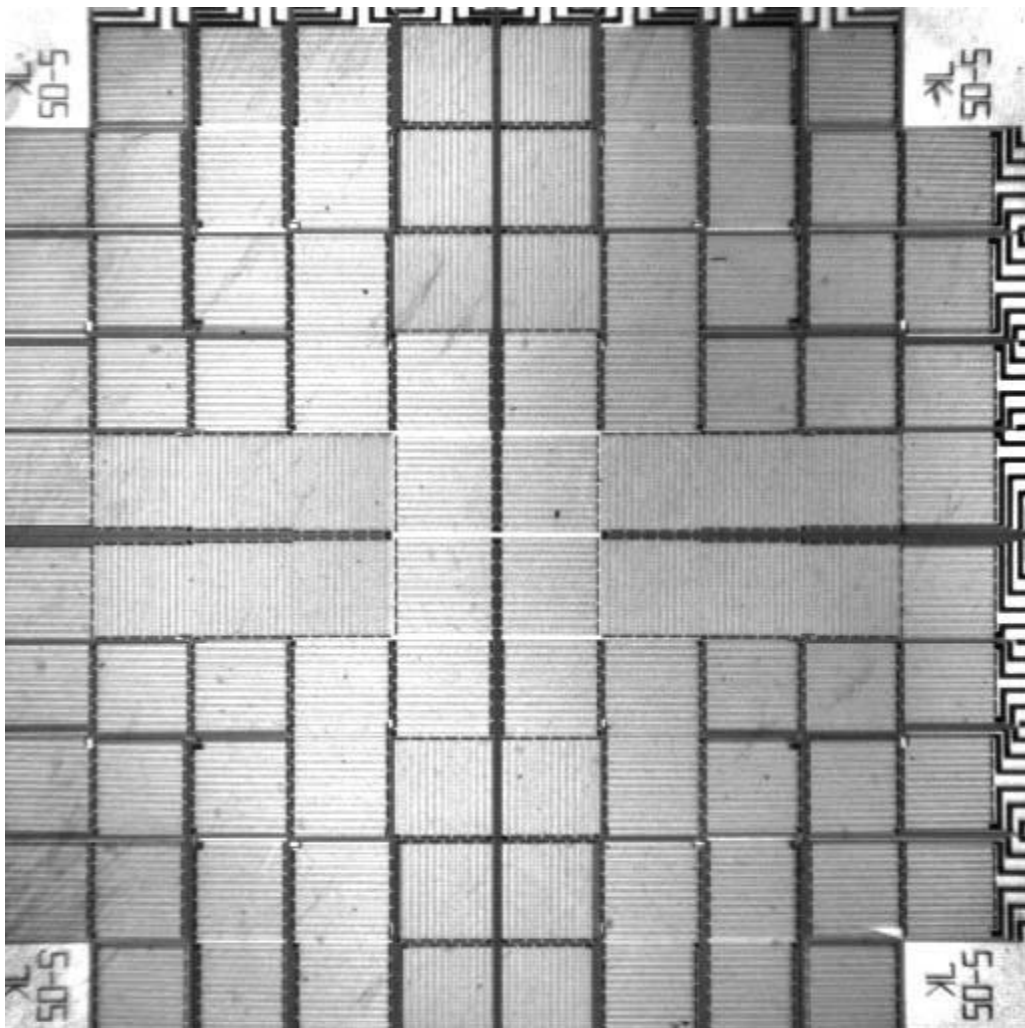


Figure C.2.—MABE 7.0 mm array imaged through HSC, incorrectly aligned, note translation to right and top from Figure C.1.

Appendix D.—Extraction and Visual Inspection Photos

This appendix contains the photos taken during the extraction and visual inspection of the cartridge heaters. See Section 4.5.1.



Figure D.1.—Heater 1 power cable.

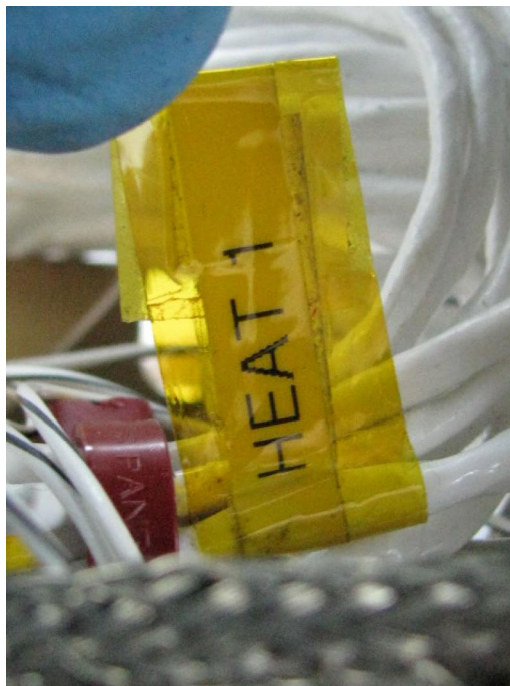


Figure D.2.—Heater 1 power cable.

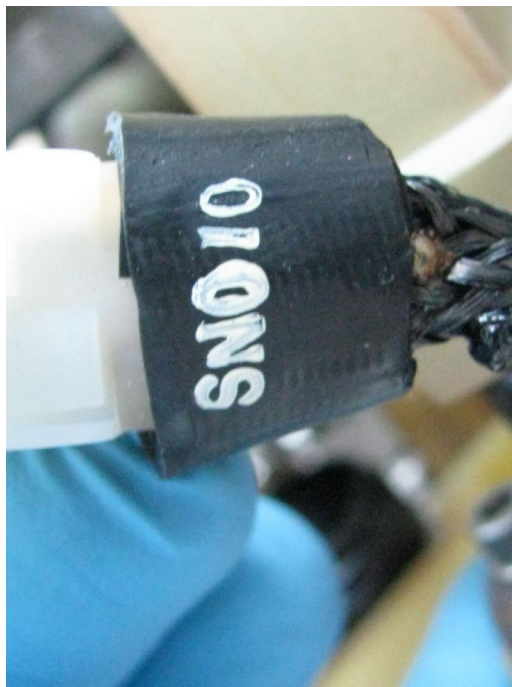


Figure D.3.—Heater 1 Molex connector, note discoloration on wire braid.

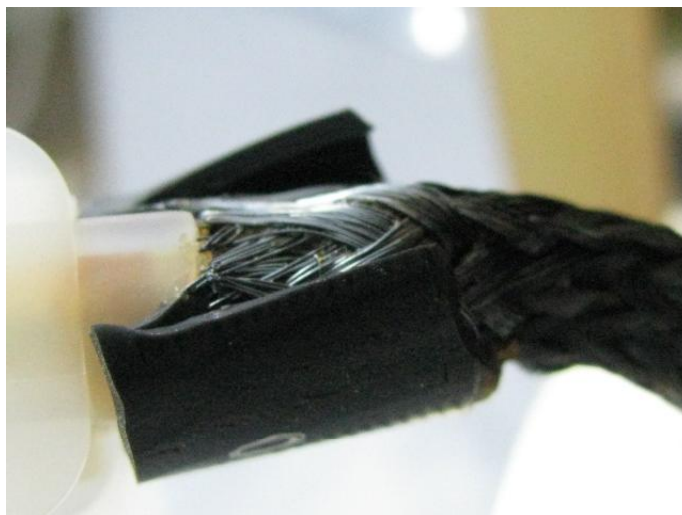


Figure D.4.—Heater 1 Molex connector, strain relief sliced open, note discoloration on wire braid.



Figure D.5.—Heater 1 Molex connector, strain relief sliced open, note discoloration on wire braid.



Figure D.6.—Heater 1 feedthrough into TC.



Figure D.7.—Heater 1 feedthrough into TC.
Note melted shrink wrap.



Figure D.8.—Heater 1 feedthrough into TC.



Figure D.9.—Heater 1 power cable, note discoloration on wire braid by Molex connector and melted ty-rap.



Figure D.10.—Heater 1 Feedthrough into TC.

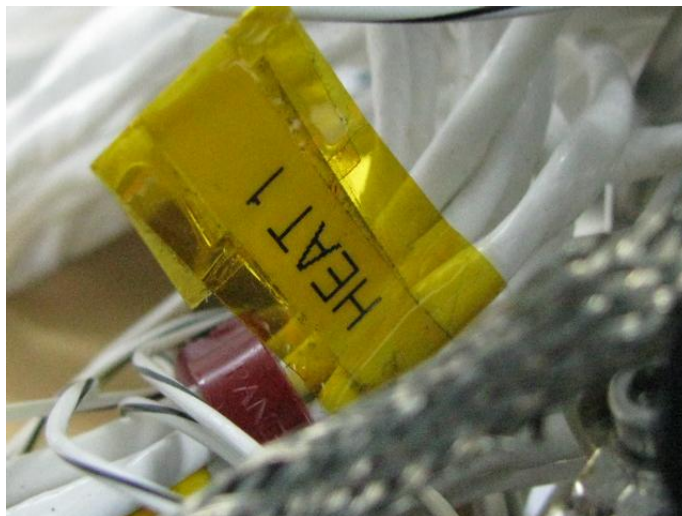


Figure D.11.—Heater 1, melted ty-rap.



Figure D.12.—Heater 1 Molex connector, note discoloration on wire braid.



Figure D.13.—Heater 1 extracted from tee to maximum possible extent.



Figure D.14.—Heater 1 extracted with tee from TC, note melted and blackened surface.



Figure D.15.—Heater 1 extracted with tee from TC, note melted and blackened surface.



Figure D.16.—Close-up of Heater 1 melted surface.



Figure D.17.—Close-up of Heater 1 melted surface near tip of heater.



Figure D.18.—Close-up of Heater 1 melted surface.

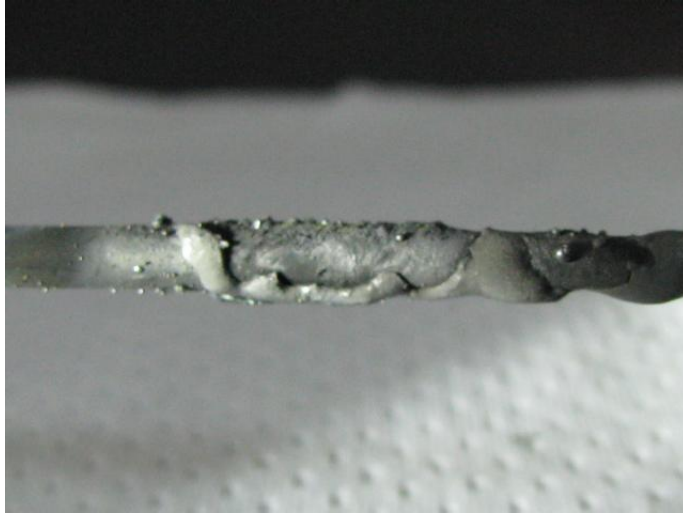


Figure D.19.—Close-up of Heater 1 melted surface.

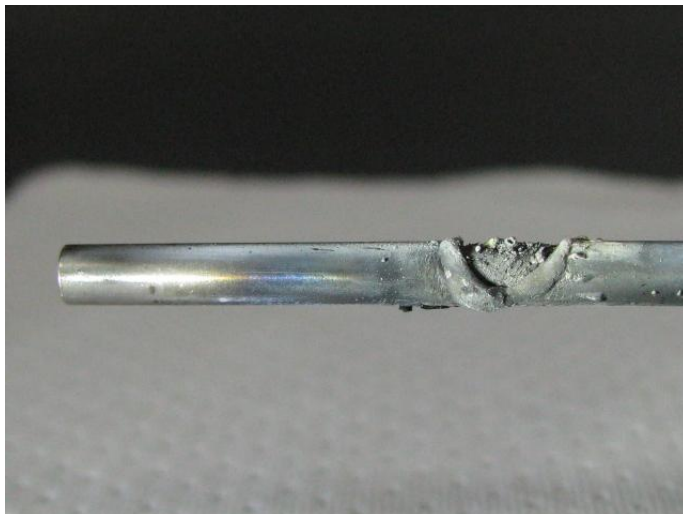


Figure D.20.—Close-up of melted surface near Heater 1 tip.

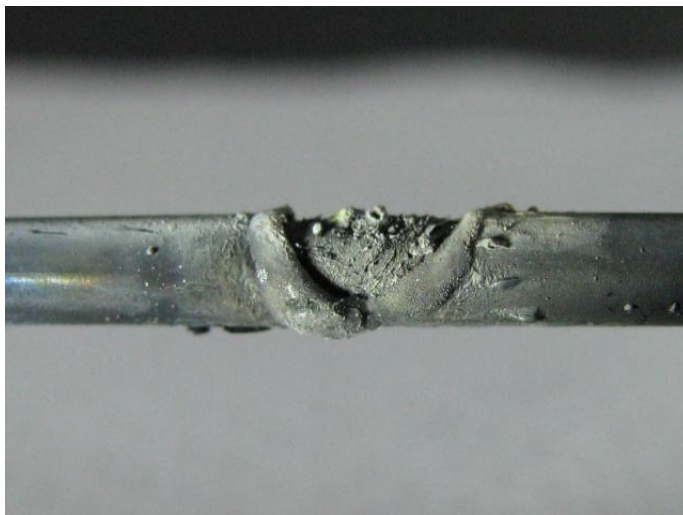


Figure D.21.—Close-up of melted surface near Heater 1 tip.

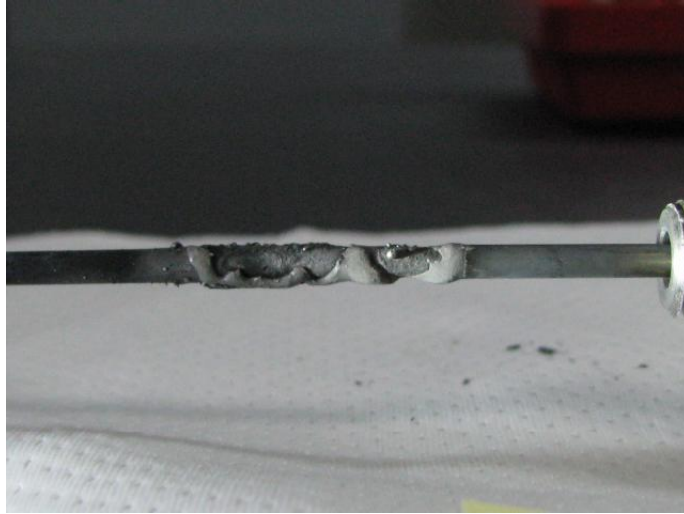


Figure D.22.—Close-up of Heater 1 melted surface.

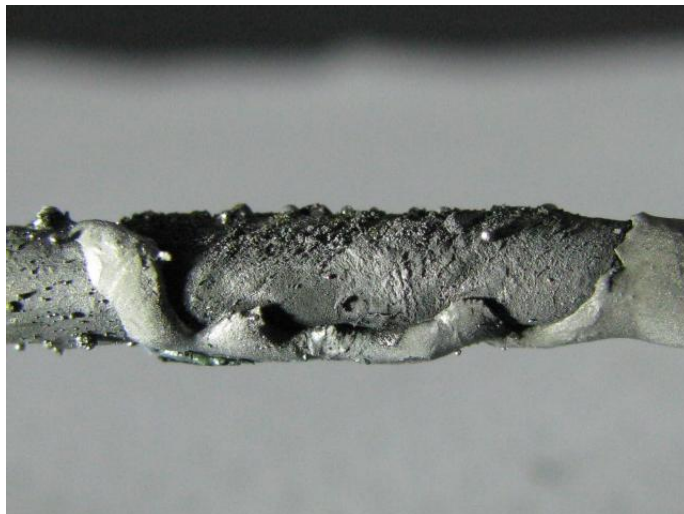


Figure D.23.—Close-up of Heater 1 melted surface.



Figure D.24.—Close-up of Heater 1 melted surface.



Figure D.25.—Close-up of Heater 1 melted surface.

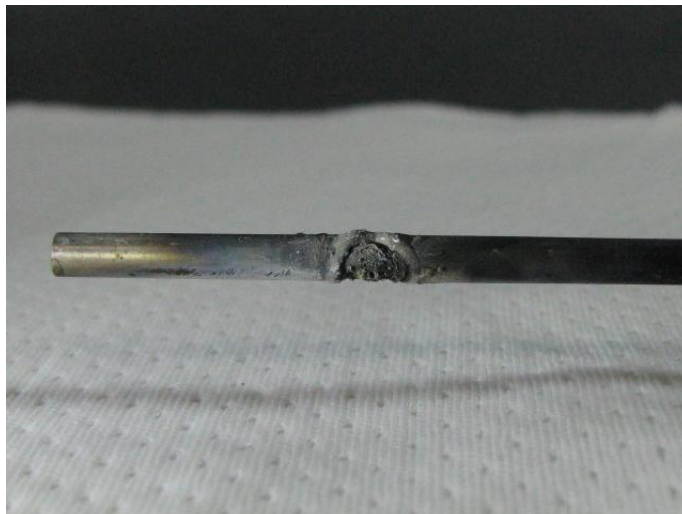


Figure D.26.—Close-up of melted surface near Heater 1 tip.

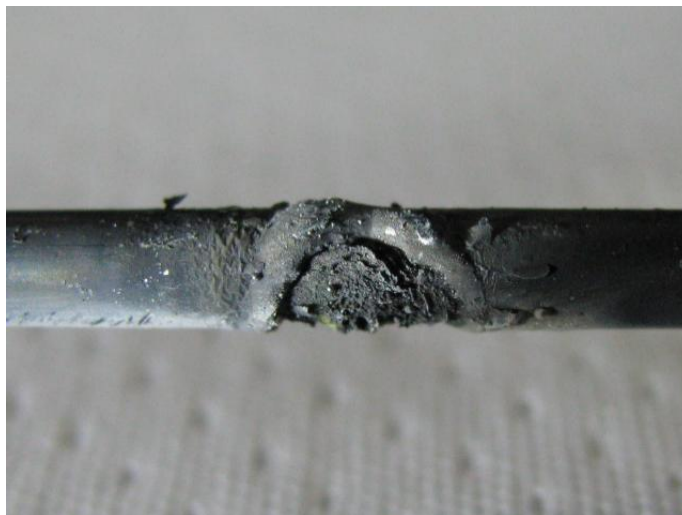


Figure D.27.—Close-up of melted surface near Heater 1 tip.



Figure D.28.—Close-up of melted surface near Heater 1 tip.



Figure D.29.—Heater 1 melted surface.

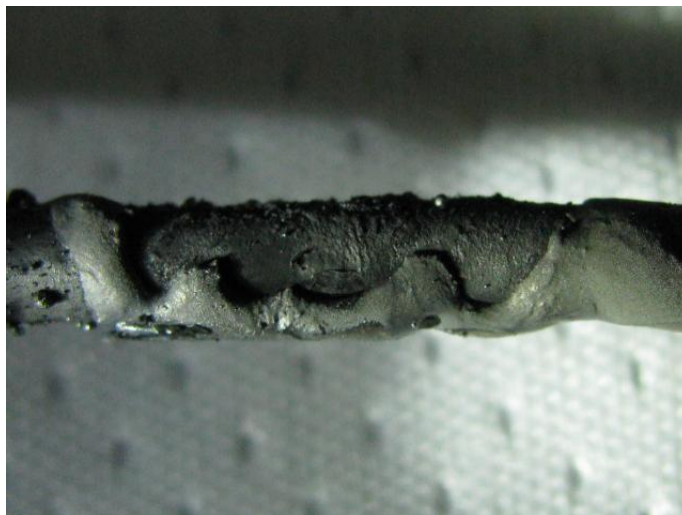


Figure D.30.—Close-up of Heater 1 melted surface.



Figure D.31.—Fluid immersed portion of Heater 1: Note two melted areas of Heater 1



Figure D.32.—Fluid immersed portion of Heater 1: Note two melted areas of Heater 1.



Figure D.33.—Feed through port for Heater 1.

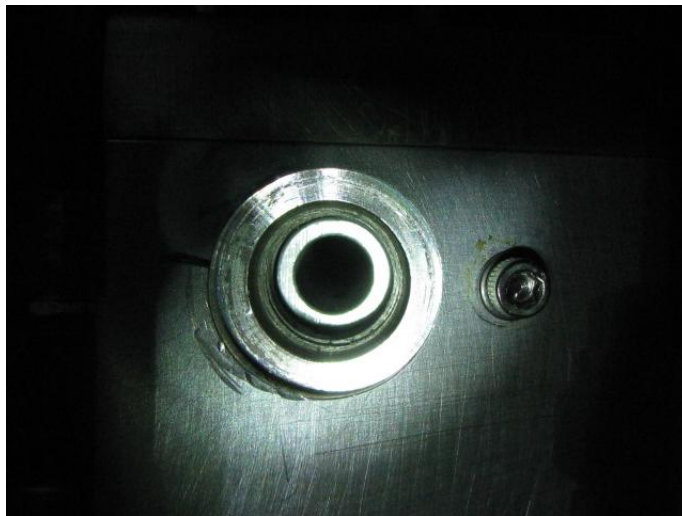


Figure D.34.—Feed through port for Heater 1.

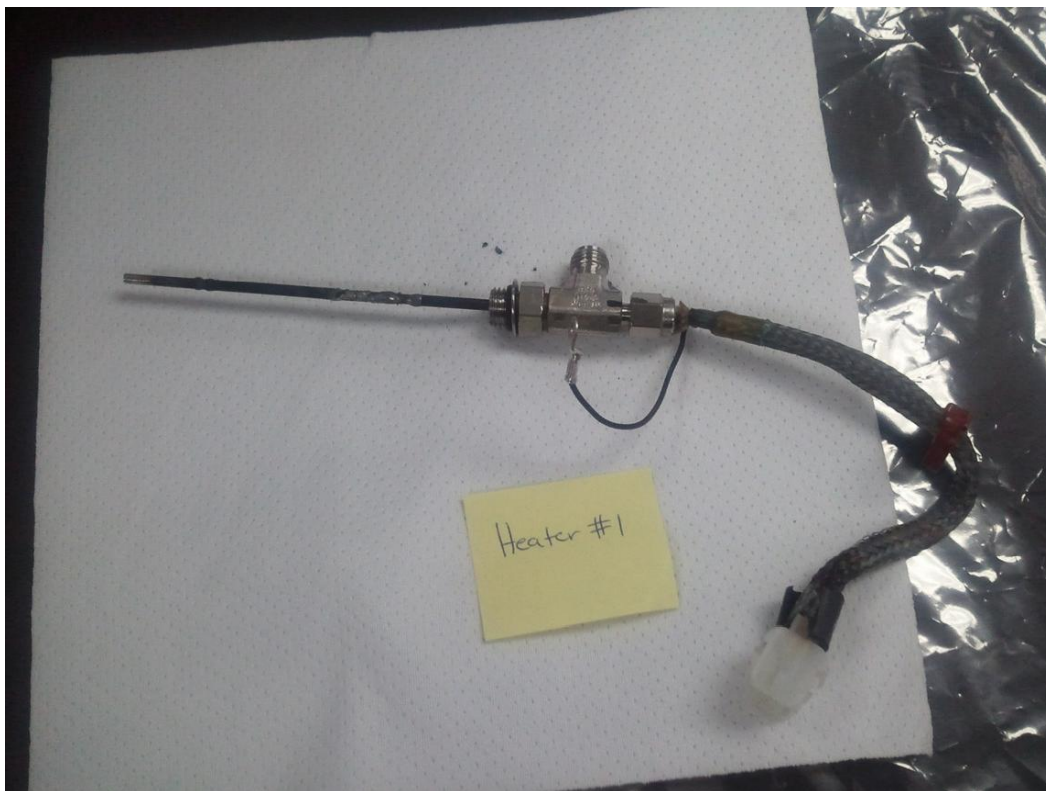


Figure D.35.—Heater 1 assembly, note melted areas on heater and damage to power harness.

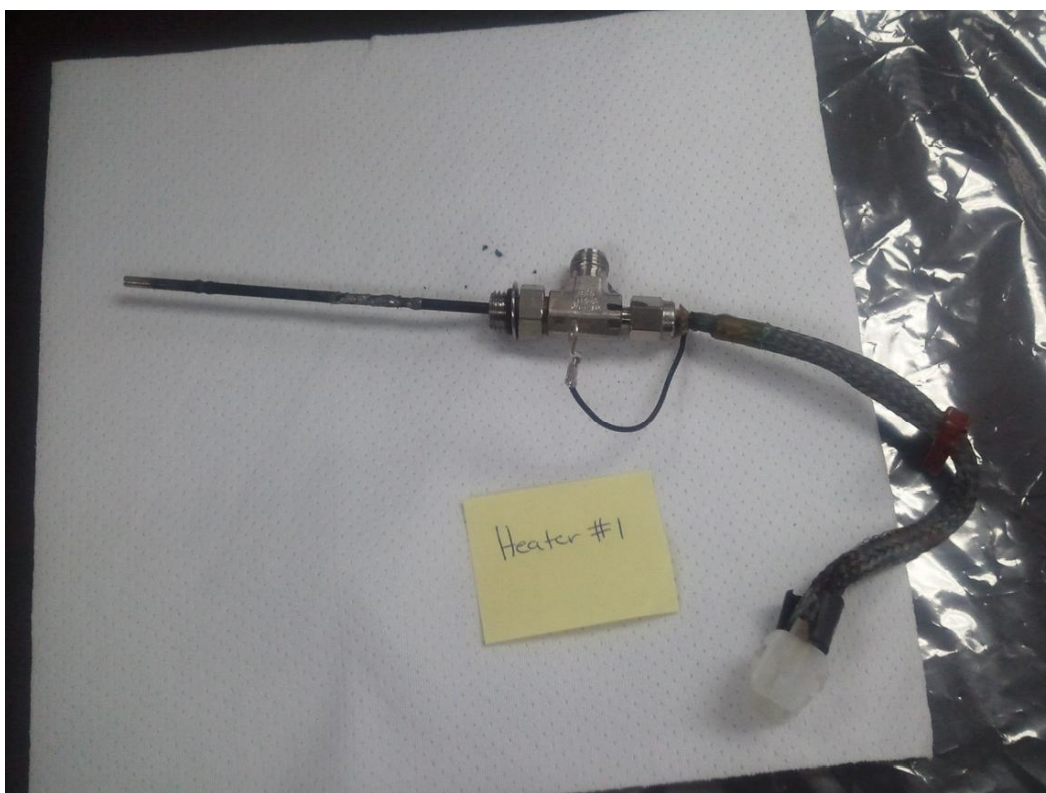


Figure D.36.—Heater 1 assembly, note melted areas on heater and damage to power harness.



Figure D.37.—Fluid immersed portion of Heater 1: Note two melted areas.



Figure D.38.—Fluid immersed portion of Heater 1: Note two melted areas.



Figure D.39.—Heater 1: Note melted area.



Figure D.40.—Heater 1: Note melted area.



Figure D.41.—Heater 1: Note melted area.



Figure D.42.—Heater 1: Note melted area.



Figure D.43.—Heater 1: Note melted area.



Figure D.44.— Heater 1: Note melted area



Figure D.45.—Heater 1: Note melted areas.



Figure D.46.—Heater 1: Note melted areas.



Figure D.47.—Heater 1 Molex connector, note discoloration on wire braid.



Figure D.48.—Heater 1 Molex connector, note discoloration on wire braid.



Figure D.49.—Heater 1 Molex connector, note discoloration on wire braid.



Figure D.50.—Wire harness for Heater 1: Note melted ty-rap.



Figure D.51.—Wire harness for Heater 1: Note melted ty-rap.



Figure D.52.—Wire harness for Heater 1: Note melted ty-rap.



Figure D.53.—Wire harness for Heater 1: Note melted ty-rap.



Figure D.54.—Wire harness for Heater 1: Note melted ty-rap and discoloration on wire braid.



Figure D.55.—Heater 1 connection into TC.

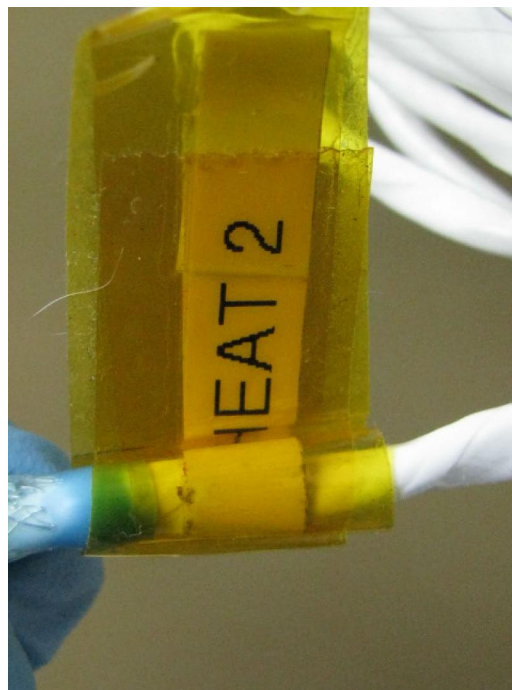


Figure D.56.—Heater 2 label.



Figure D.57.—Heater 2 connection into TC.



Figure D.58.—Heater 2 Molex connector.



Figure D.59.—Heater 2 connection into TC.



Figure D.60.—Heater 2 connection into TC.



Figure D.61.—Heater 2 connection into TC.

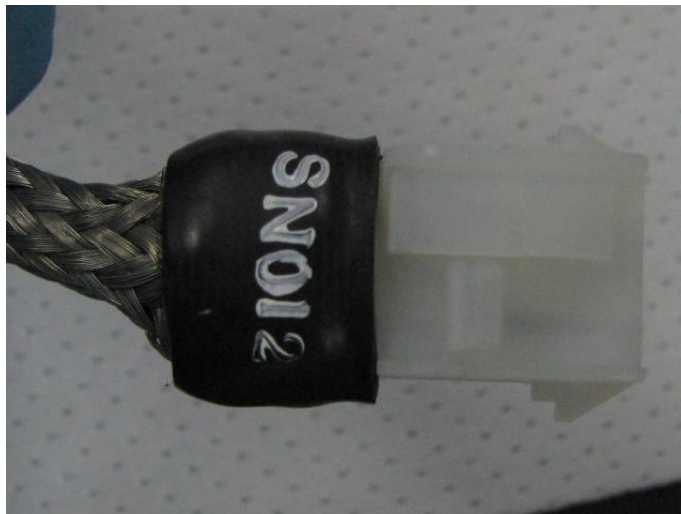


Figure D.62.— Heater 2 Molex connector.



Figure D.63.— Heater 2 assembly: Note discoloration on fluid immersed portion.



Figure D.64.—Heater 2 fluid immersed portion: Note bluing and blackening.



Figure D.65.—Heater 2 fluid immersed portion: Note bluing and blackening.



Figure D.66.—Heater 2 fluid immersed portion: Note bluing and blackening.



Figure D.67.—Heater 2 fluid immersed portion: Note blackening.

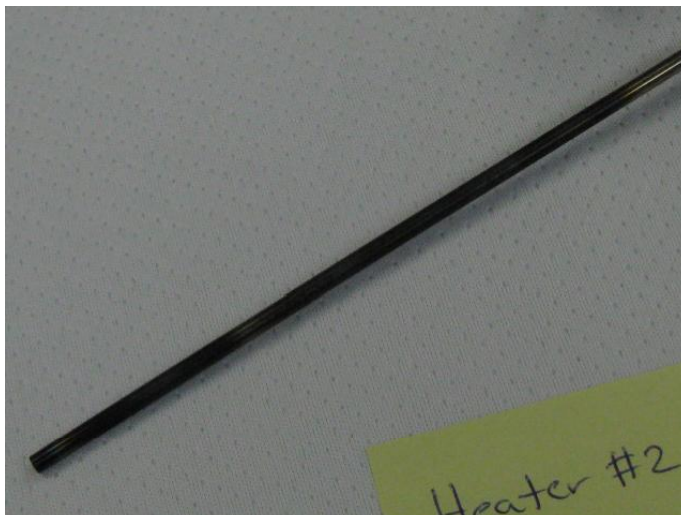


Figure D.68.—Heater 2 fluid immersed portion: Note bluing and blackening.



Figure D.69.—Heater 2 assembly: Note bluing and blackening on fluid immersed portion.

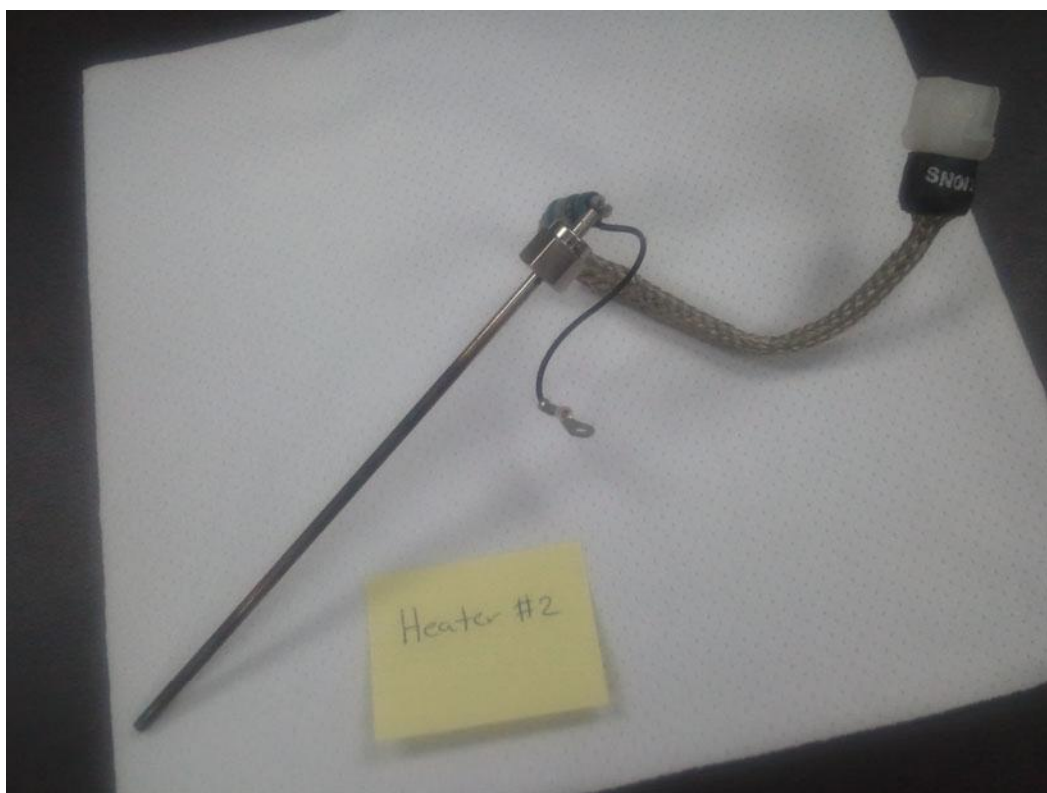


Figure D.70.—Heater 2 assembly: Note bluing and blackening on fluid immersed portion.



Figure D.71.—Heater 2 assembly: Note bluing and blackening on fluid immersed portion.

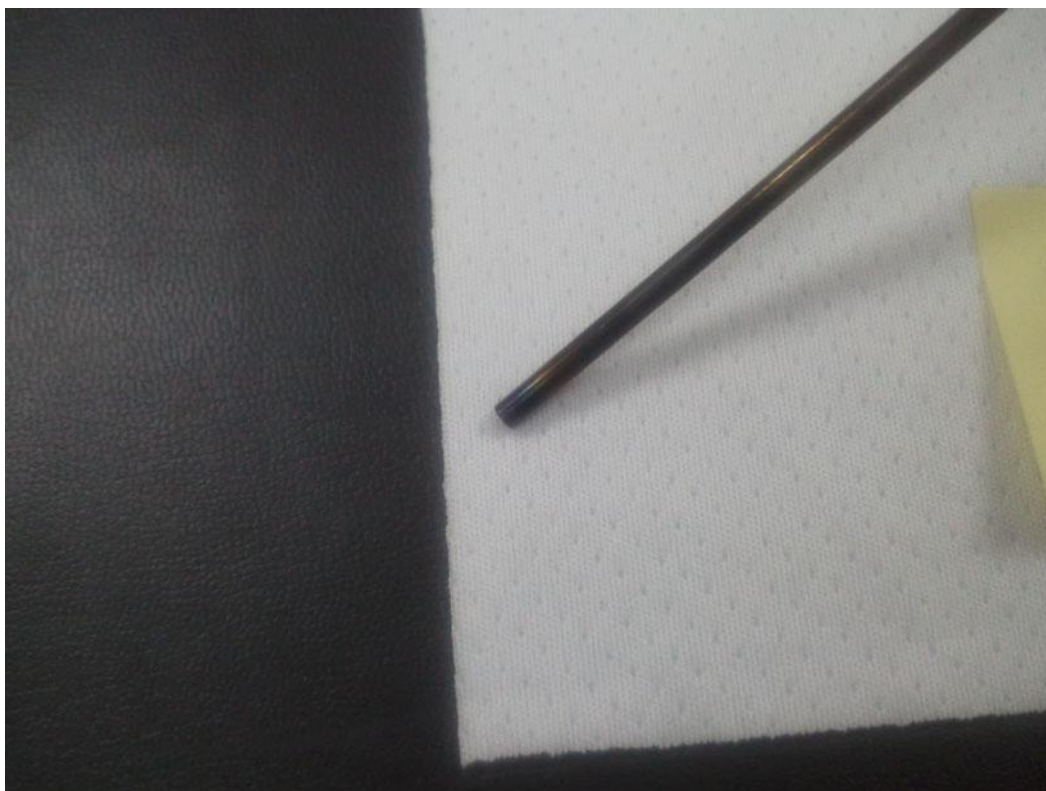


Figure D.72.—Heater 2 fluid immersed portion: Note bluing and blackening.



Figure D.73.—Heater 3 label.



Figure D.74.—Heater 3 connection into TC.

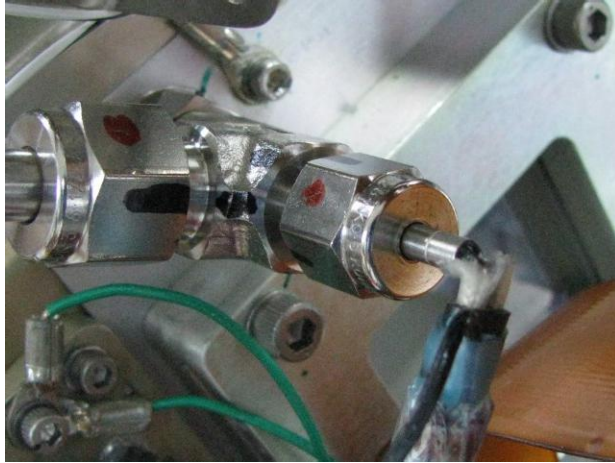


Figure D.75.—Heater 3 connection into TC.



Figure D.76.—Heater 3 connection into TC.



Figure D.77.—Heater 3 connection into TC.

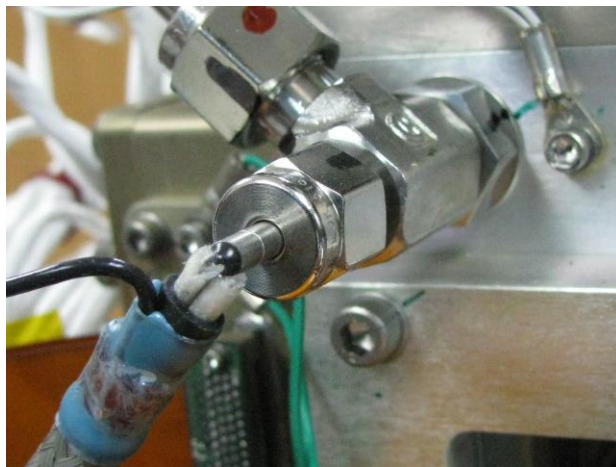


Figure D.78.—Heater 3 connection into TC.



Figure D.79.—Heater 3 Molex connector.



Figure D.80.—Heater 3 connection into TC.



Figure D.81.—Heater 3 Molex connector.

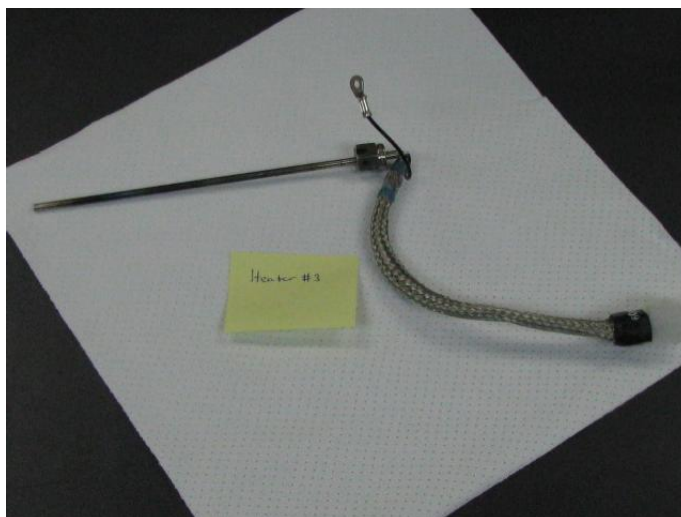


Figure D.82.—Heater 3 assembly: Note bluing and blackening on fluid immersed portion.



Figure D.83.—Heater 3 assembly: Note bluing and blackening on fluid immersed portion.

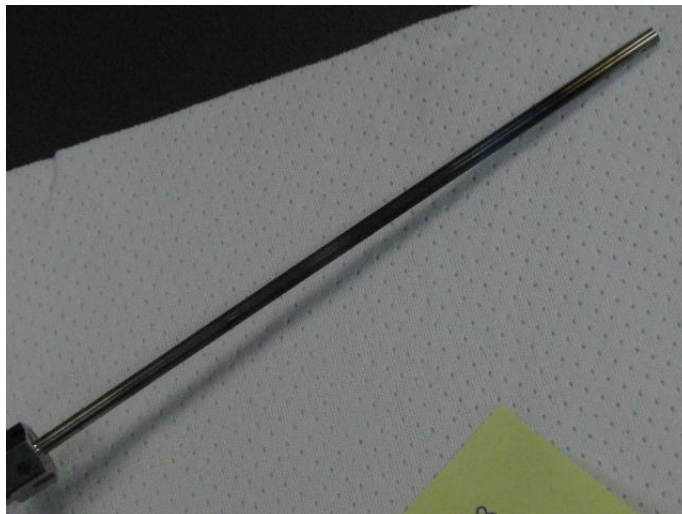


Figure D.84.—Heater 3 fluid immersed portion: Note bluing and blackening.



Figure D.85.—Heater 3 fluid immersed portion: Note bluing and blackening.



Figure D.86.—Heater 3 fluid immersed portion: Note bluing and blackening.



Figure D.87.—Heater 3 fluid immersed portion: Note bluing and blackening.



Figure D.88.—Heater 3 fluid immersed portion: Note bluing and blackening.



Figure D.89.—Heater 3 fluid immersed portion: Note bluing and blackening.

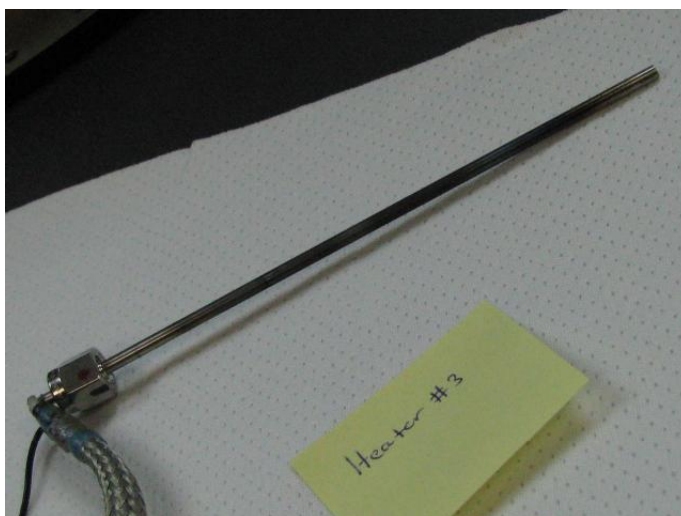


Figure D.90.—Heater 3 fluid immersed portion: Note bluing and blackening.



Figure D.91.—Heater 3 assembly: Note bluing and blackening on fluid immersed portion.



Figure D.92.—Heater 3 fluid immersed portion: Note bluing and blackening.

Appendix E.—X-Ray Inspection Photos

This appendix contains the photos of the cartridge heater x-ray images. See Section 4.5.3. For Reference:

- Bulk Fluid Heater 1 (S/N 010) = A
- Bulk Fluid Heater 2 (S/N 012) = B
- Bulk Fluid Heater 3 (S/N 009) = C

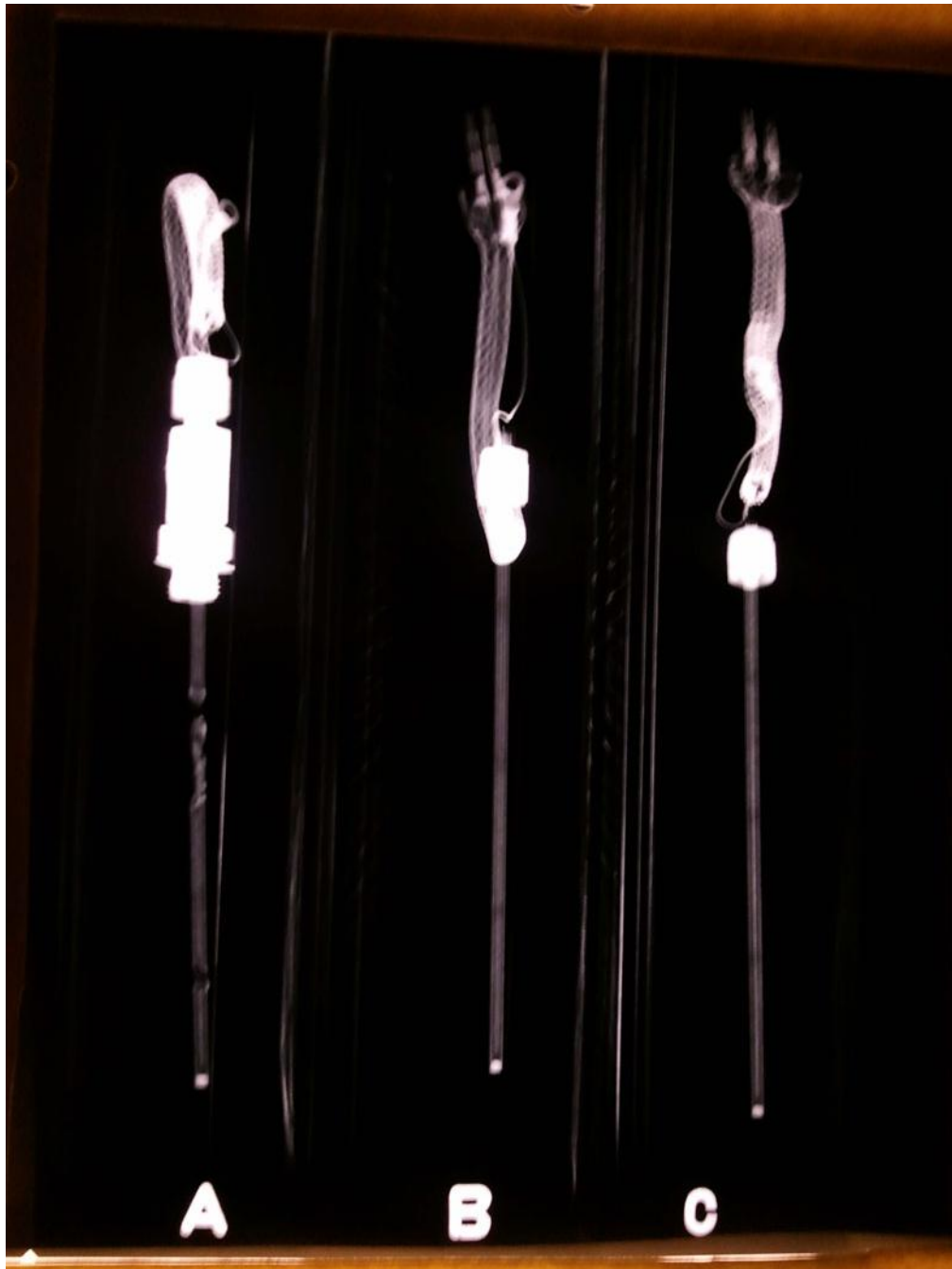


Figure E.1.—Planar view of heater assemblies bulk fluid heaters of 1, 2, and 3, respectively. Note damage in heater 1.

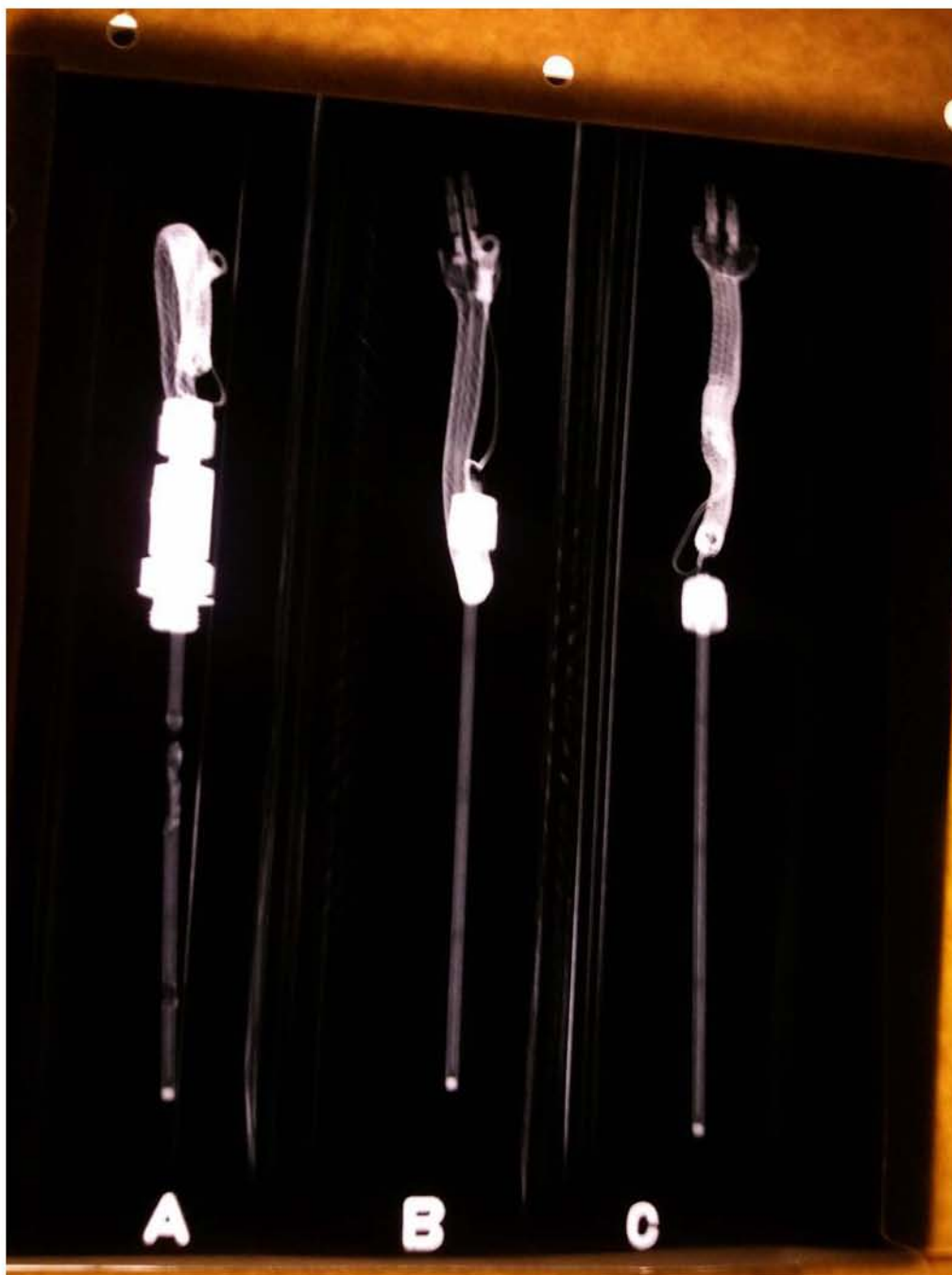


Figure E.2.—Planar view of heater assemblies bulk fluid heaters of 1, 2, and 3, respectively.
Note damage in heater 1.



Figure E.3.—Rotated planar view of heater assemblies bulk fluid heaters of 1, 2, and 3, respectively. Note damage in Heater 1.

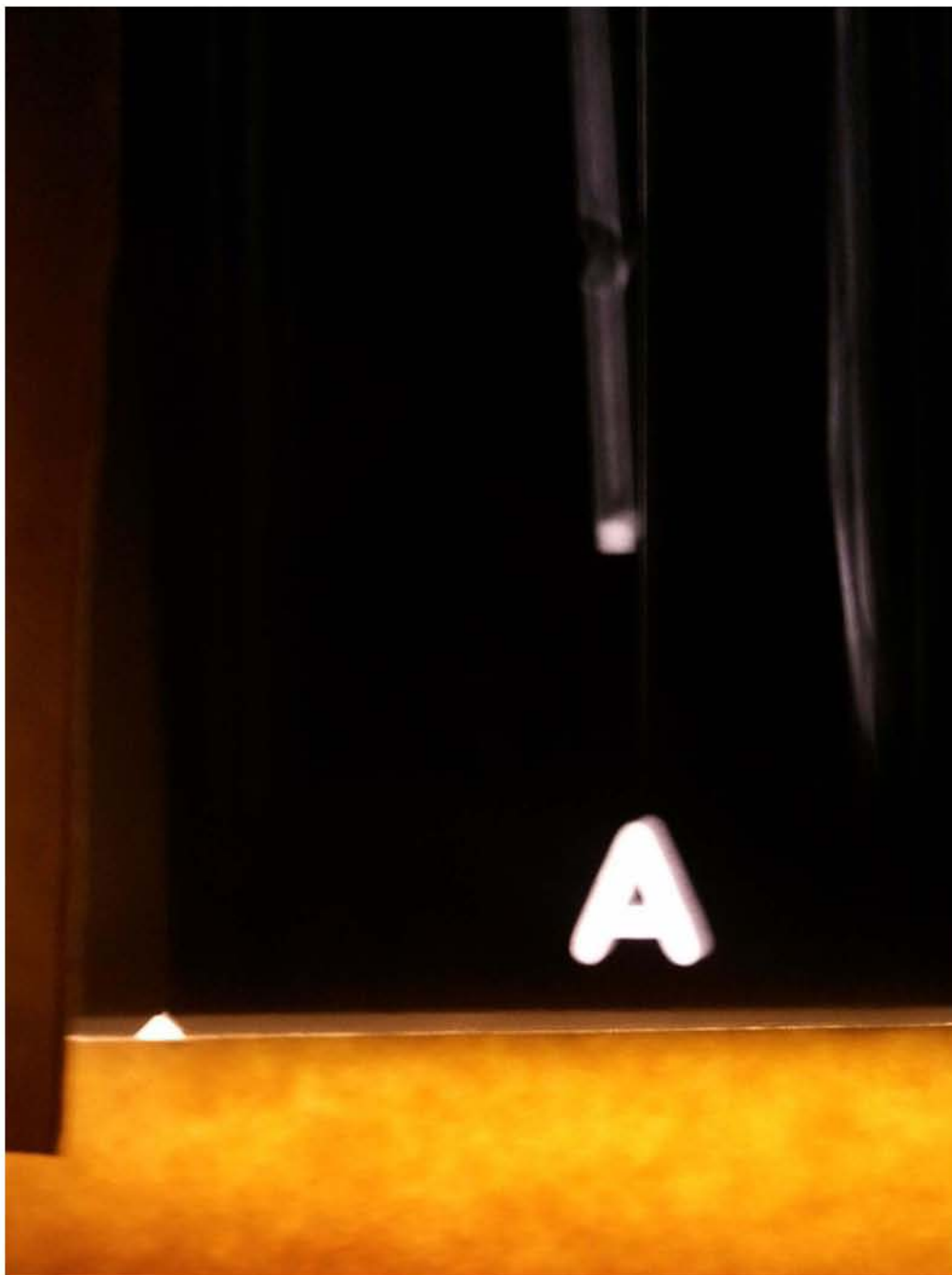


Figure E.4.—Close-up of Bulk Fluid Heater 1 damage at tip.



Figure E.5.—Close-up of Bulk Fluid Heater 1 fitting.

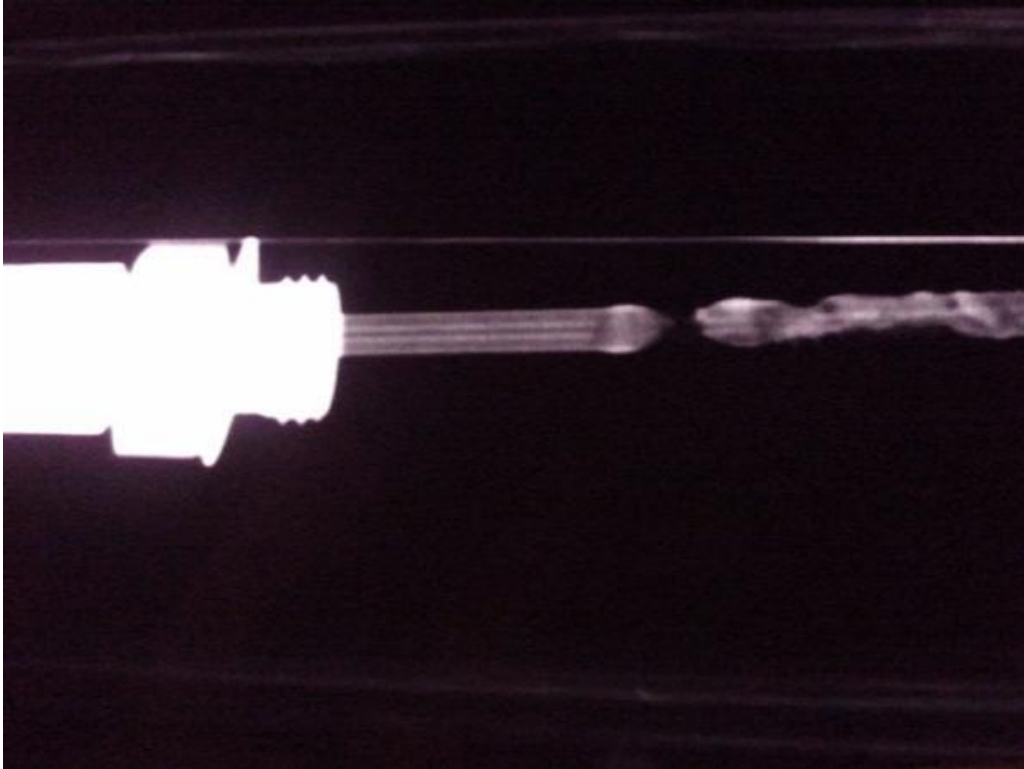


Figure E.6.—Close-up of Bulk Fluid Heater 1 damage along cartridge.



Figure E.7.—Close-up of Bulk Fluid Heater 1 damage along cartridge.



Figure E.8.—Close-up of Bulk Fluid Heater 1 damage at tip.

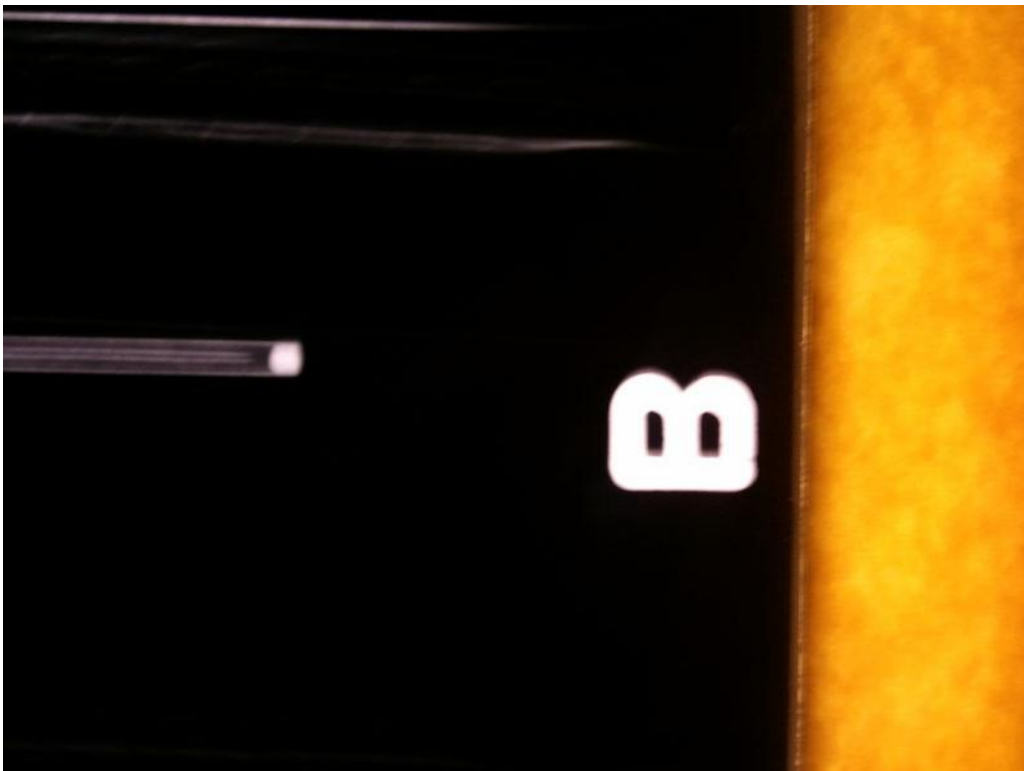


Figure E.9.—Close-up of Bulk Fluid Heater 2 Tip.

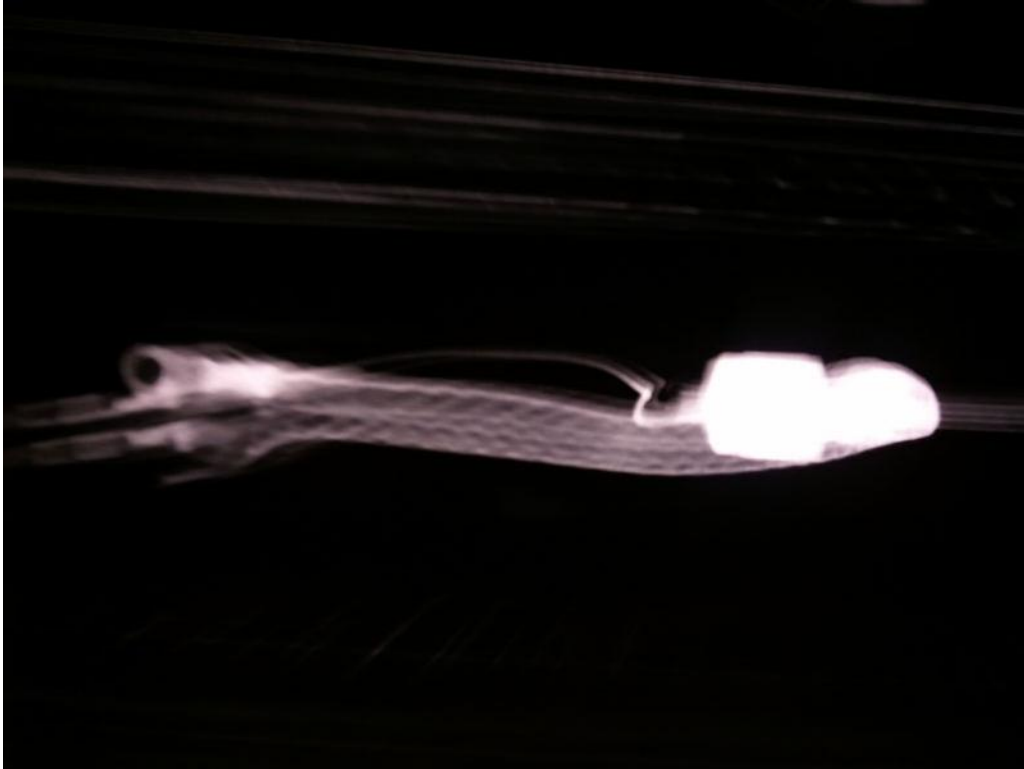


Figure E.10.—Wiring harness for Bulk Fluid Heater 2.

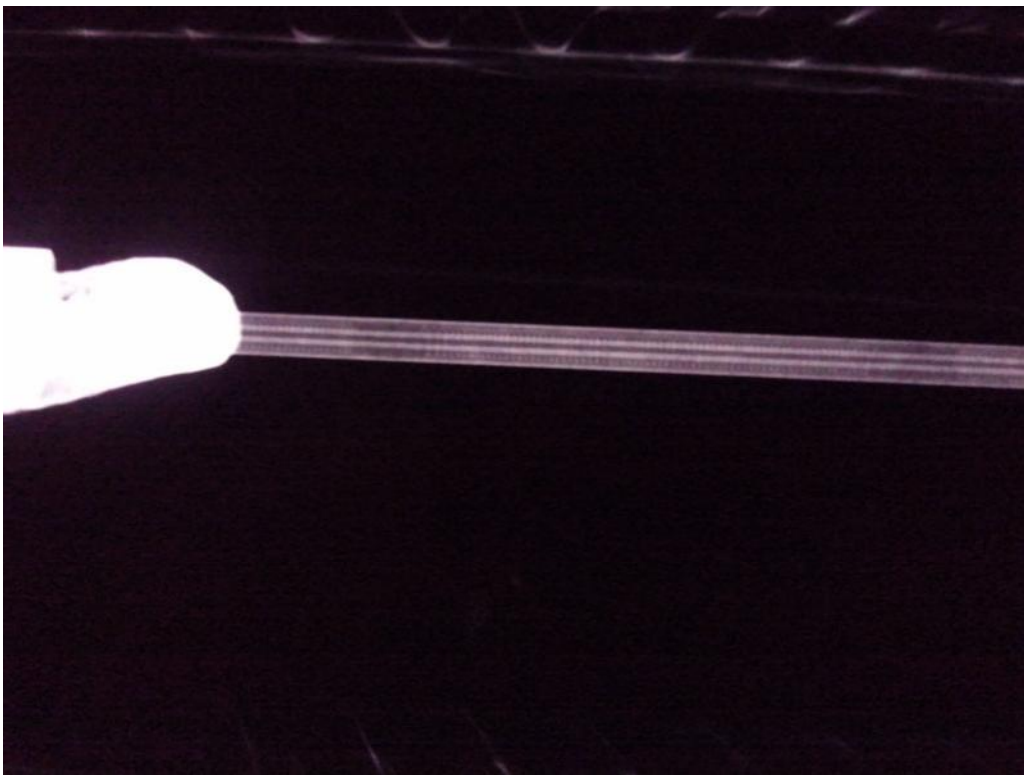


Figure E.11.—Close-up of Bulk Fluid Heater 2 along cartridge. Note irregularities in internal heater wire.

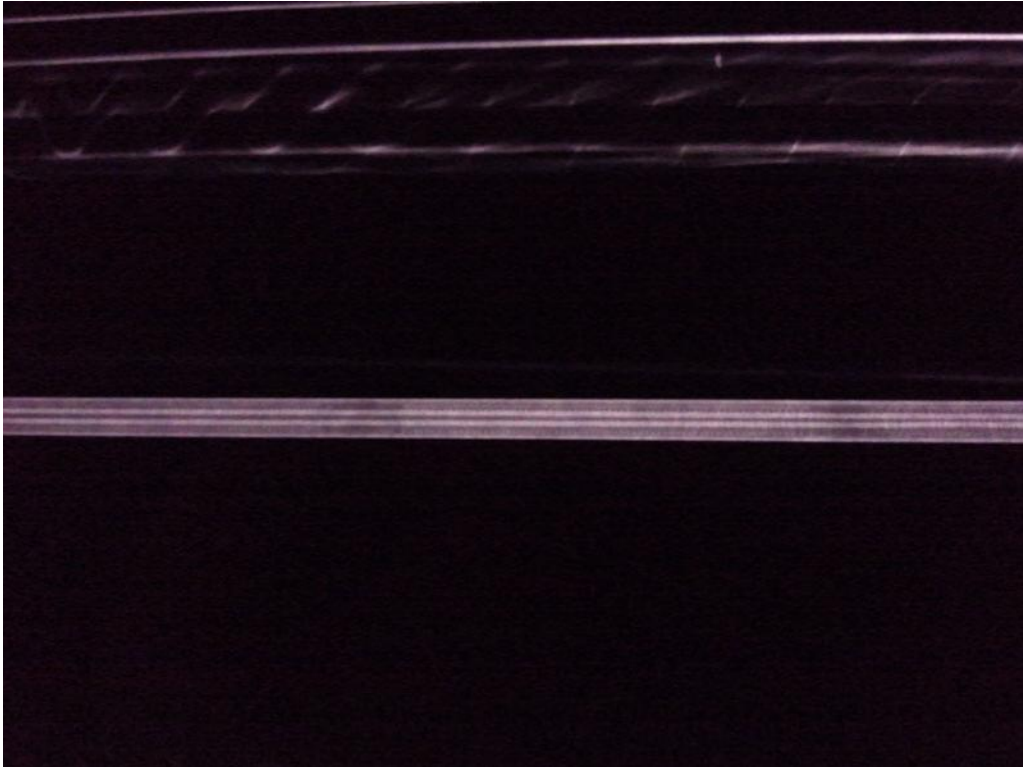


Figure E.12.—Close-up of Bulk Fluid Heater 2 along cartridge. Note irregularities in internal heater wire.

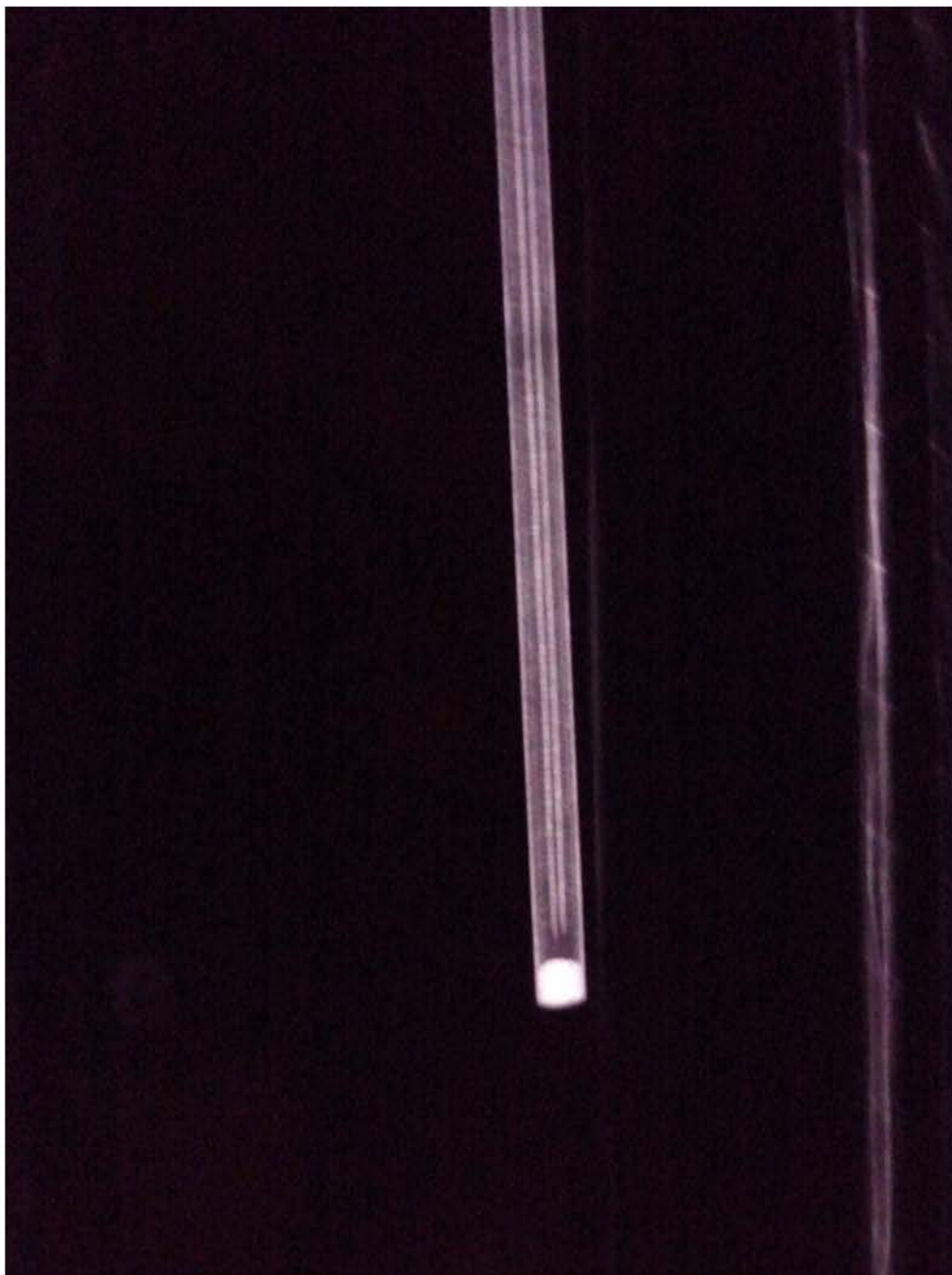


Figure E.13.—Close-up of Bulk Fluid Heater 2 along cartridge. Note irregularities in internal heater wire.



Figure E.14.—Close-up of Bulk Fluid 3 Tip.

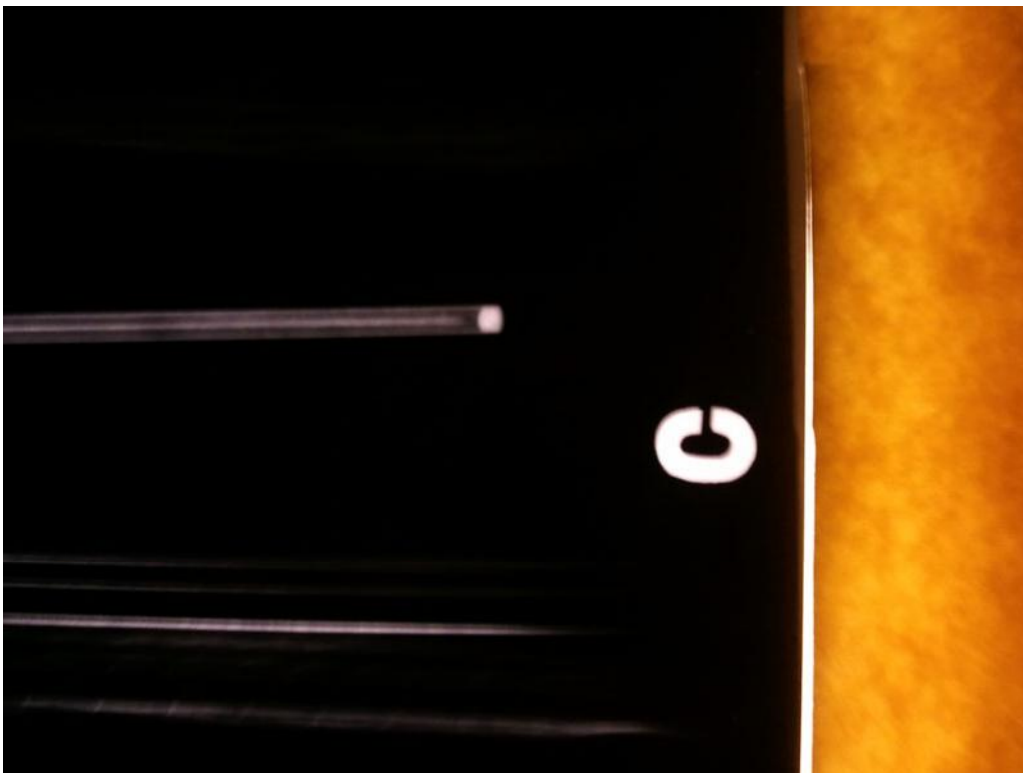


Figure E.15.—Close-up of Bulk Fluid Heater 3 along cartridge. Note irregularities in internal heater wire.

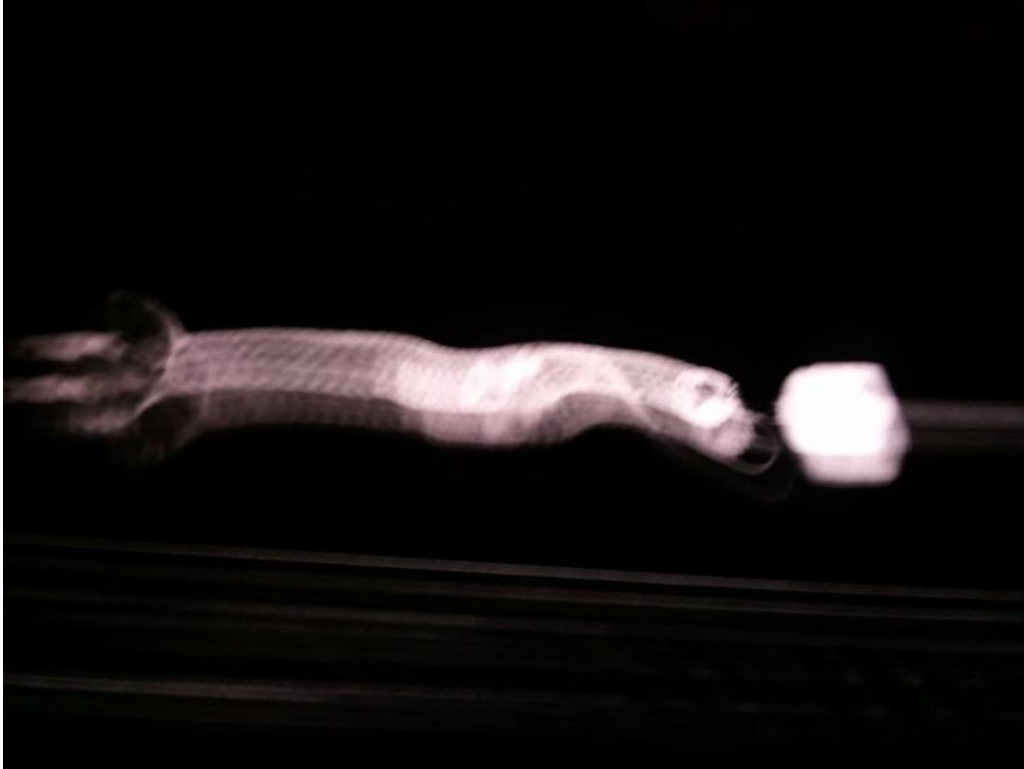


Figure E.16.—Wiring harness for Bulk Fluid Heater 3.

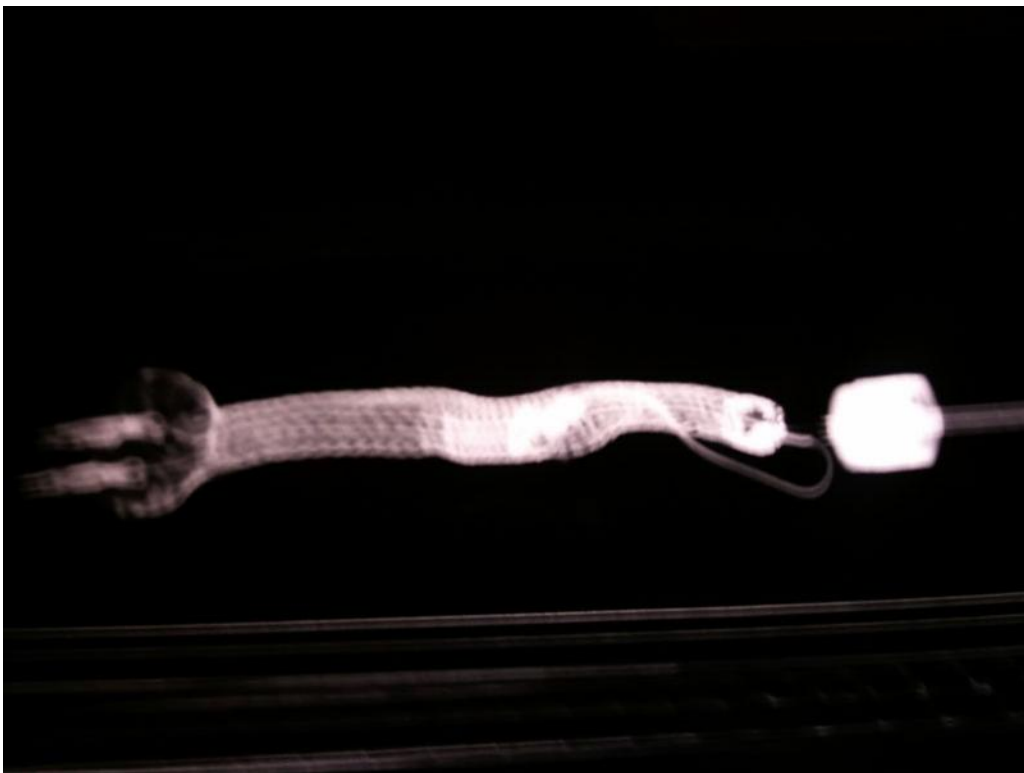


Figure E.17.—Wiring harness for Bulk Fluid Heater 3.

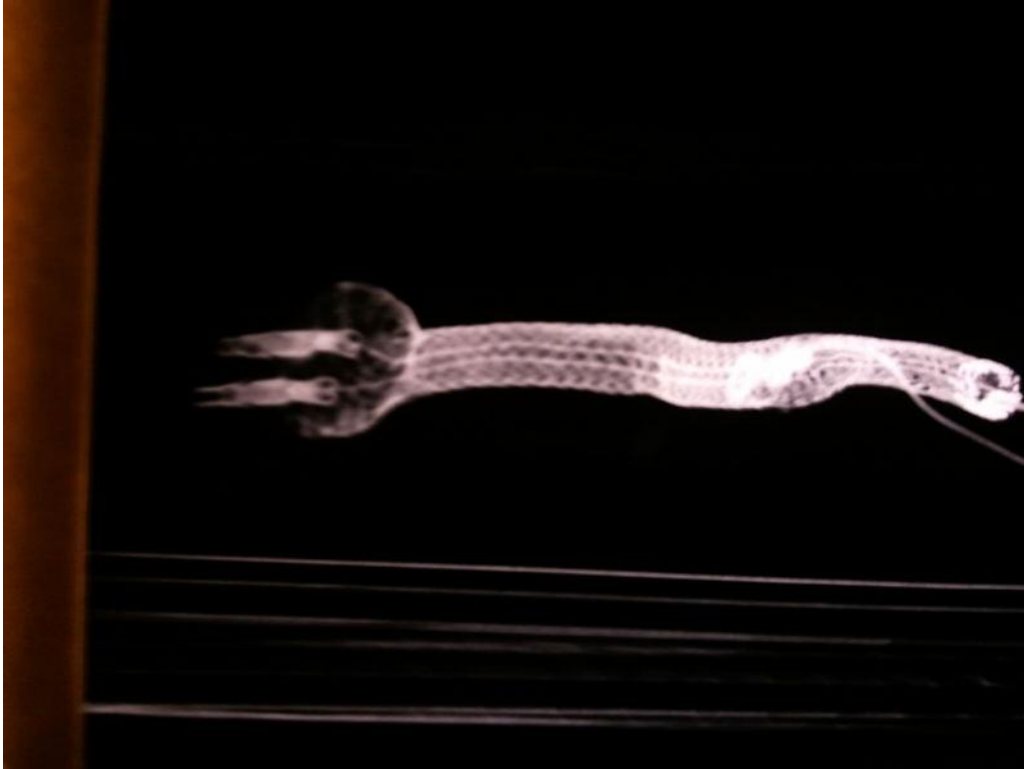


Figure E.18.—Wiring harness for Bulk Fluid Heater 3.

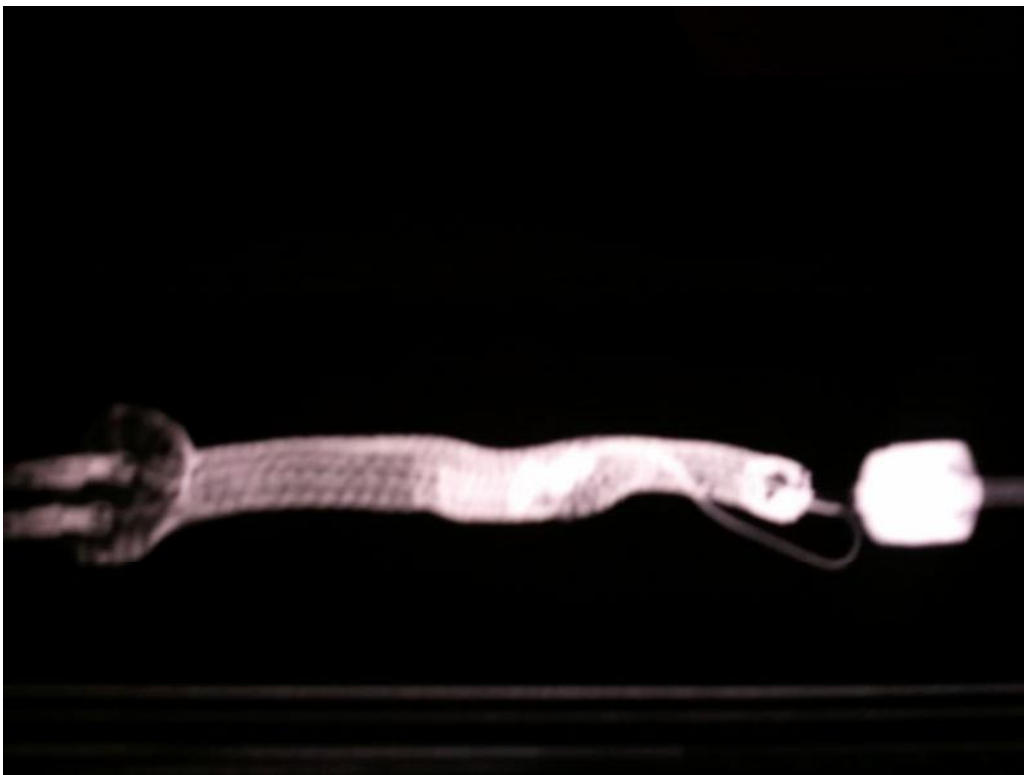


Figure E.19.—Wiring harness for Bulk Fluid Heater 3.

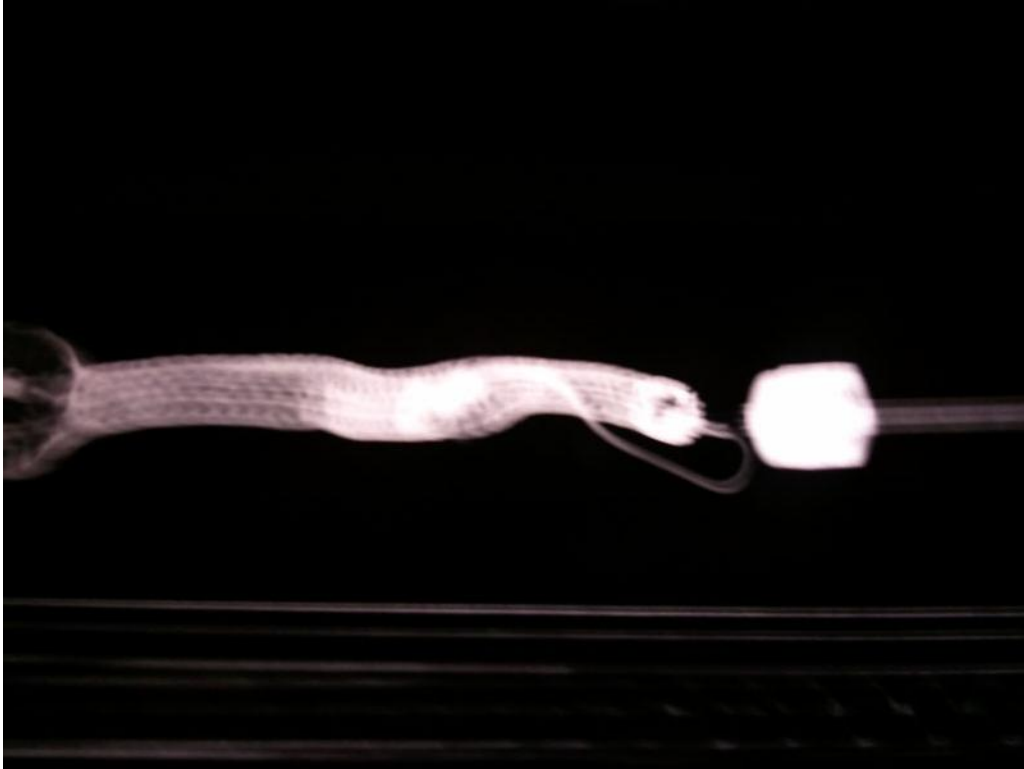


Figure E.20.—Wiring harness for Bulk Fluid Heater 3.

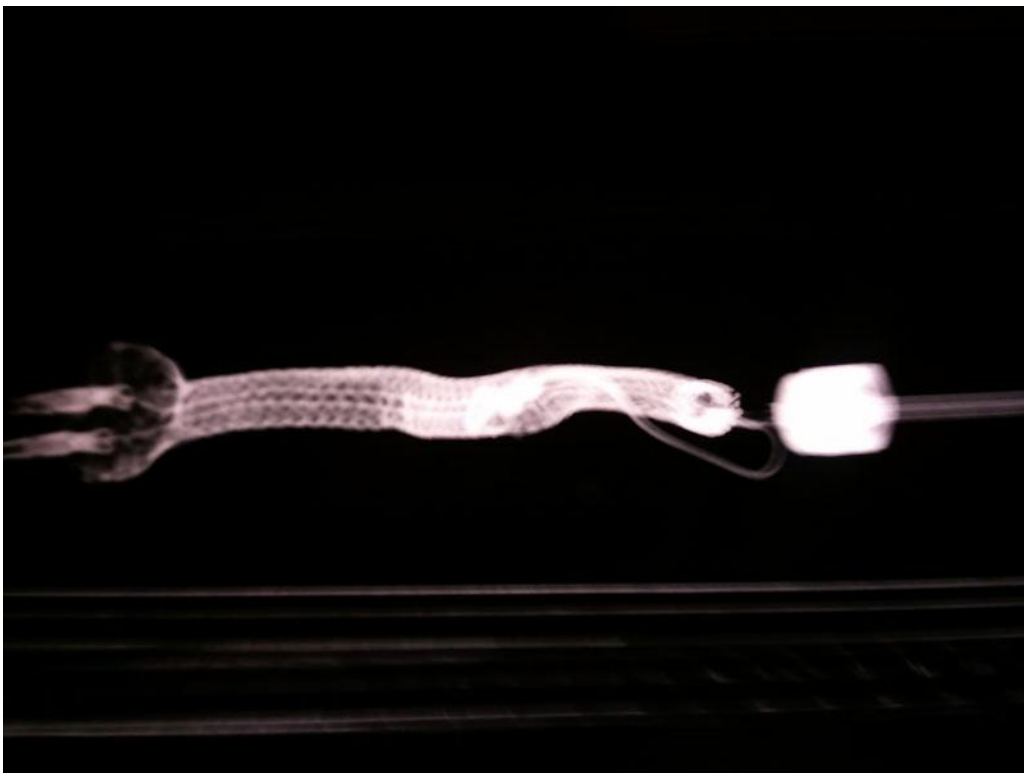


Figure E.21.—Wiring harness for Bulk Fluid Heater 3.

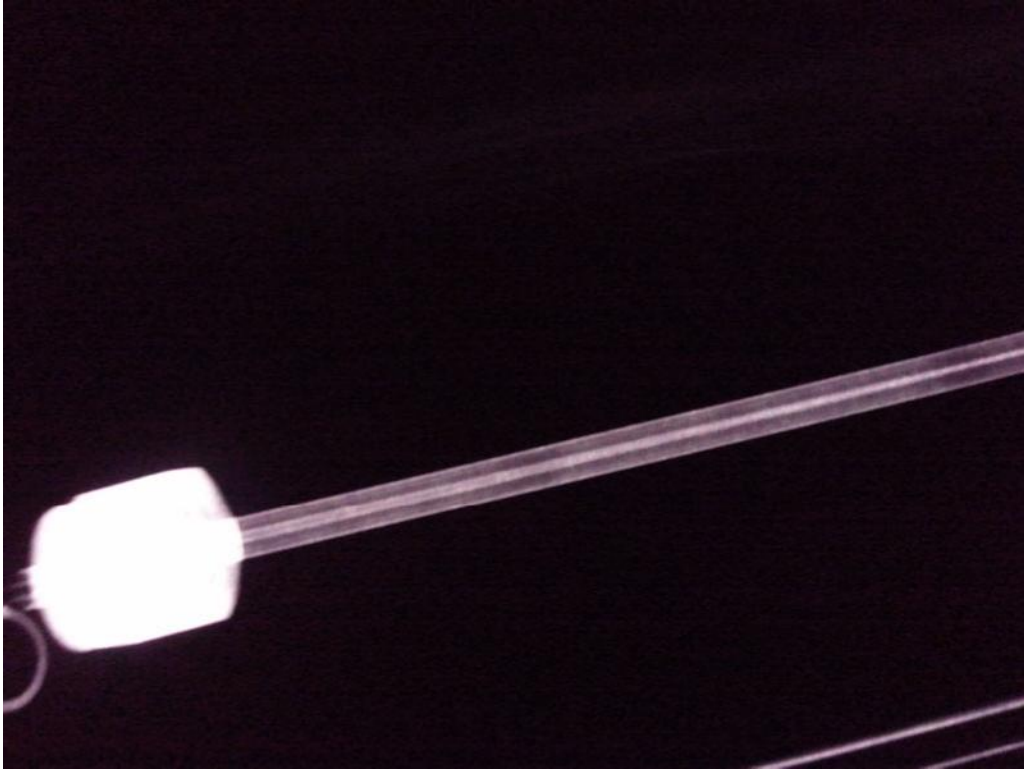


Figure E.22.—Close-up of Bulk Fluid Heater 3 along cartridge. Note irregularities in internal heater wire.

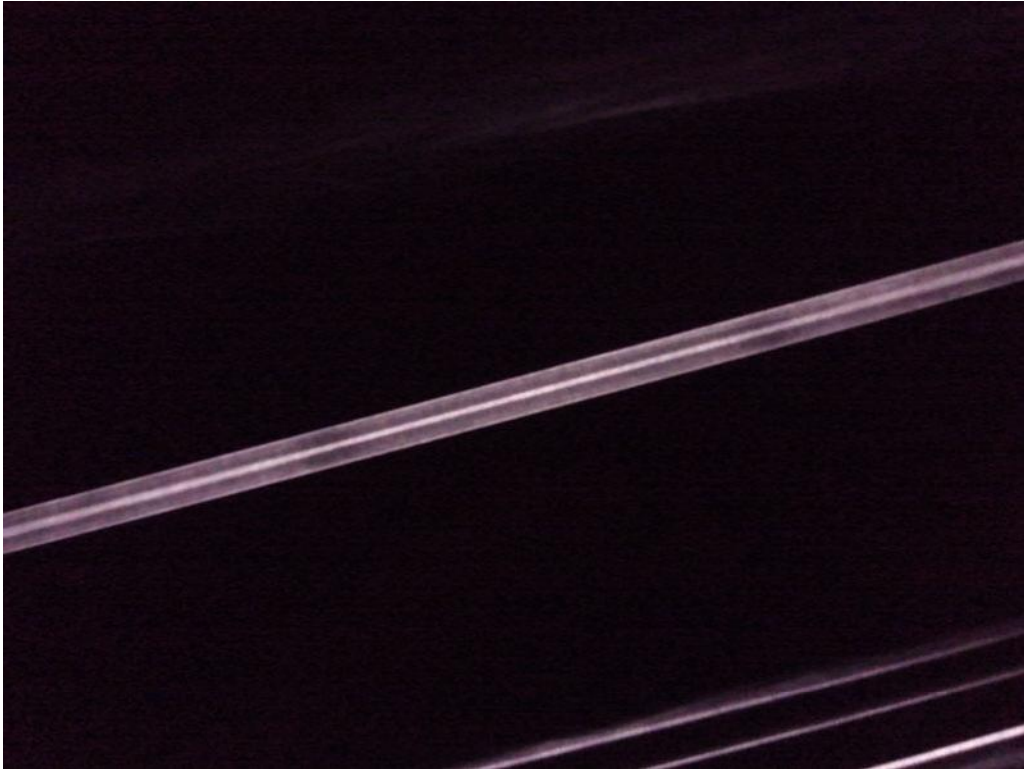


Figure E.23.—Close-up of Bulk Fluid Heater 3 along cartridge. Note irregularities in internal heater wire.

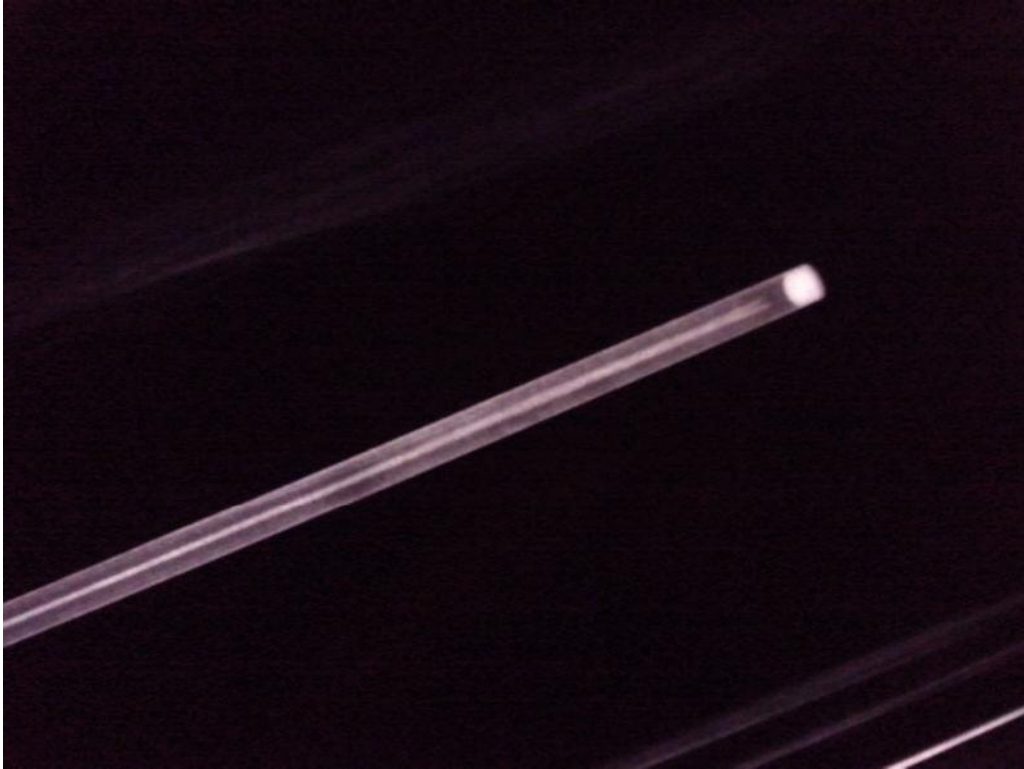


Figure E.24.—Close-up of Bulk Fluid Heater 3 along cartridge. Note irregularities in internal heater wire.

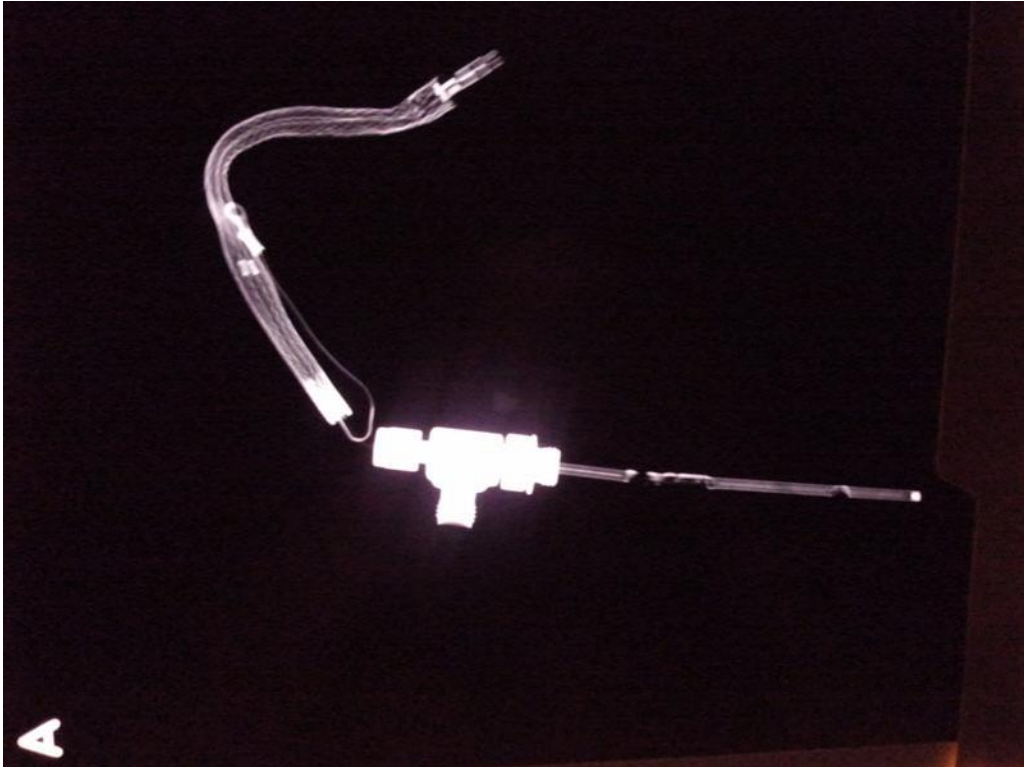


Figure E.25.—Bulk Fluid Heater Assembly 1.



Figure E.26.— Bulk Fluid Heater Assembly 1

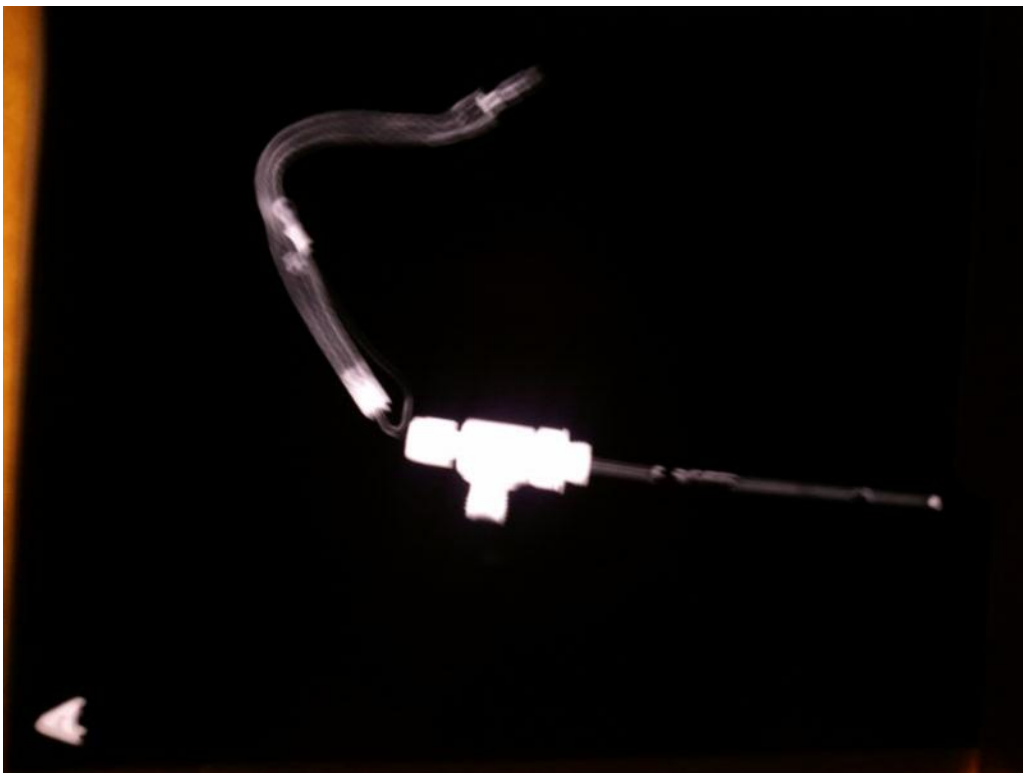


Figure E.27.— Bulk Fluid Heater Assembly 1



Figure E.28.— Bulk Fluid Heater Assembly 1

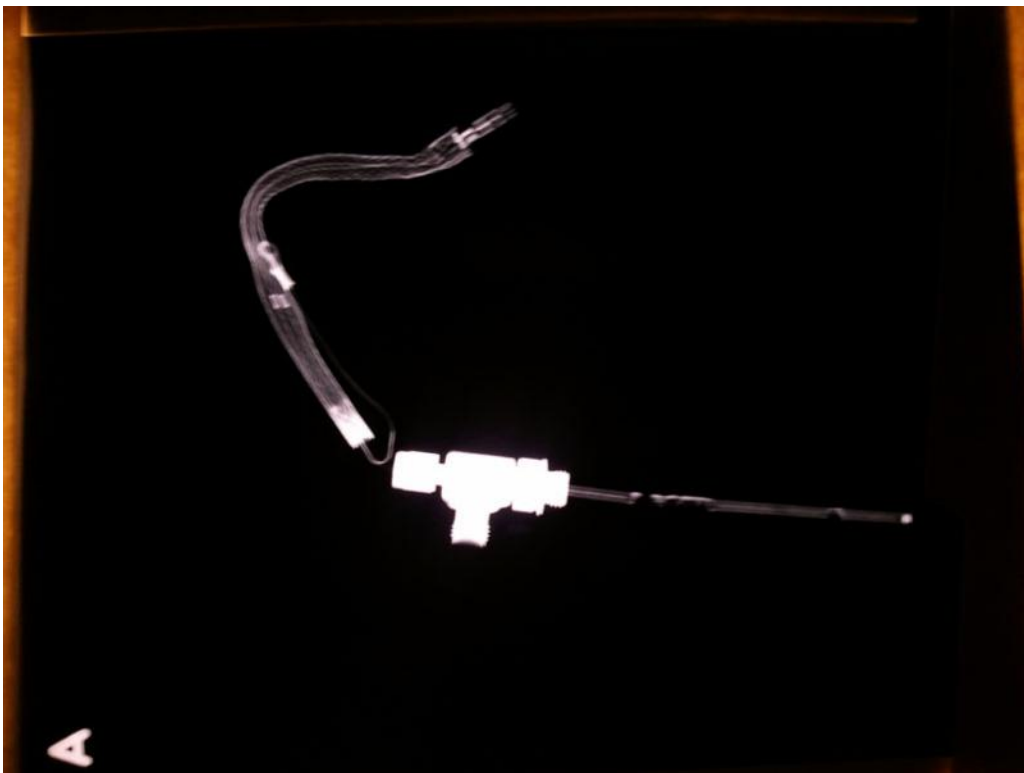


Figure E.29.—Bulk Fluid Heater Assembly 1.



Figure E.30.—Wiring harness for Bulk Fluid Heater 1.



Figure E.31.—Wiring harness for Bulk Fluid Heater 1.



Figure E.32.—Wiring harness for Bulk Fluid Heater 1.



Figure E.33.—Wiring harness for Bulk Fluid Heater 1.

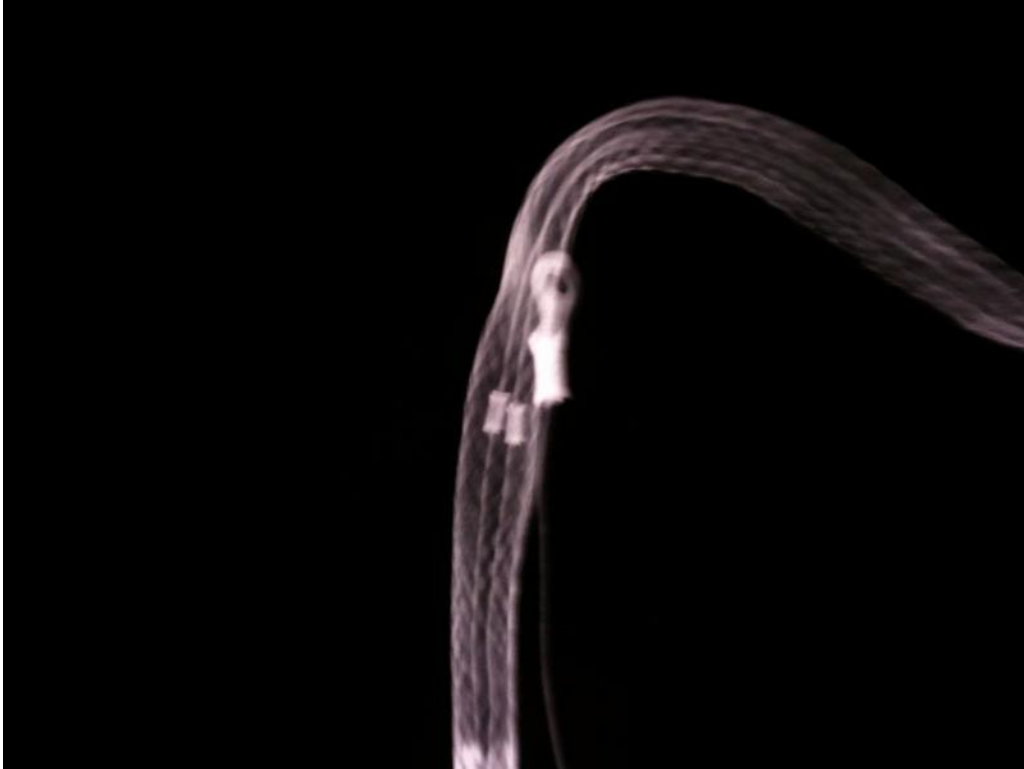


Figure E.34.—Wiring harness for Bulk Fluid Heater 1.

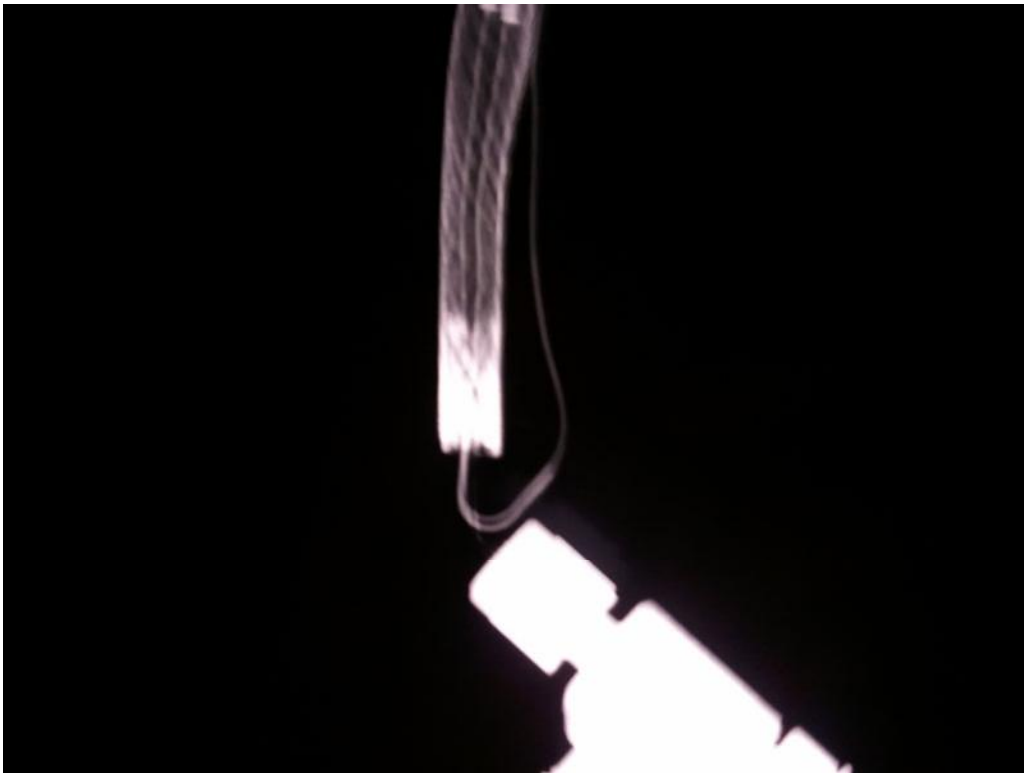


Figure E.35.—Wiring harness for Bulk Fluid Heater 1.

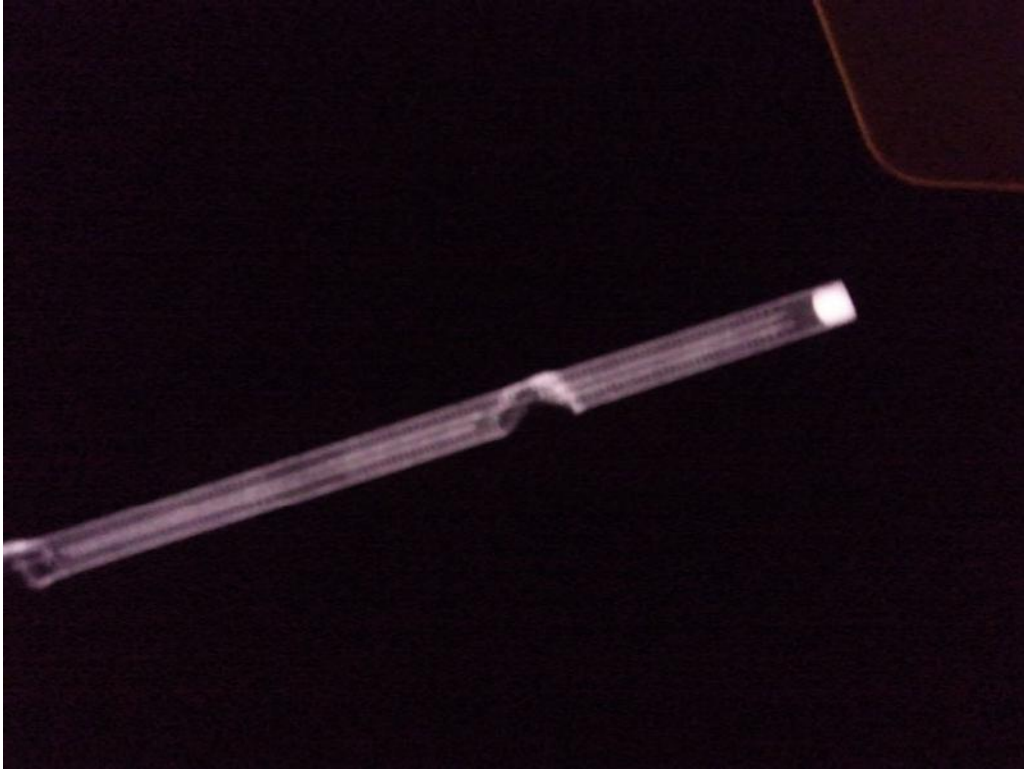


Figure E.36.—Close-up of Bulk Fluid Heater 1 damage along cartridge.

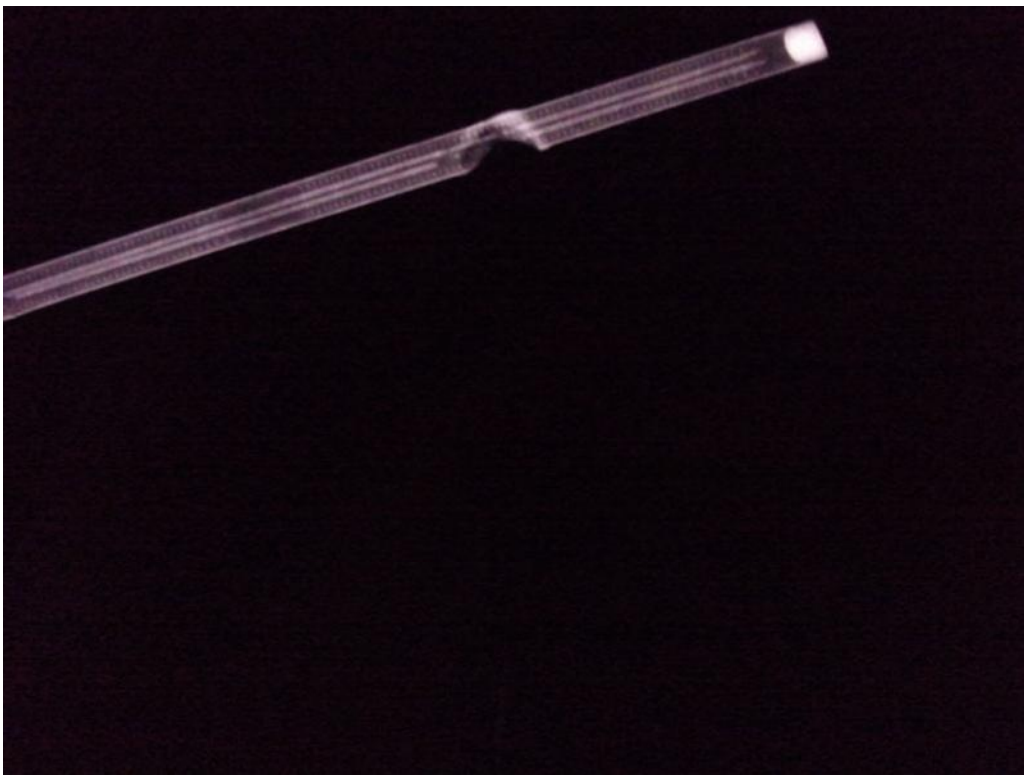


Figure E.37.—Close-up of Bulk Fluid Heater 1 damage near cartridge tip.

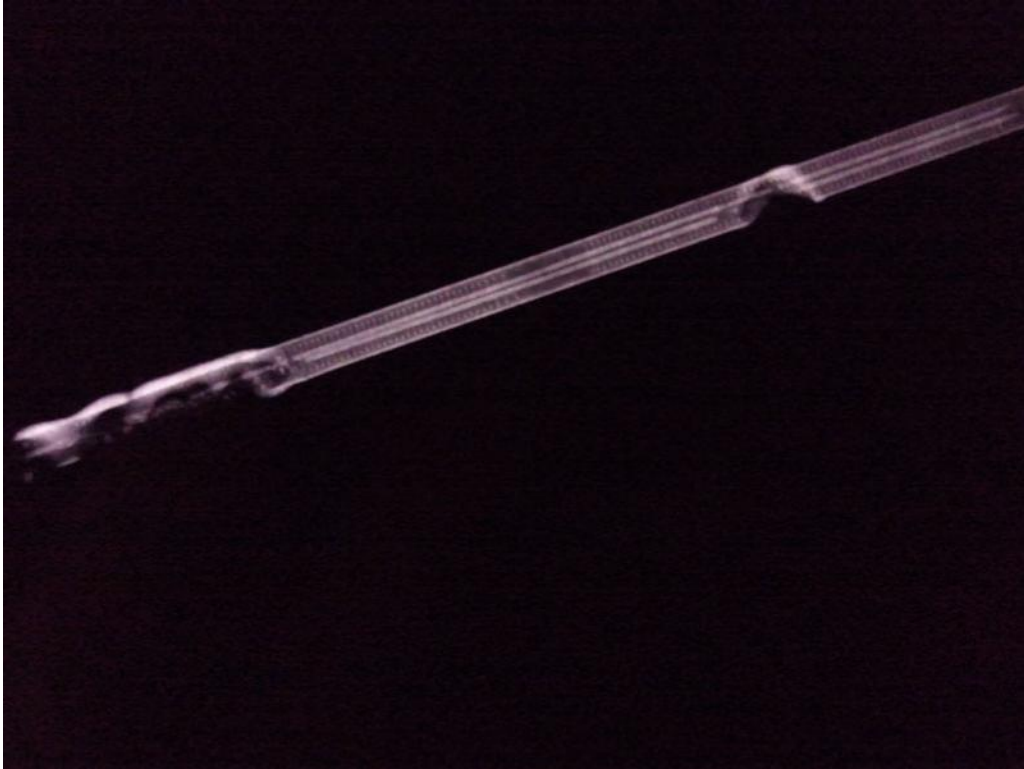


Figure E.38.—Close-up of Bulk Fluid Heater 1 damage along cartridge.



Figure E.39.—Close-up of Bulk Fluid Heater 1 damage along cartridge.

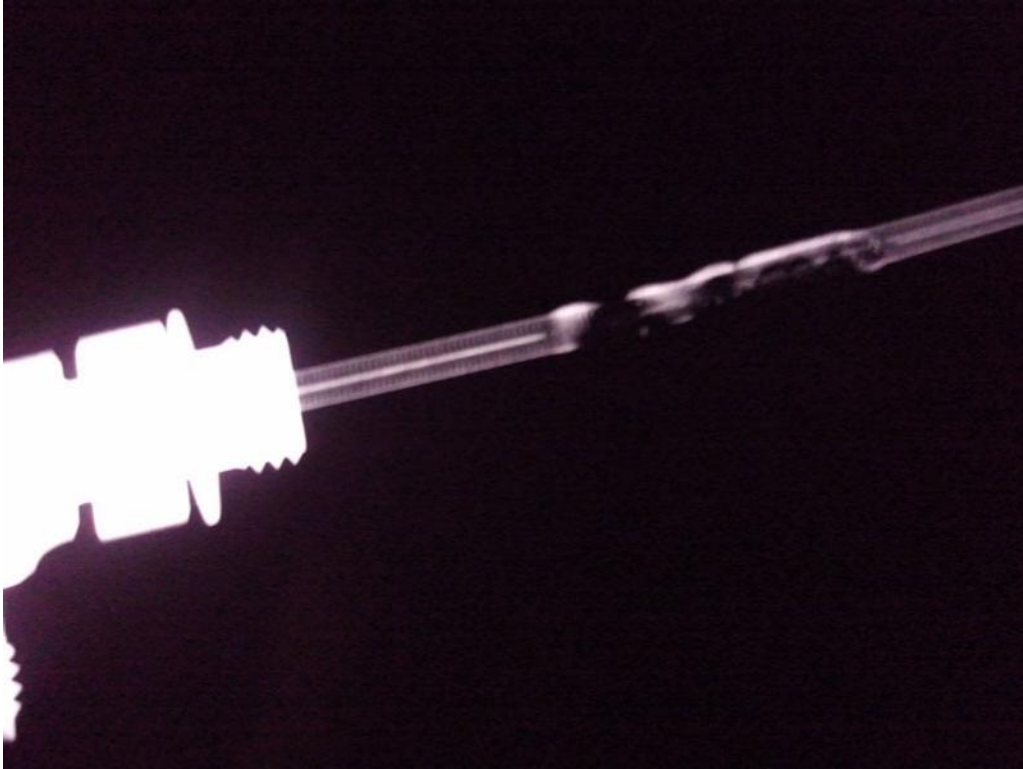


Figure E.40.—Close-up of Bulk Fluid Heater 1 damage along cartridge.

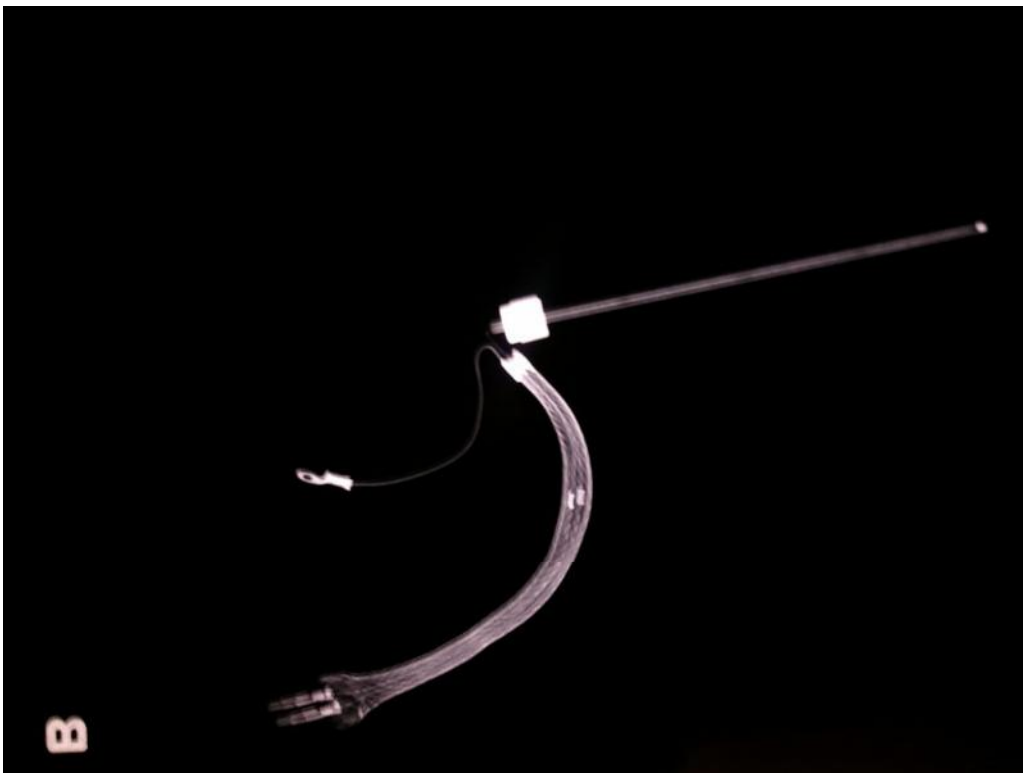


Figure E.41.—Planar view of heater assembly for Bulk Fluid Heater 2.



Figure E.42.—Planar view of heater assembly for Bulk Fluid Heater 2.

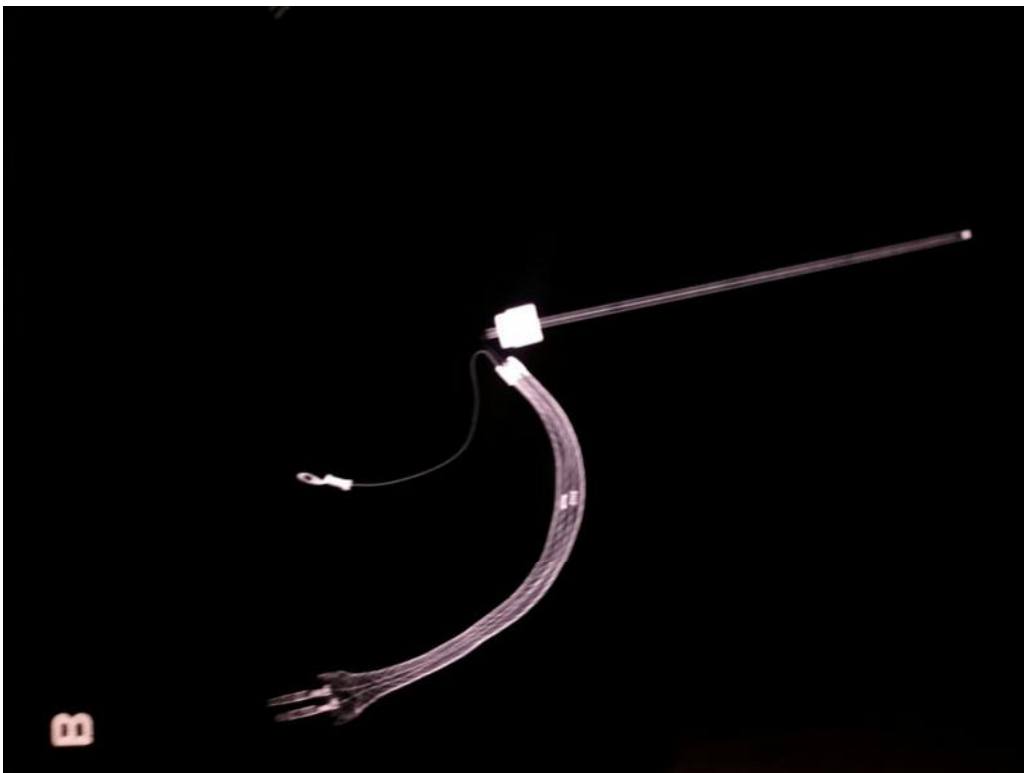


Figure E.43.—Planar view of heater assembly for Bulk Fluid Heater 2.

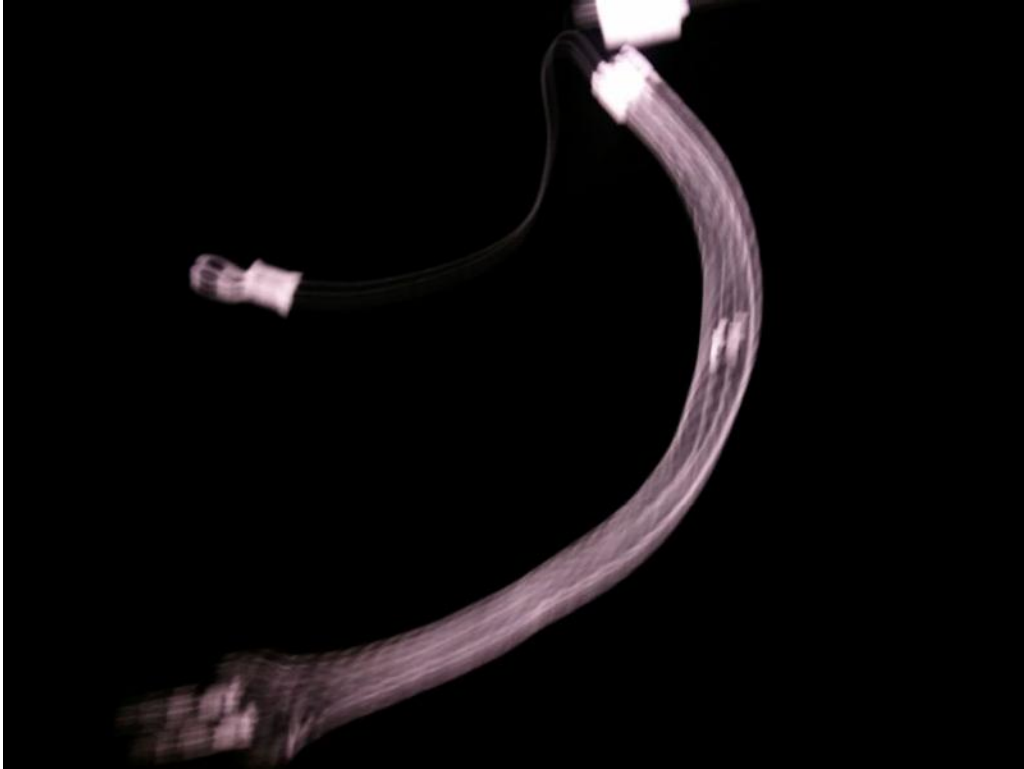


Figure E.44.—Wiring harness for Bulk Fluid Heater 2.

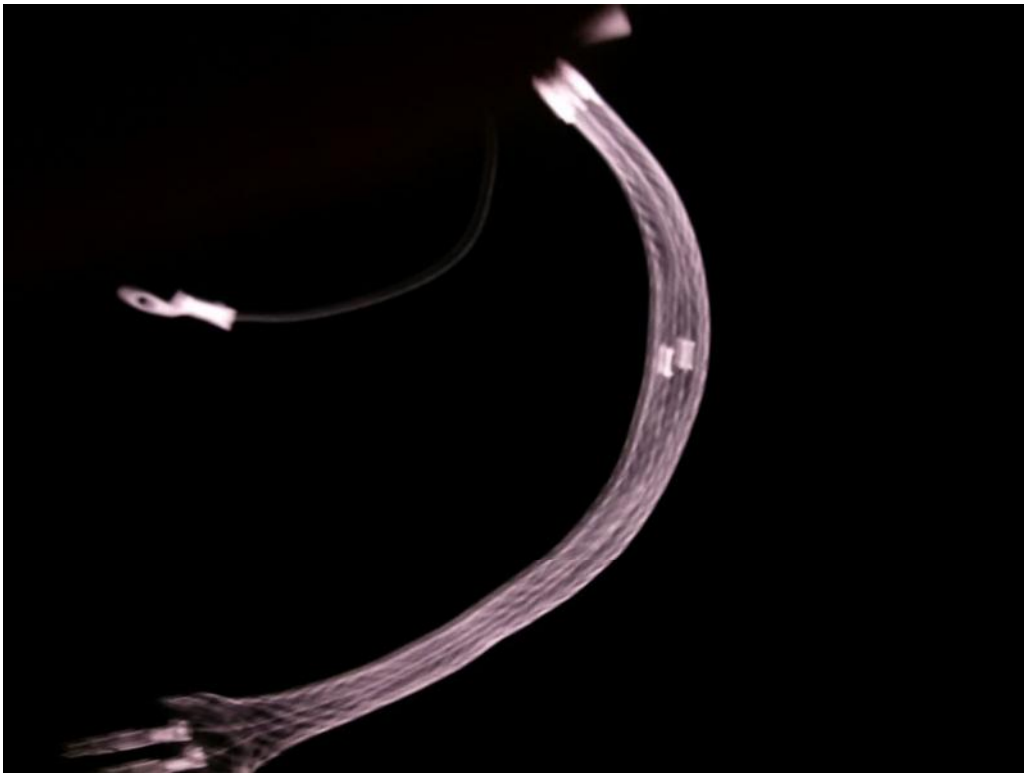


Figure E.45.—Wiring harness for Bulk Fluid Heater 2.



Figure E.46.—Connector for Bulk Fluid Heater 2.

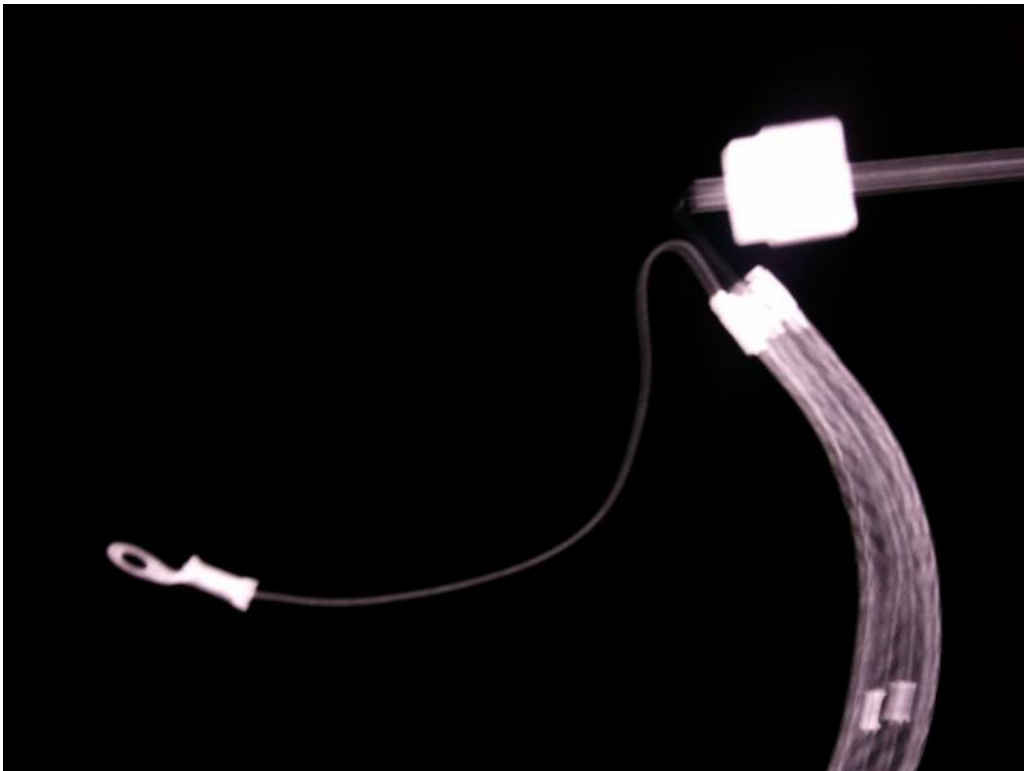


Figure E.47.—Grounding strap for Bulk Fluid Heater 2.



Figure E.48.—Heating element for Bulk Fluid Heater 2.

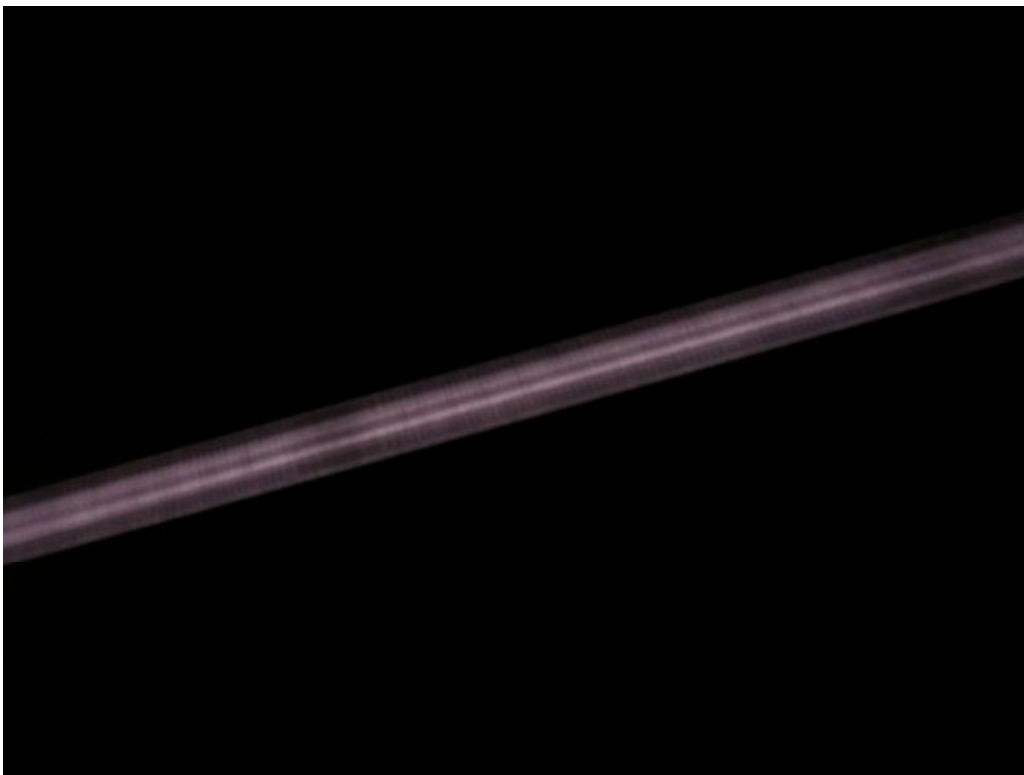


Figure E.49.—Close-up of heating element for Bulk Fluid Heater 2. Note irregularities.

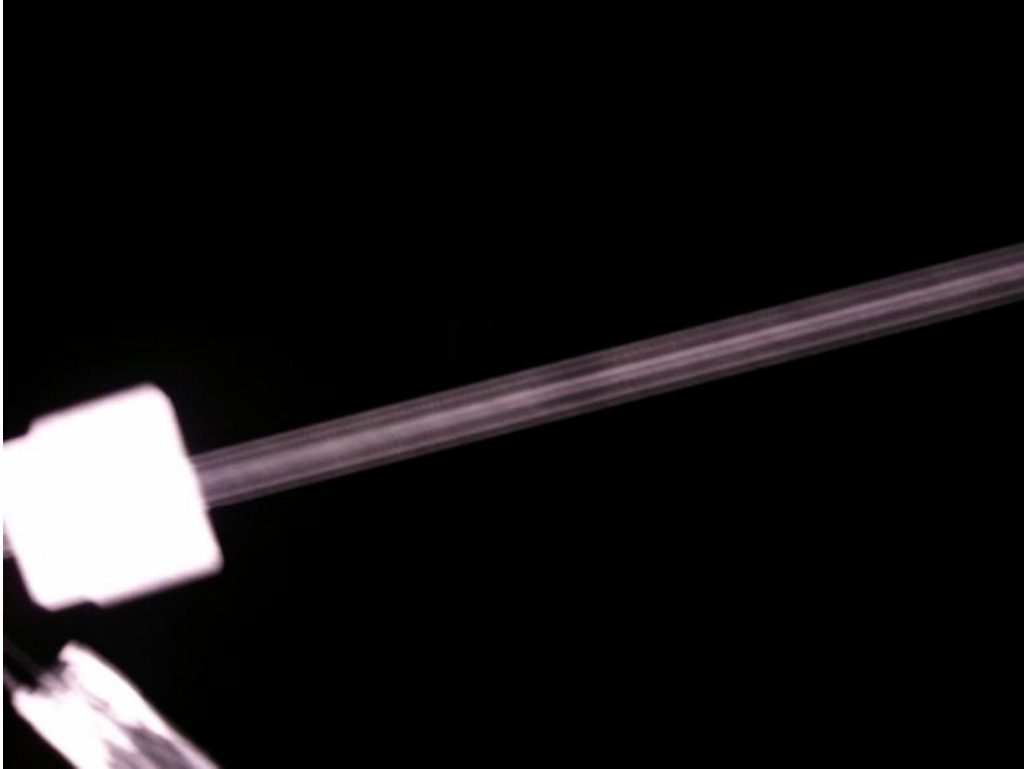


Figure E.50.—Close-up of heating element for Bulk Fluid Heater 2. Note irregularities.



Figure E.51.—Close-up of heating element for Bulk Fluid Heater 2. Note irregularities.



Figure E.52.—Close-up of heating element for Bulk Fluid Heater 2. Note irregularities.



Figure E.53.—Close-up of heating element for Bulk Fluid Heater 2. Note irregularities.



Figure E.54.—Close-up of heating element for Bulk Fluid Heater 2.



Figure E.55.—Close-up of heating element for Bulk Fluid Heater 2.



Figure E.56.—Close-up of heating element for Bulk Fluid Heater 2. Note irregularities.

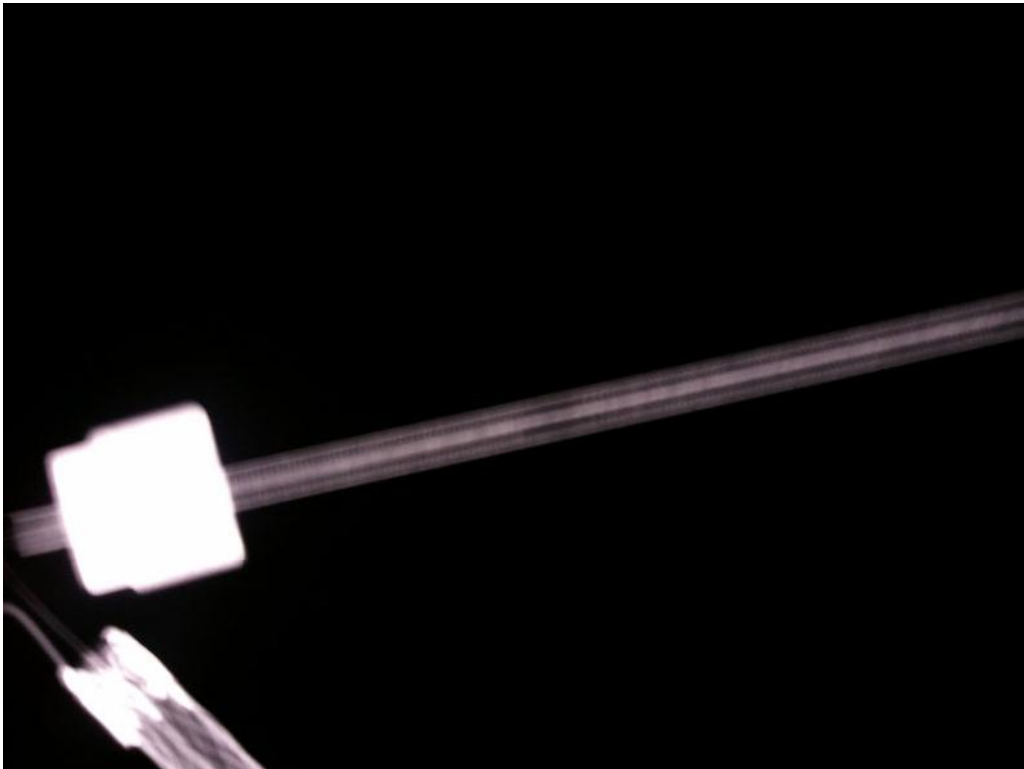


Figure E.57.—Close-up of heating element for Bulk Fluid Heater 2. Note irregularities.

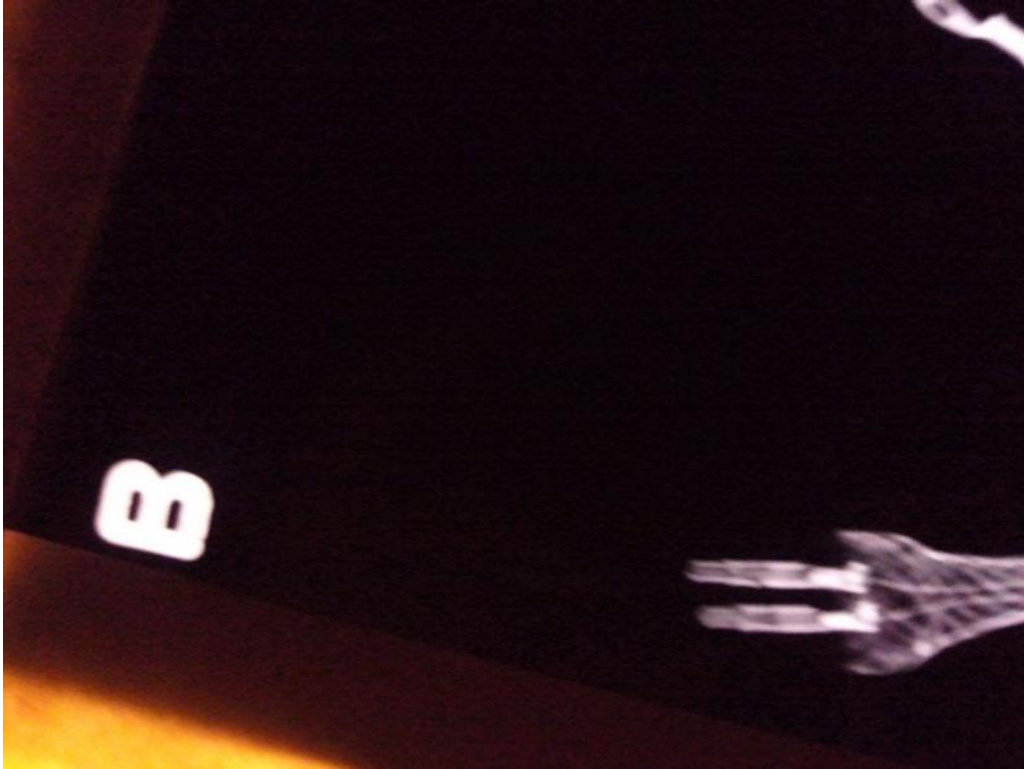


Figure E.58.—Connector for Bulk Fluid Heater 2.

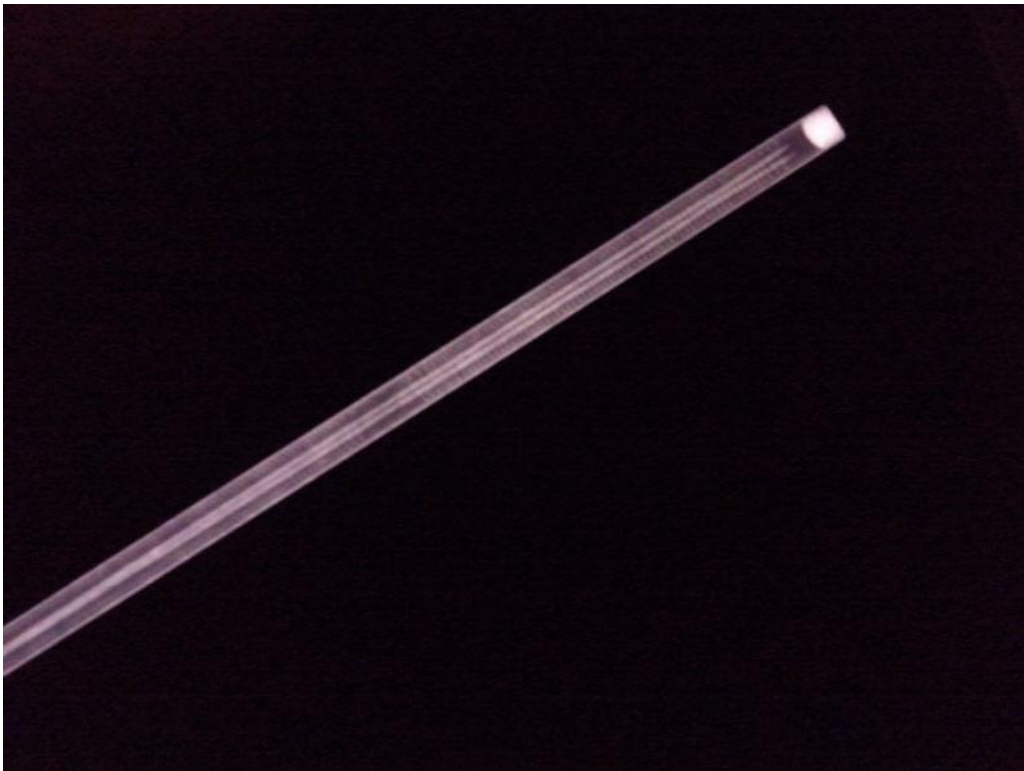


Figure E.59.— Close-up of end of heating element for Bulk Fluid Heater 2.



Figure E.60.—Close-up of heating element for Bulk Fluid Heater 2.



Figure E.61.—Close-up of heating element for Bulk Fluid Heater 2.



Figure E.62.—Close-up of heating element for Bulk Fluid Heater 2.

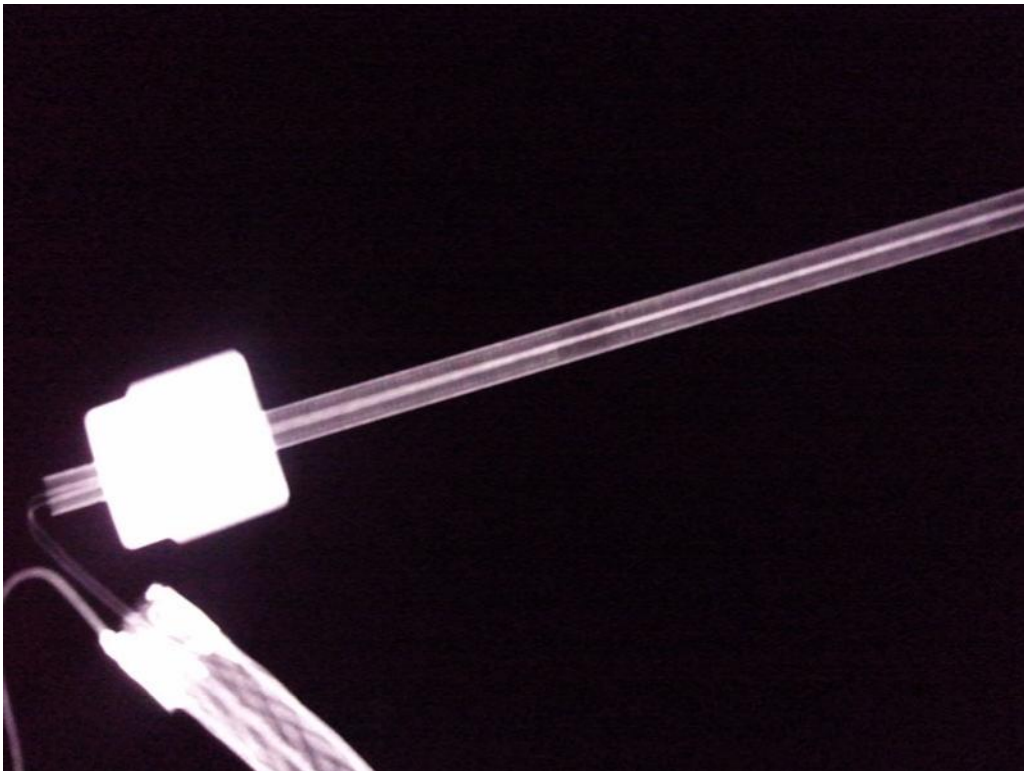


Figure E.63.—Connection to heating element for Bulk Fluid Heater 2.

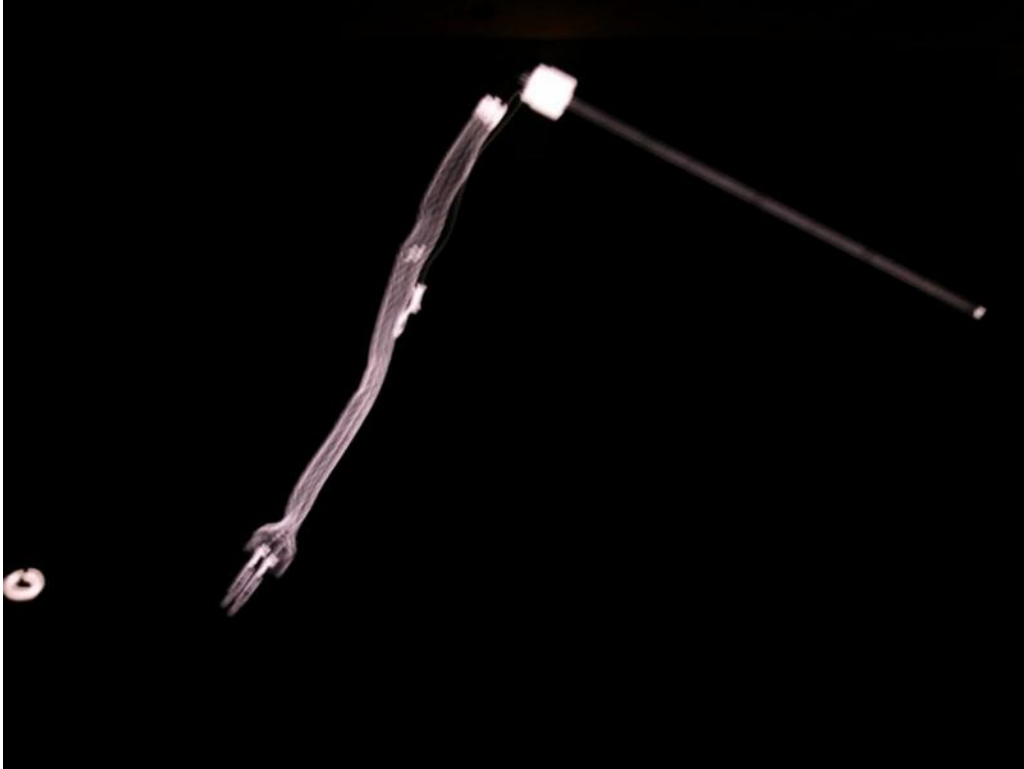


Figure E.64.—Planar view of Bulk Fluid Heater 3.



Figure E.65.—Planar view of Bulk Fluid Heater 3.



Figure E.66.—Planar view of Bulk Fluid Heater 3.

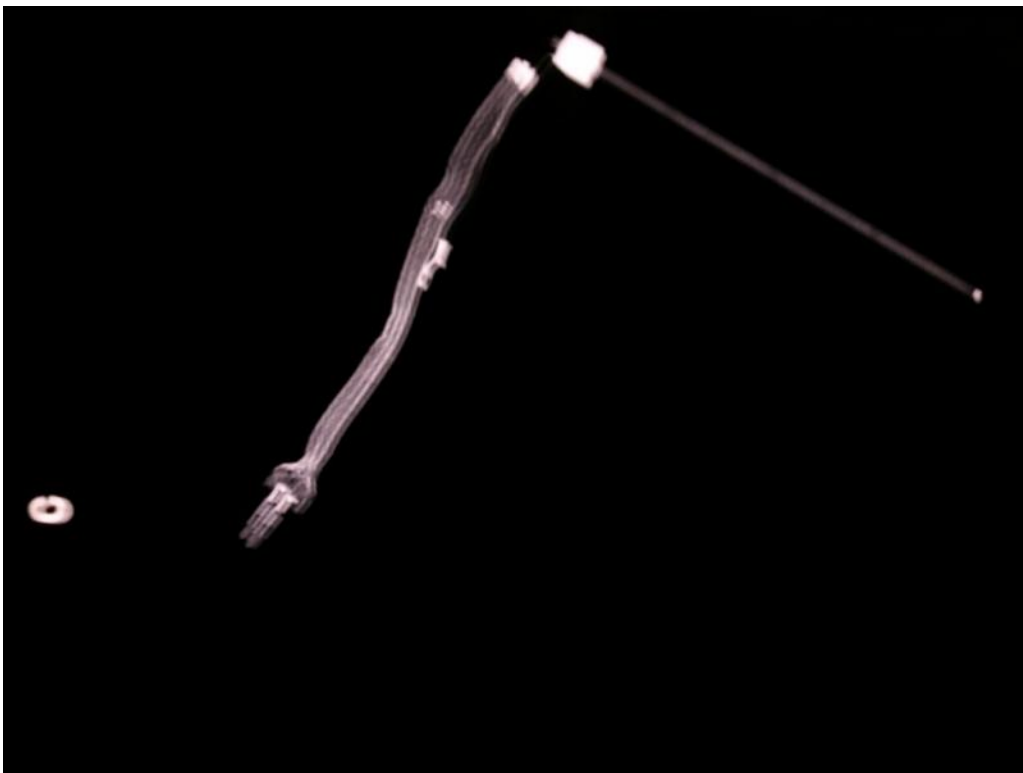


Figure E.67.—Planar view of Bulk Fluid Heater 3.



Figure E.68.—Wiring harness for Bulk Fluid Heater 3.

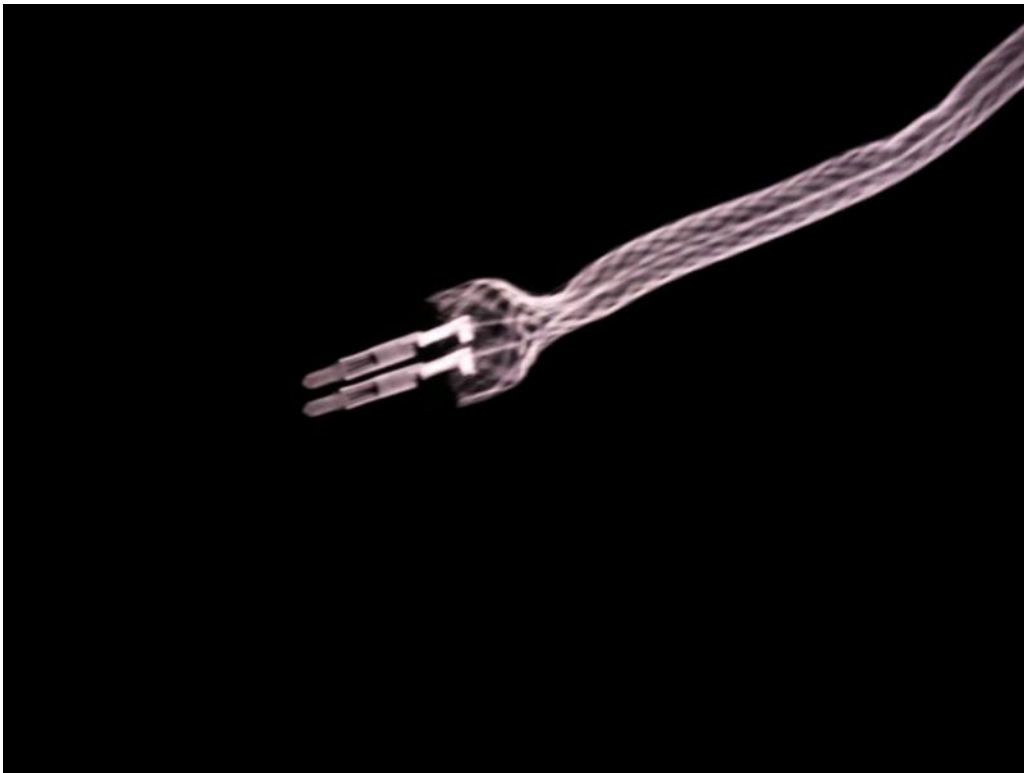


Figure E.69.—Connector for Bulk Fluid Heater 3.

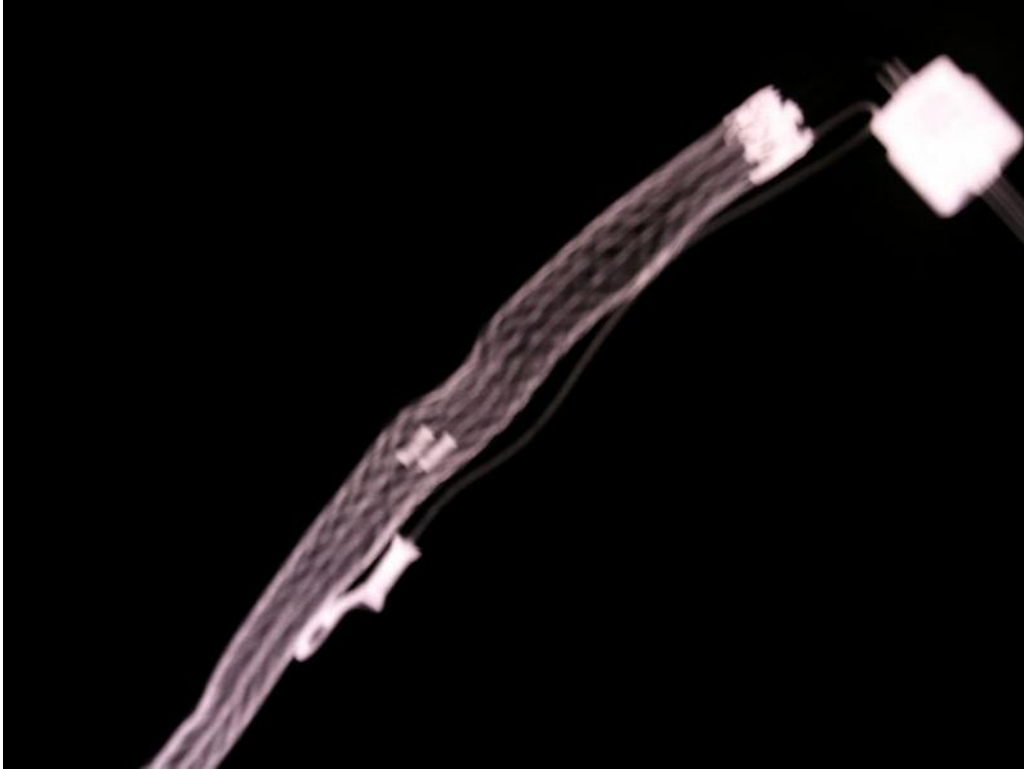


Figure E.70.—Grounding connection for Bulk Fluid Heater 3.

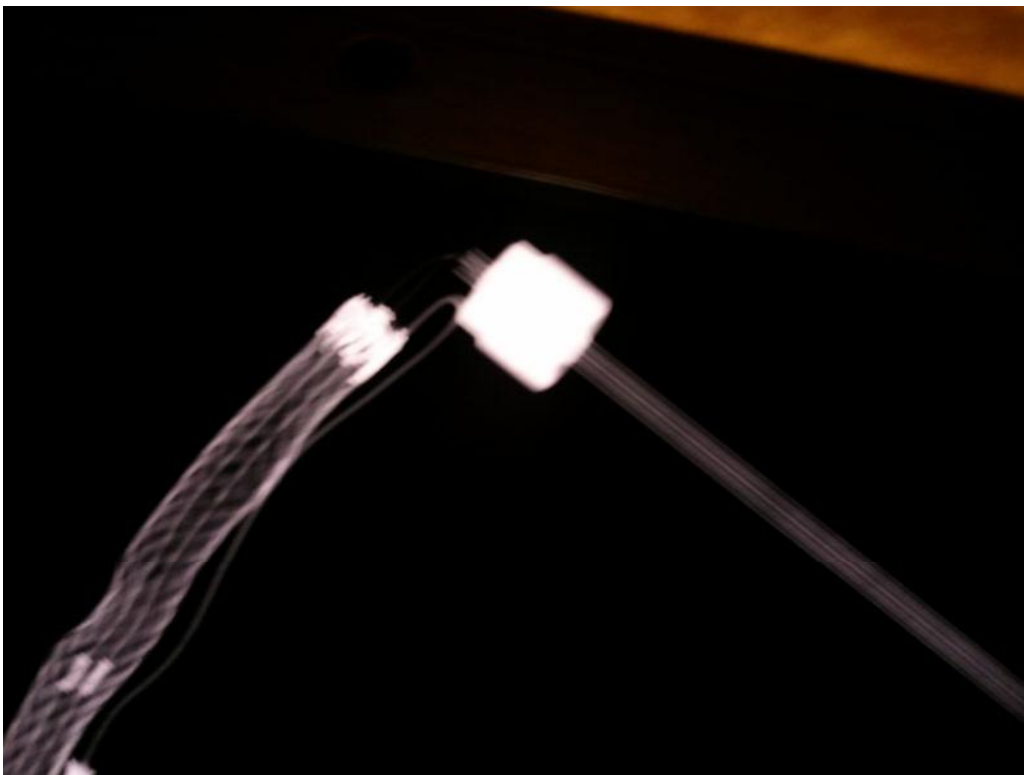


Figure E.71.—Connection to heating element for Bulk Fluid Heater 3.



Figure E.72.—Heating element for Bulk Fluid Heater 3. Note irregularities.



Figure E.73.—Heating element for Bulk Fluid Heater 3. Note irregularities.

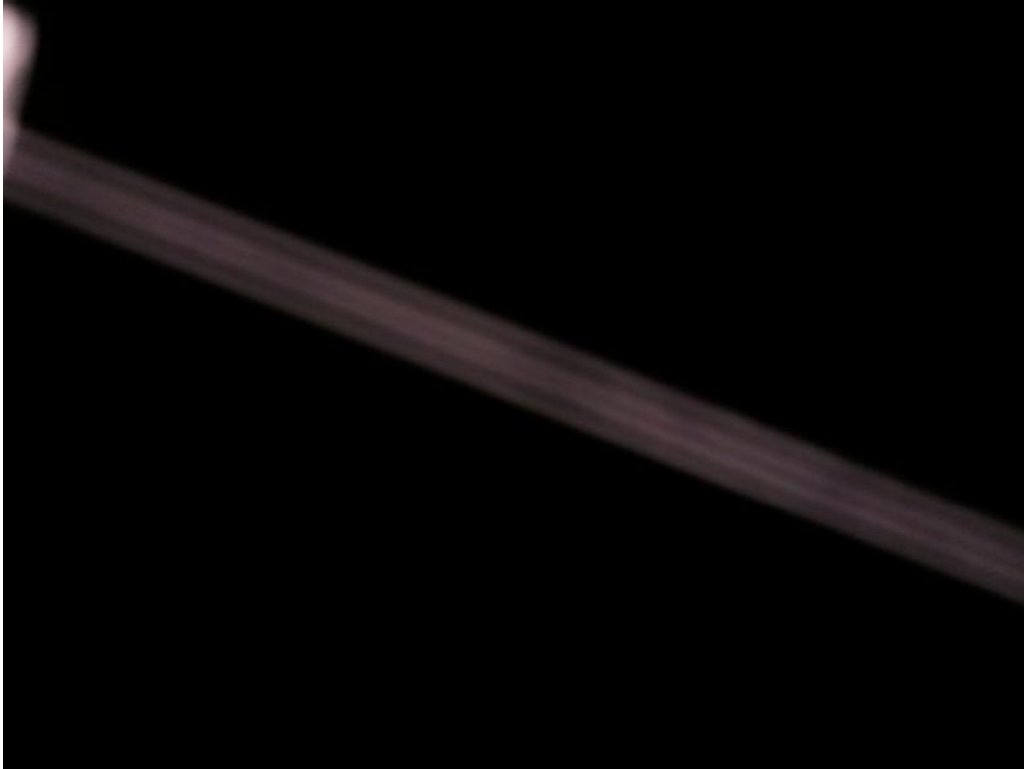


Figure E.74.—Heating element for Bulk Fluid Heater 3. Note irregularities.

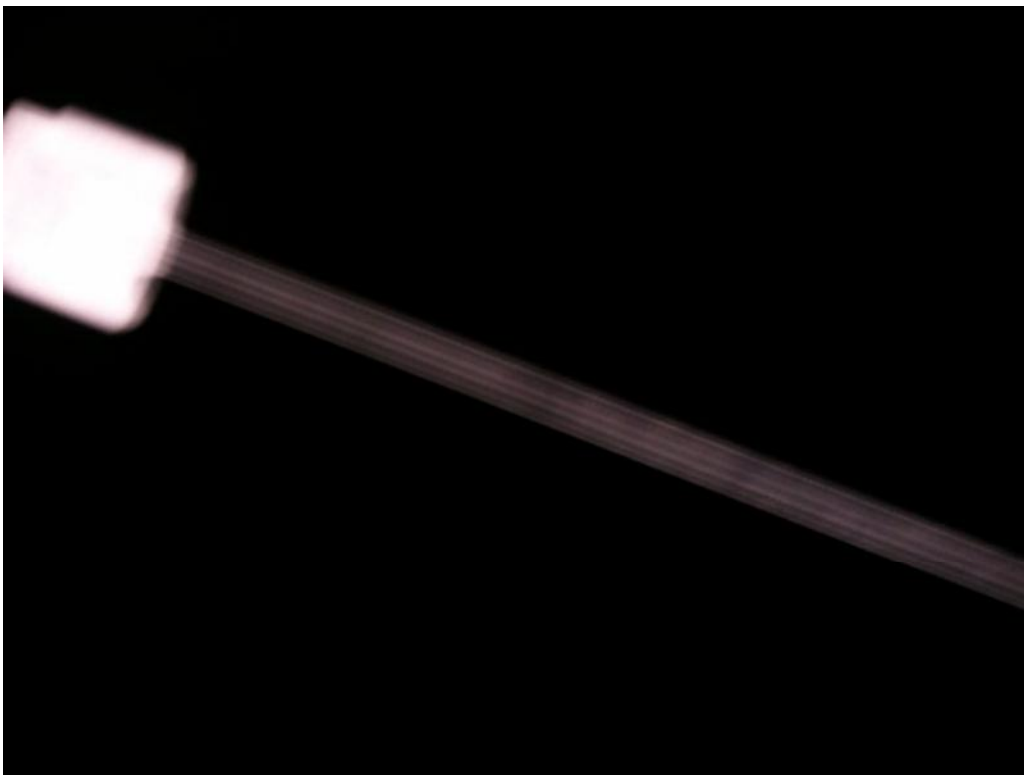


Figure E.75.—Heating element for Bulk Fluid Heater 3. Note irregularities.



Figure E.76.—Close-up of heating element for Bulk Fluid Heater 3. Note irregularities.

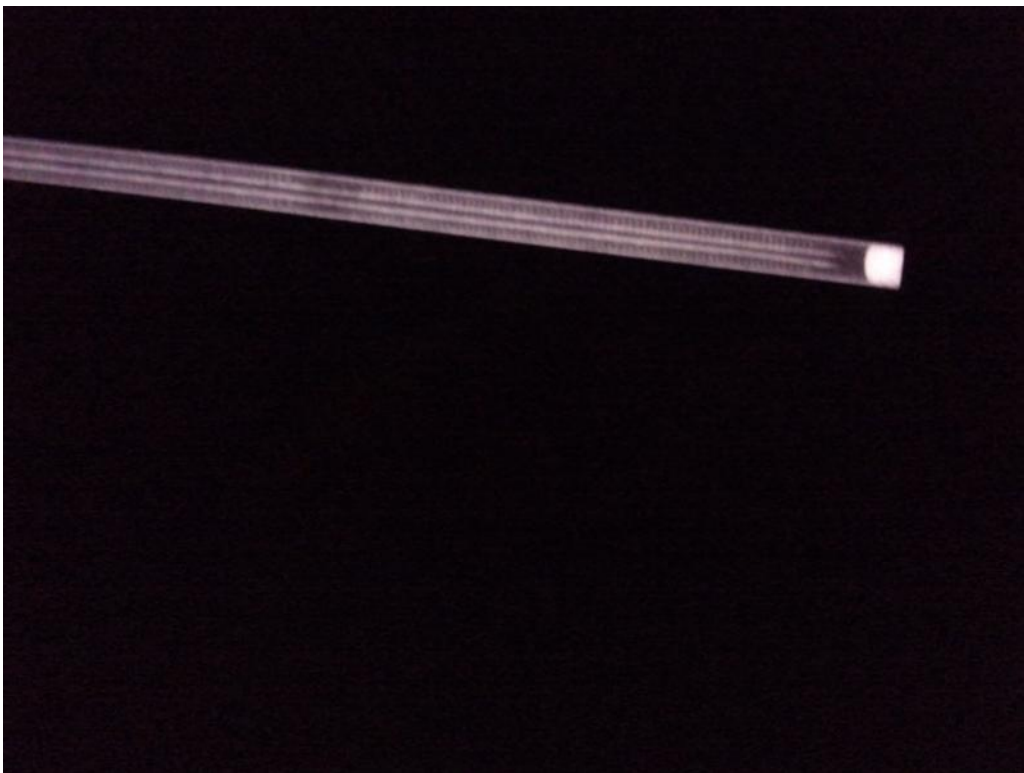


Figure E.77.—Close-up of heating element for Bulk Fluid Heater 3. Note irregularities.

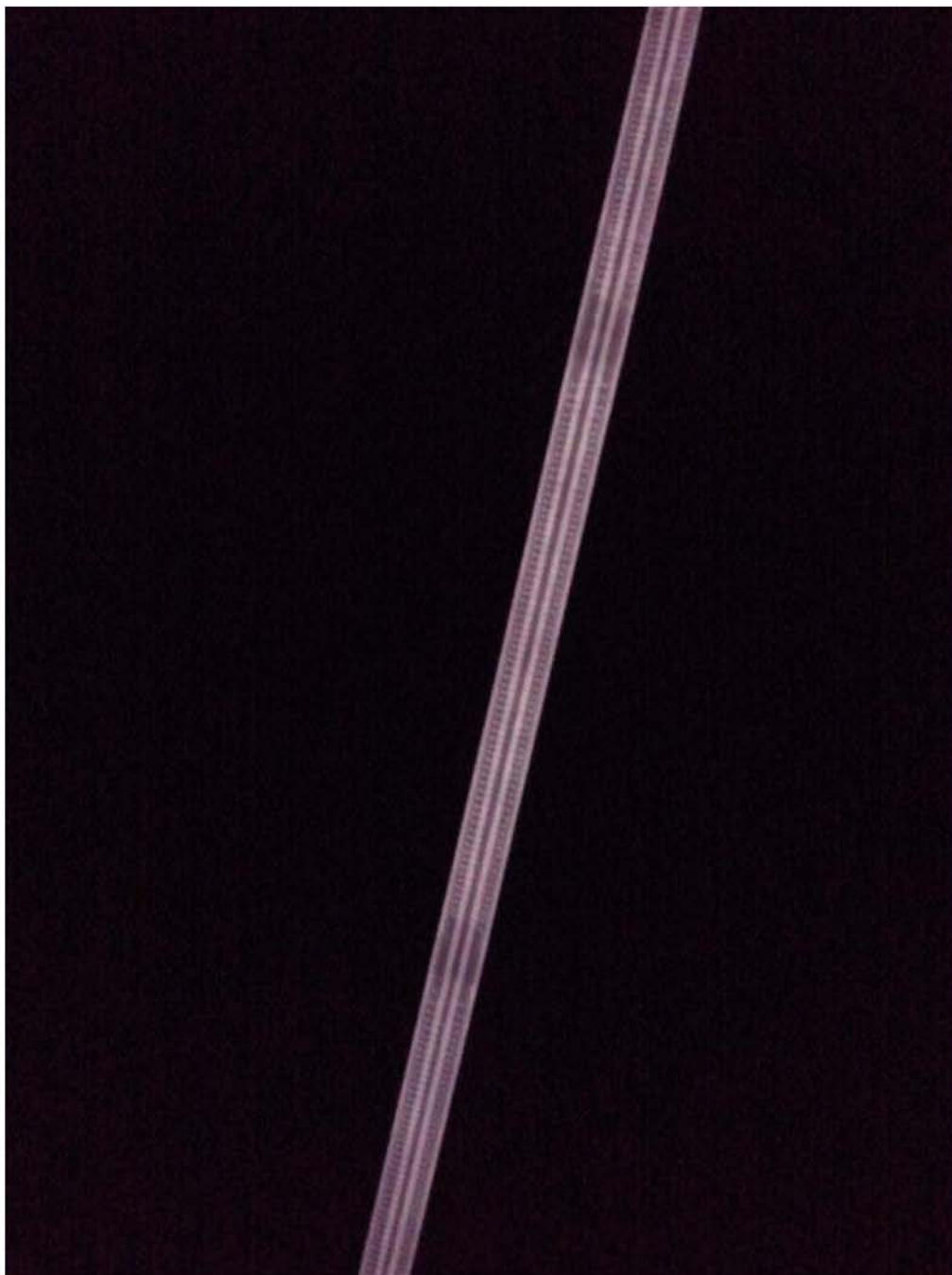


Figure E.78.—Close-up of heating element for Bulk Fluid Heater 3. Note irregularities.

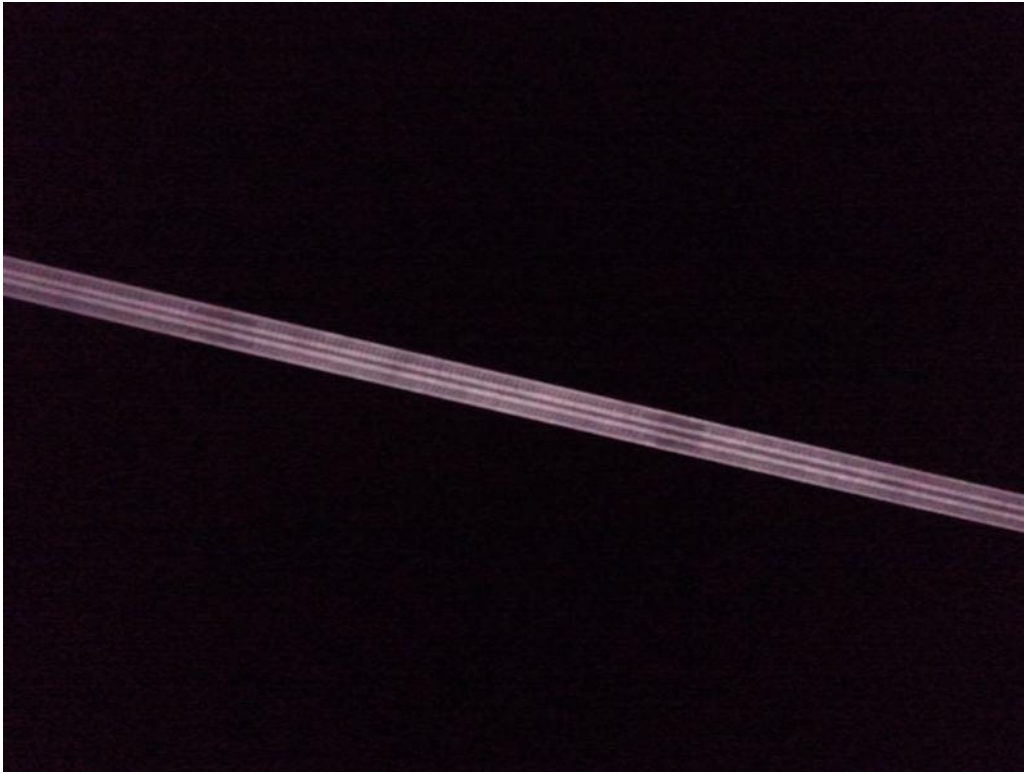


Figure E.79.—Close-up of heating element for Bulk Fluid Heater 3. Note irregularities.

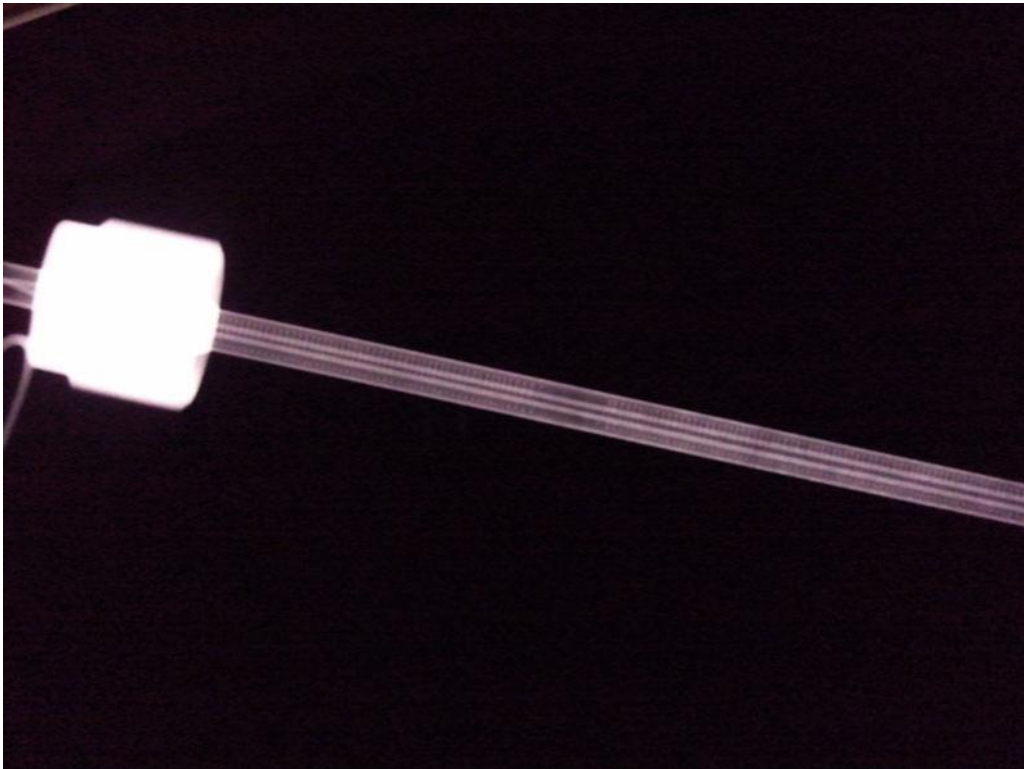


Figure E.80.—Close-up of heating element for Bulk Fluid Heater 3. Note irregularities.

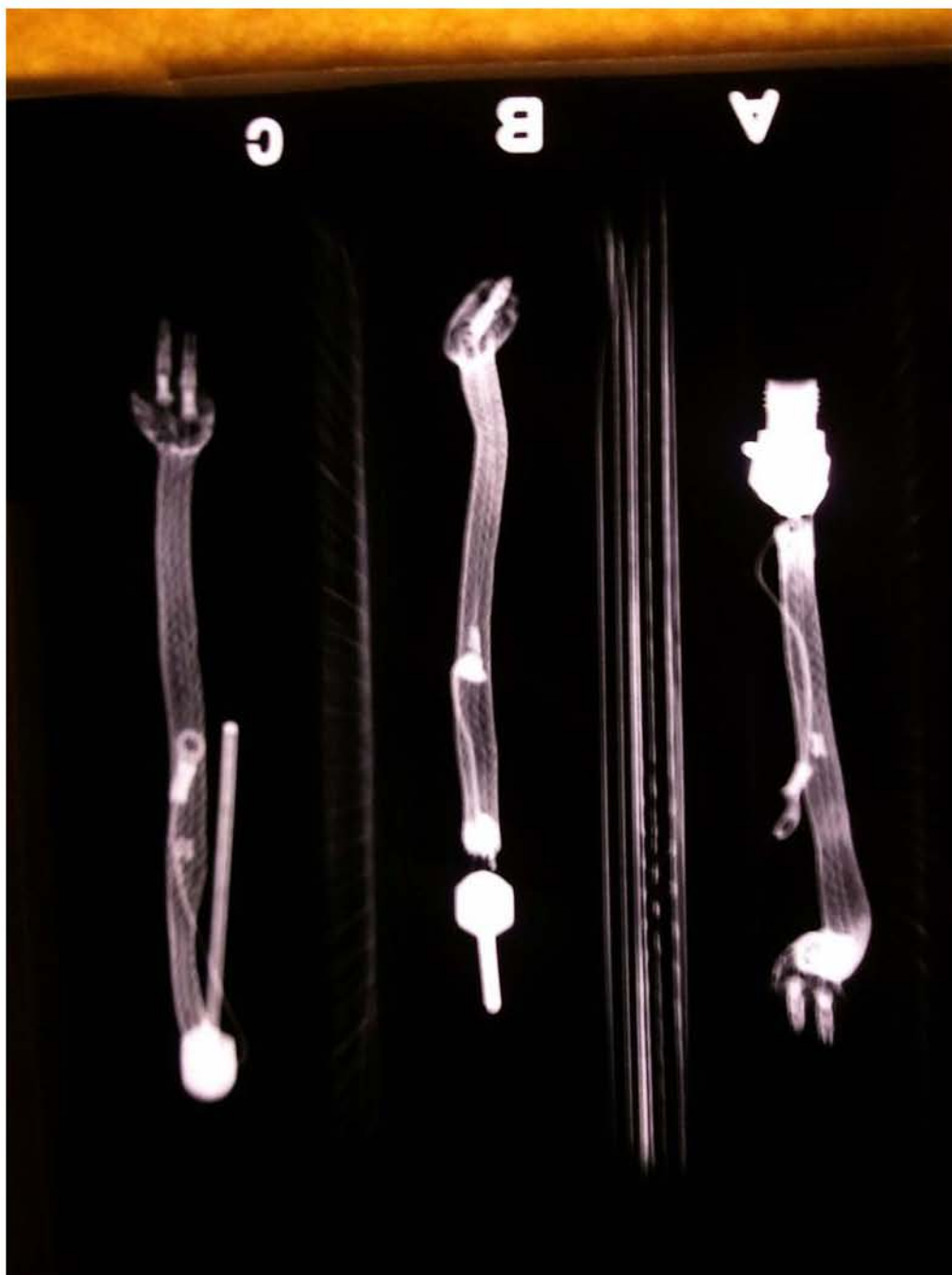


Figure E.81.—Wiring harness for Bulk Fluid Heaters.

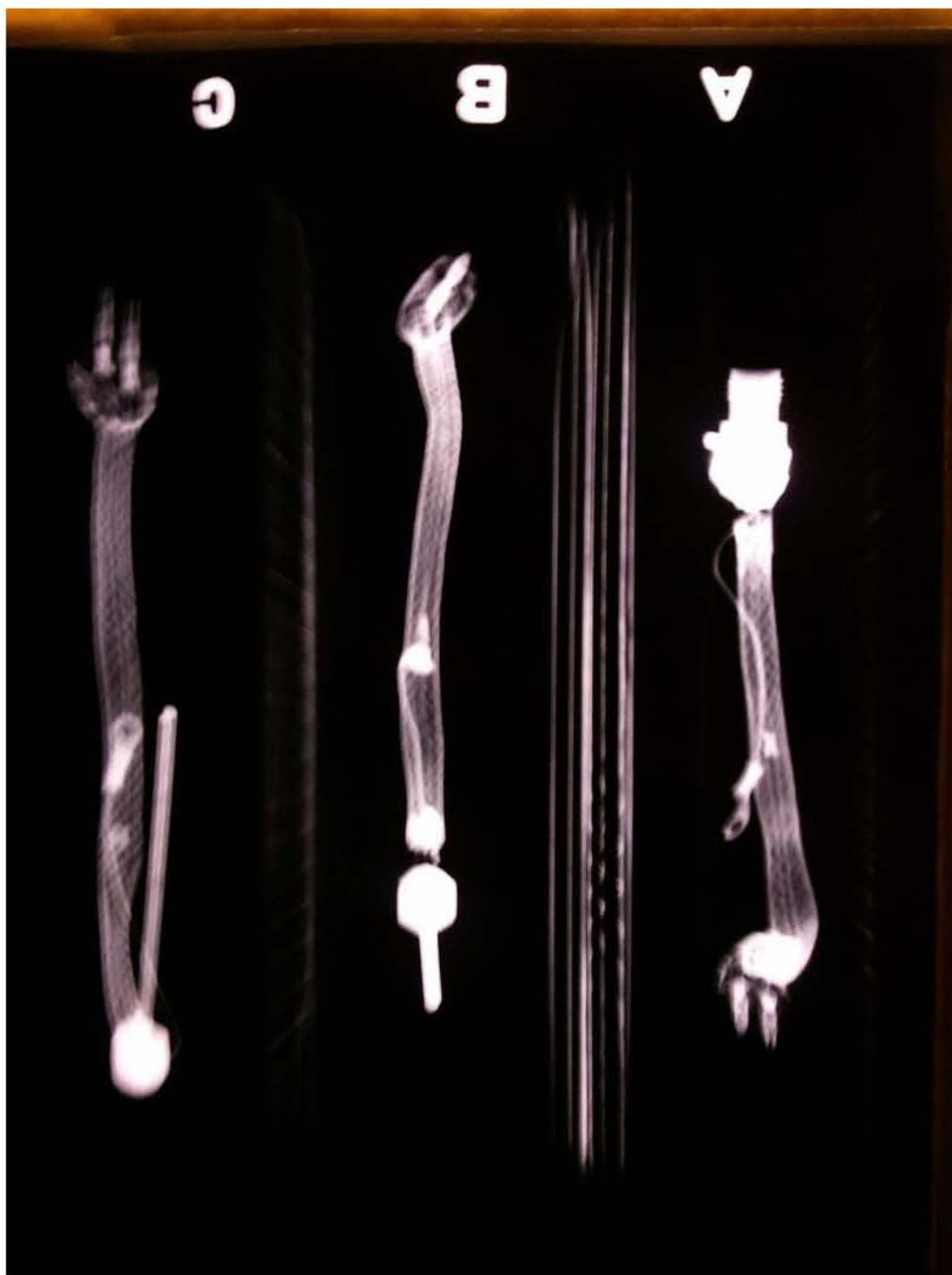


Figure E.82.— Wiring harness for Bulk Fluid Heaters.

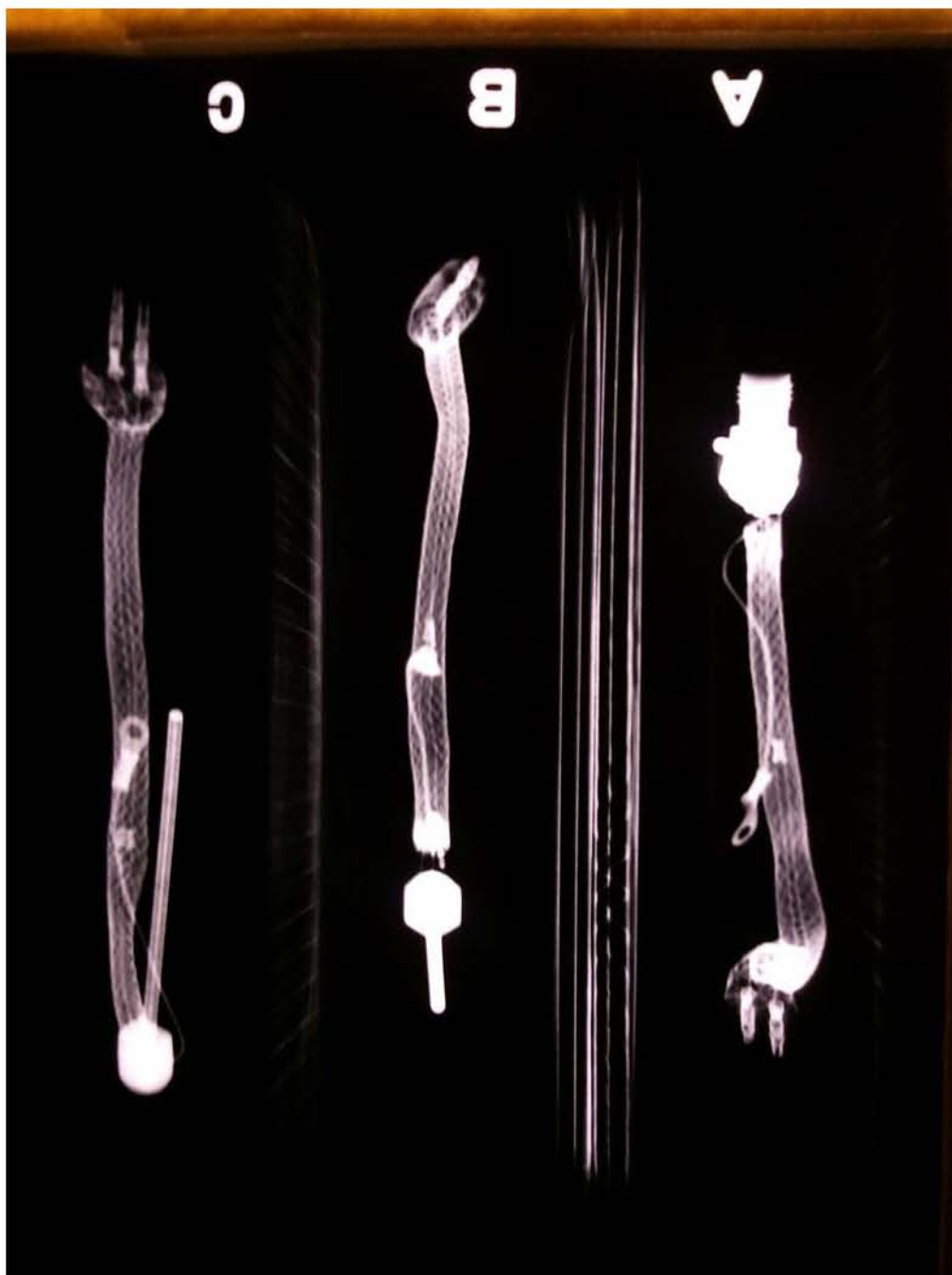


Figure E.83.—Wiring harness for Bulk Fluid Heaters.

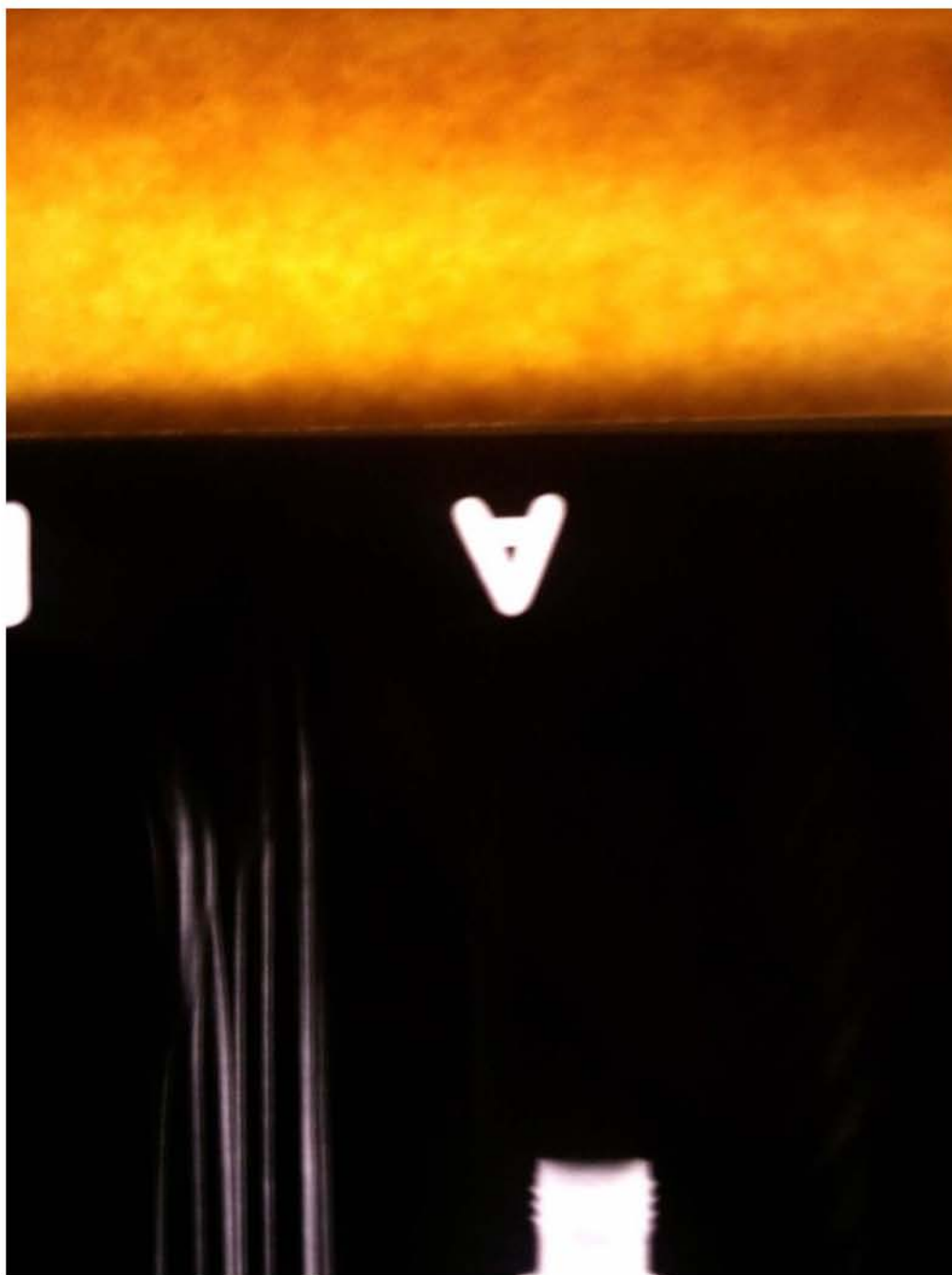


Figure E.84.— Power connection to heating element for Bulk Fluid Heater 1.

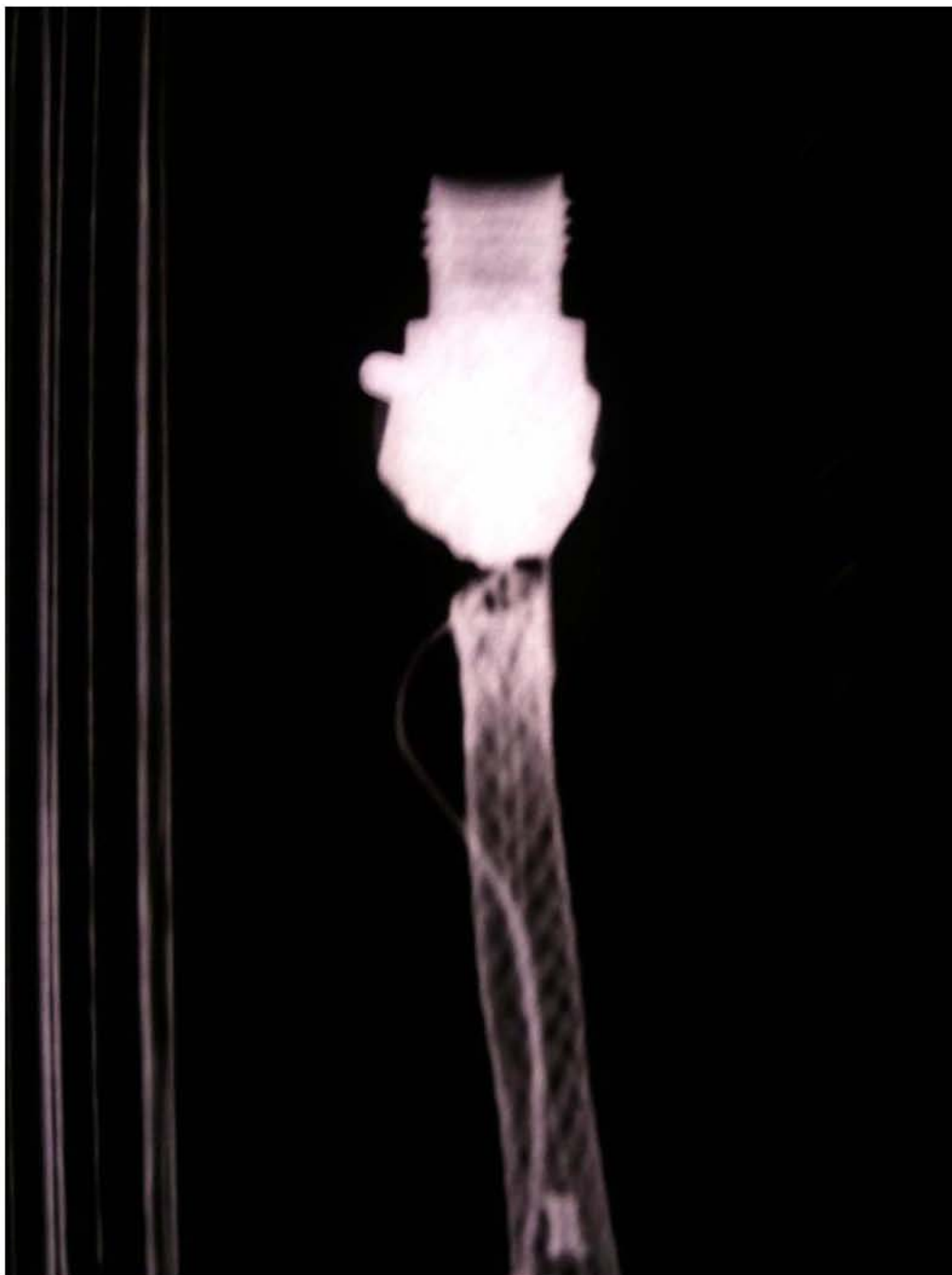


Figure E.85.—Power connection to heating element for Bulk Fluid Heater 1.

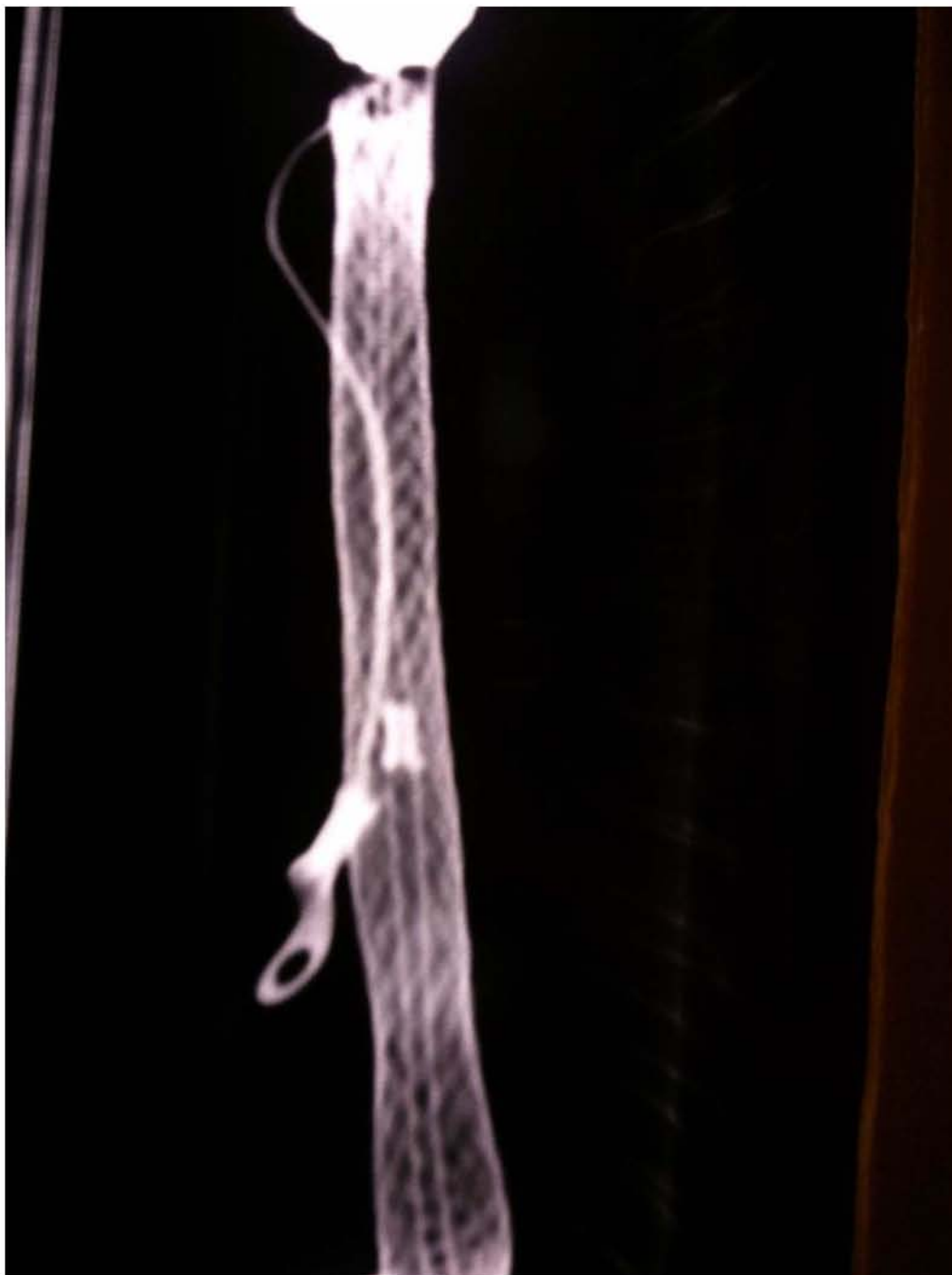


Figure E.86.—Grounding connection for Bulk Fluid Heater 1.

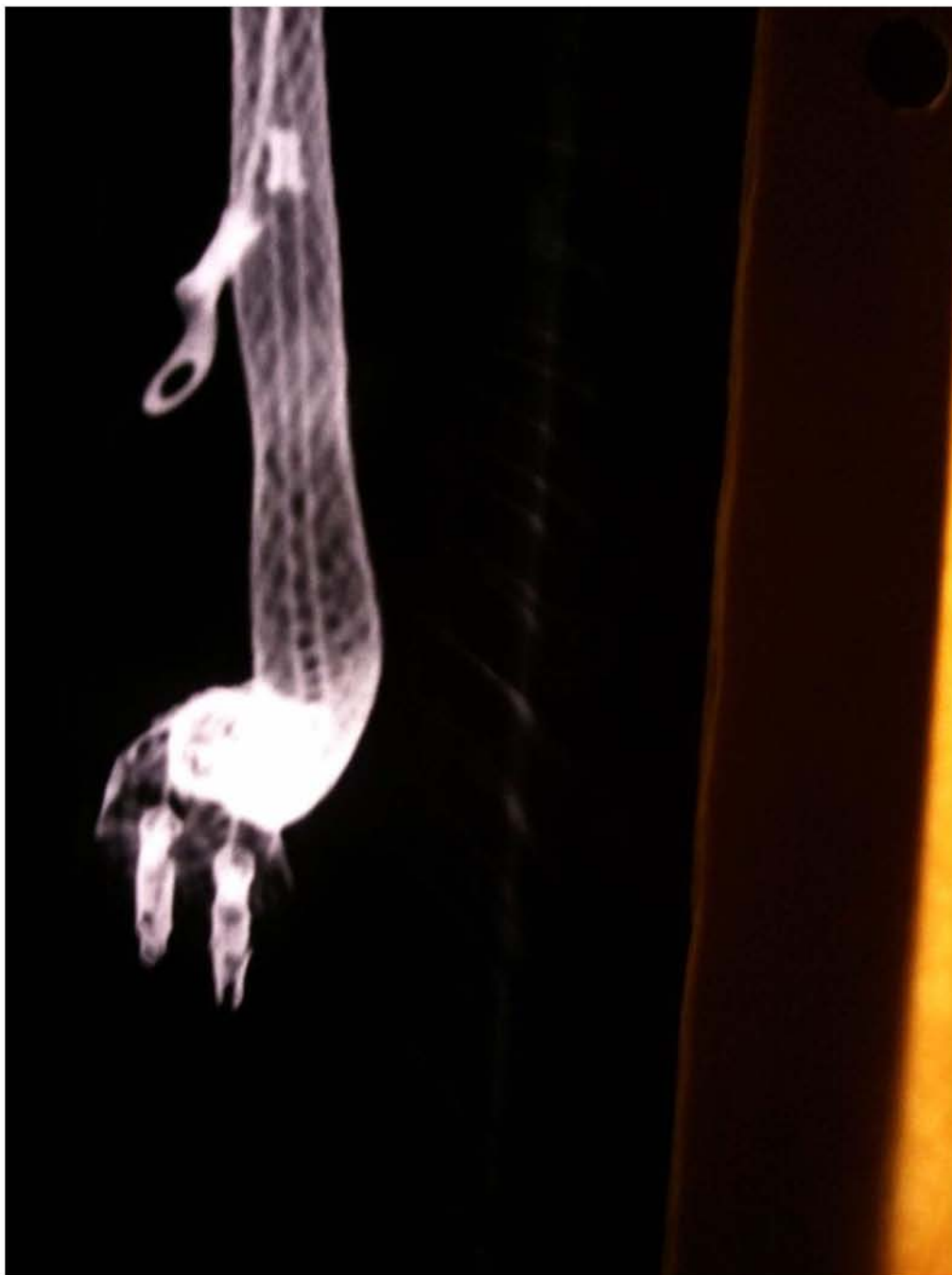


Figure E.87.—Power connectors for Bulk Fluid Heater 1.



Figure E.88.—Harness connection for Bulk Fluid Heater 2.



Figure E.89.—Power connection for Bulk Fluid Heater 2.

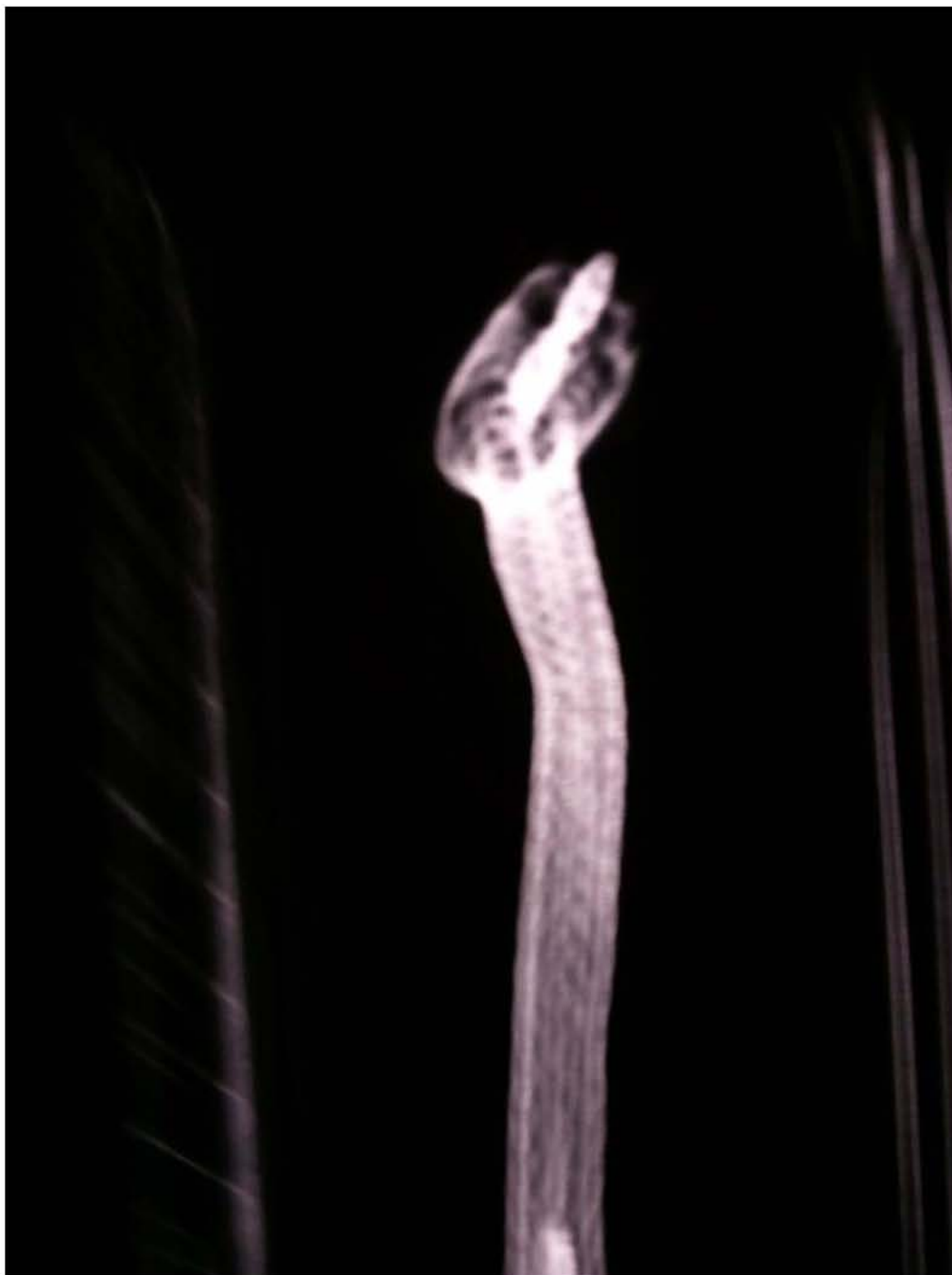


Figure E.90.—Power connection for Bulk Fluid Heater 2.

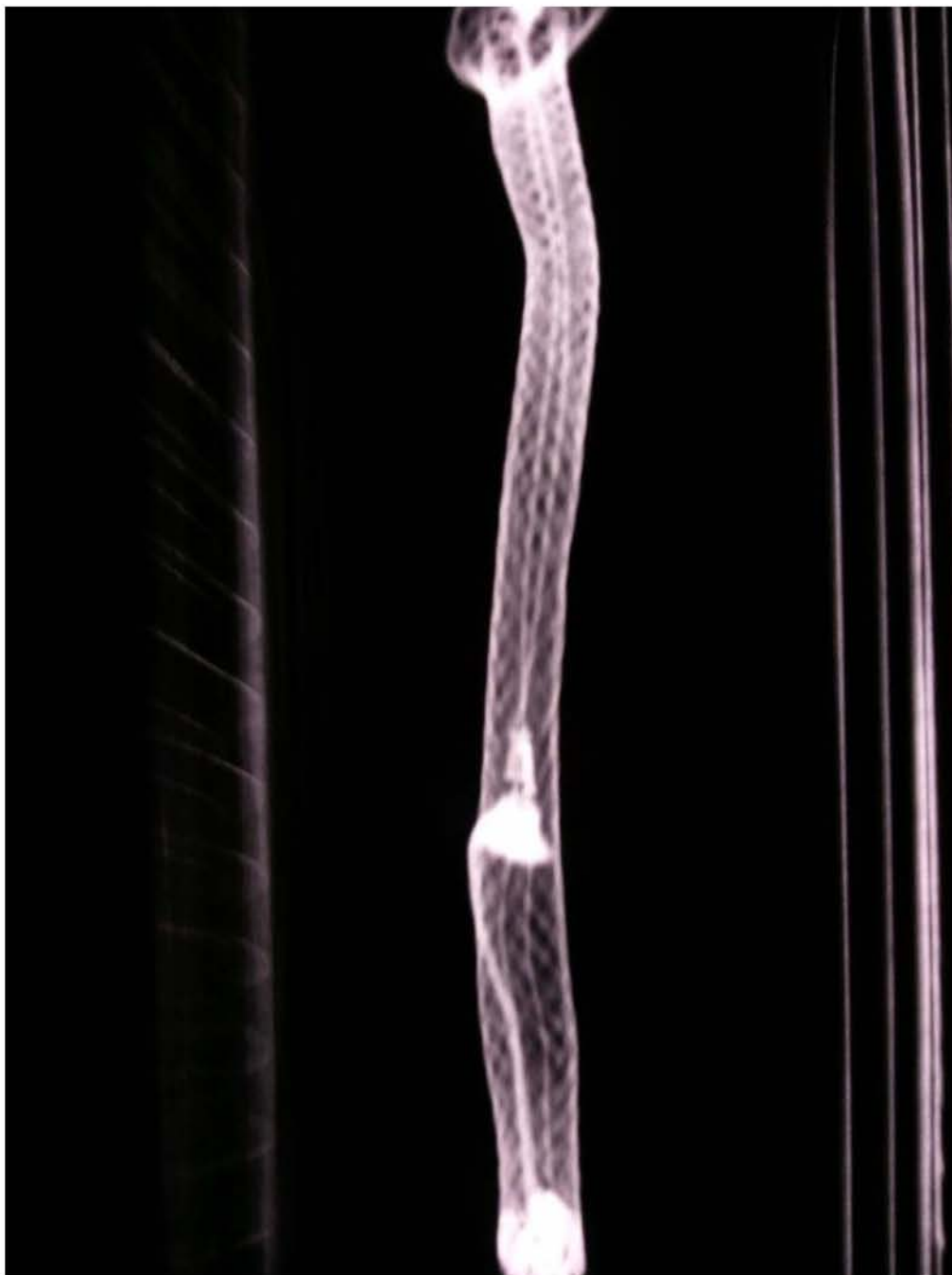


Figure E.91.—Wiring harness for Bulk Fluid Heater 2.

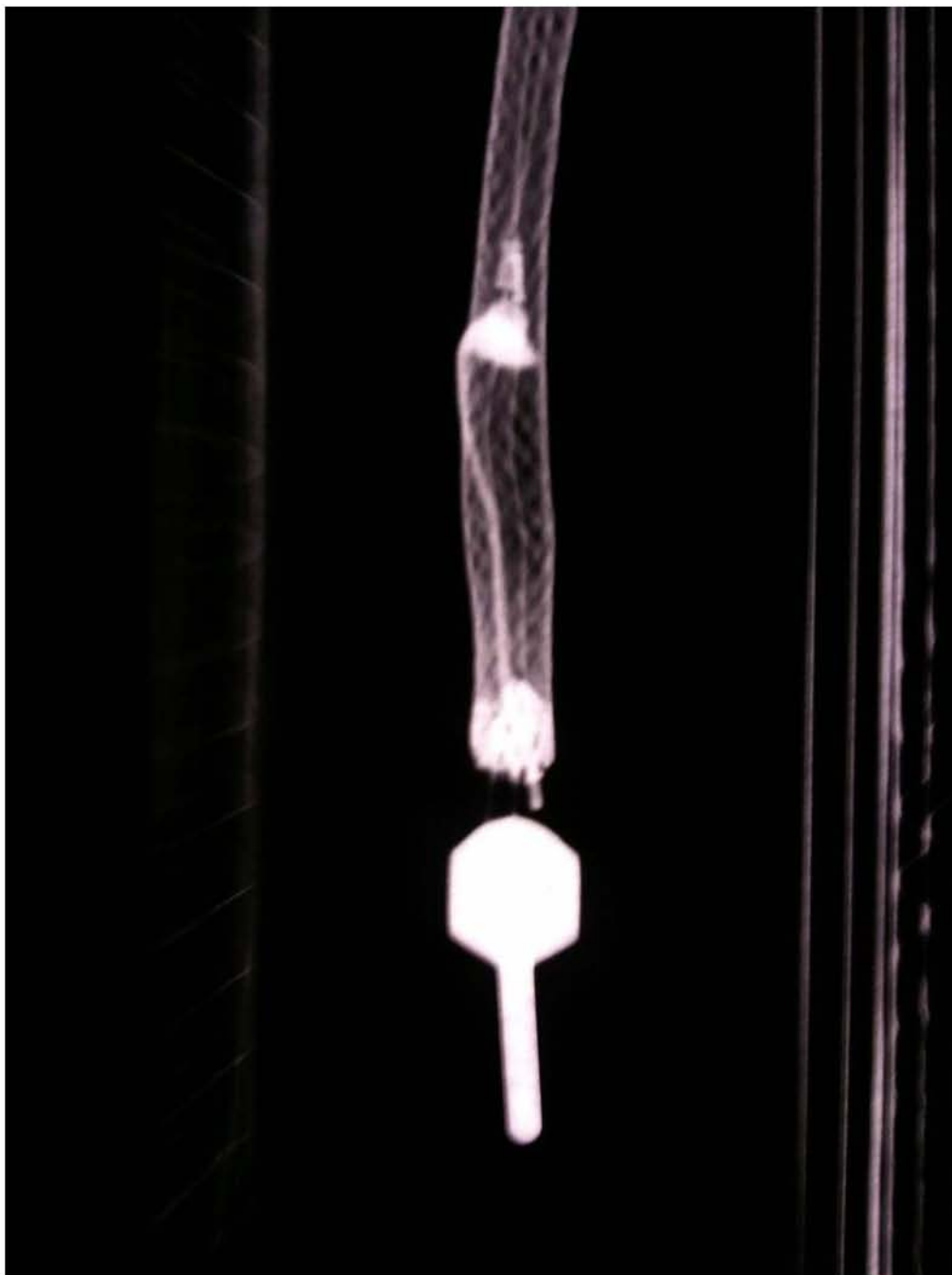


Figure E.92.—Power connection to heating element for Bulk Fluid Heater 2.

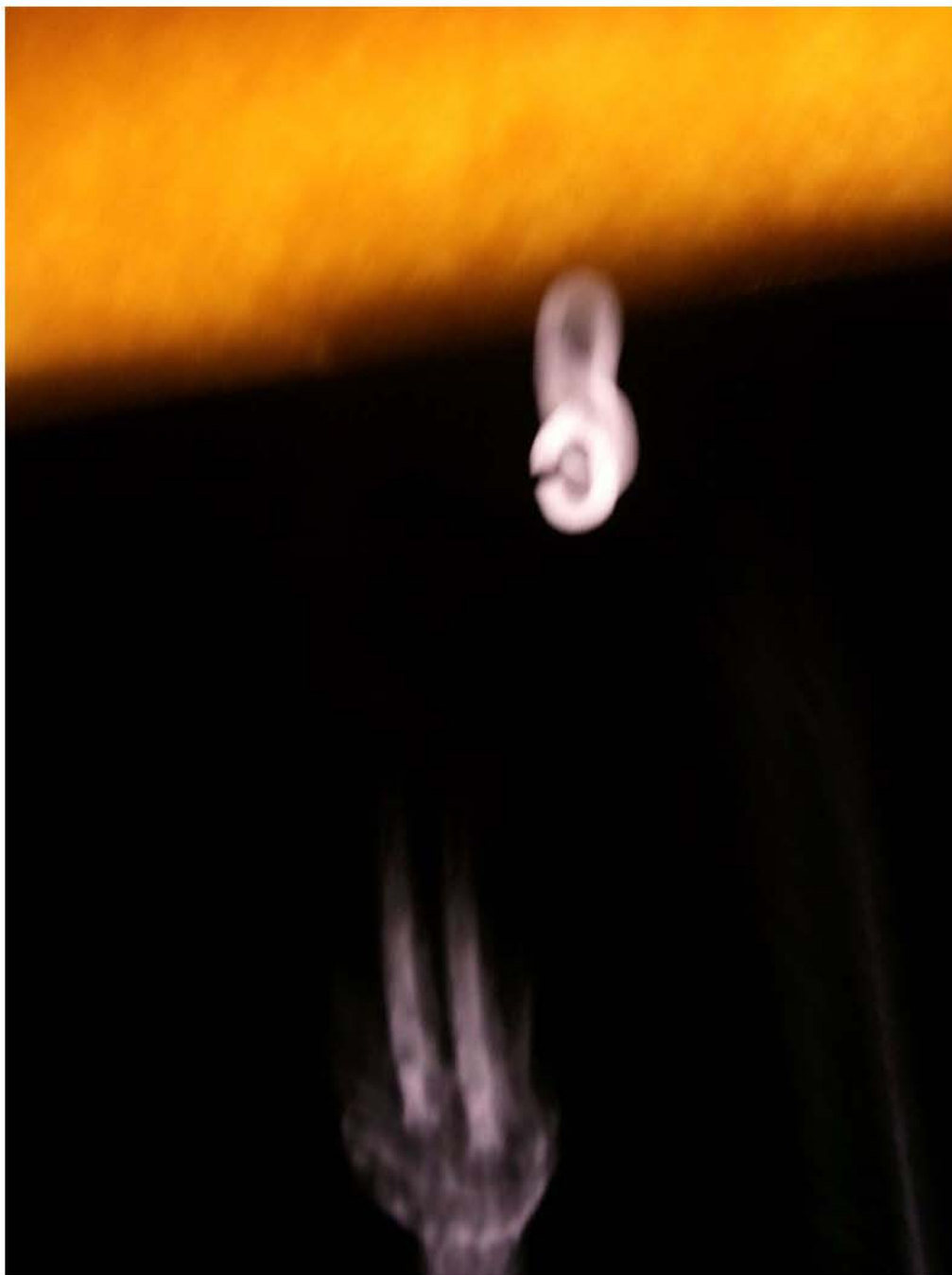


Figure E.93.—Power connection for Bulk Fluid Heater 3.

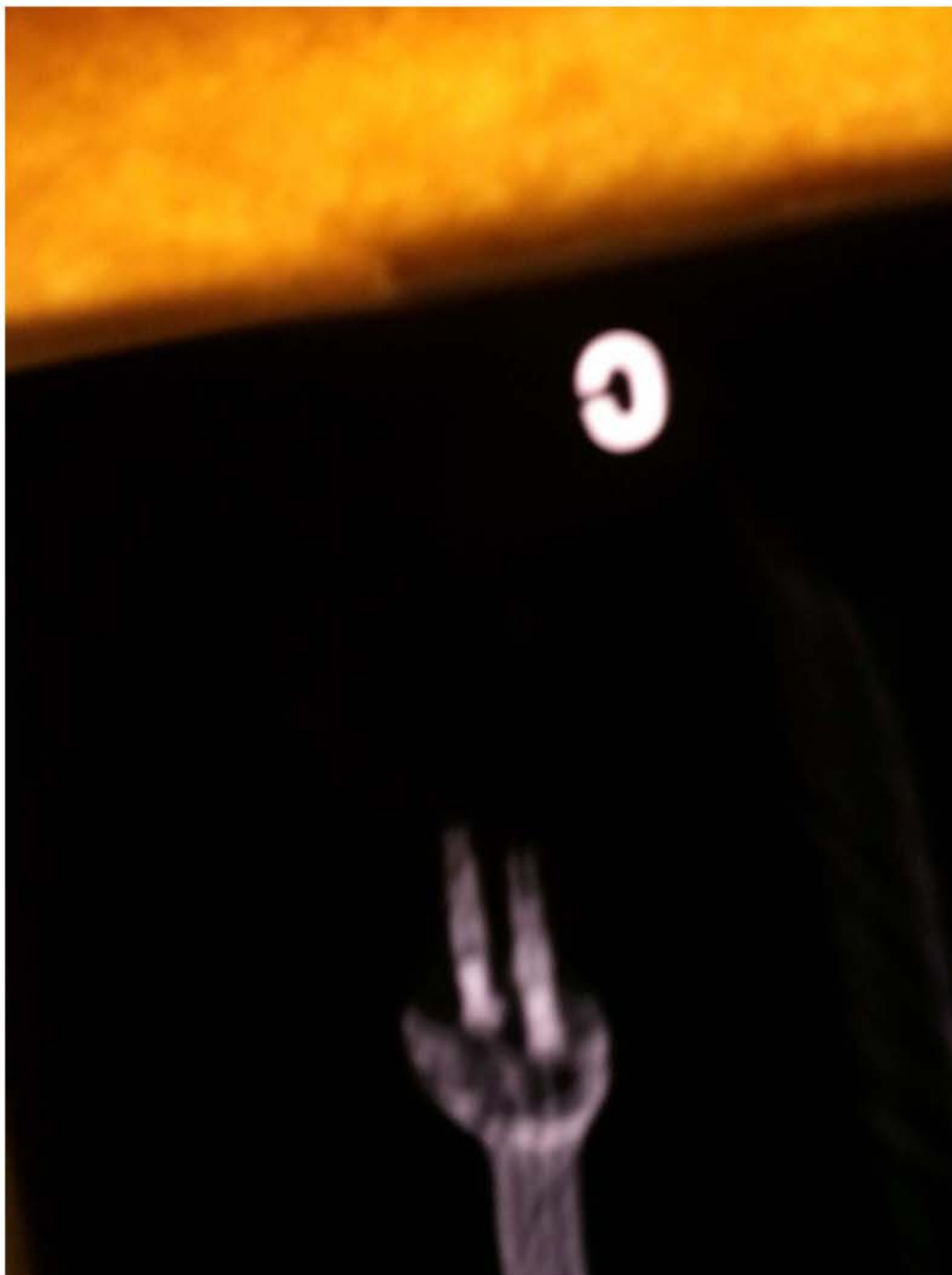


Figure E.94.—Power connection for Bulk Fluid Heater 3.



Figure E.95.—Grounding connection for Bulk Fluid Heater 3.



Figure E.96.—Power connection to heating element for Bulk Fluid Heater 3.

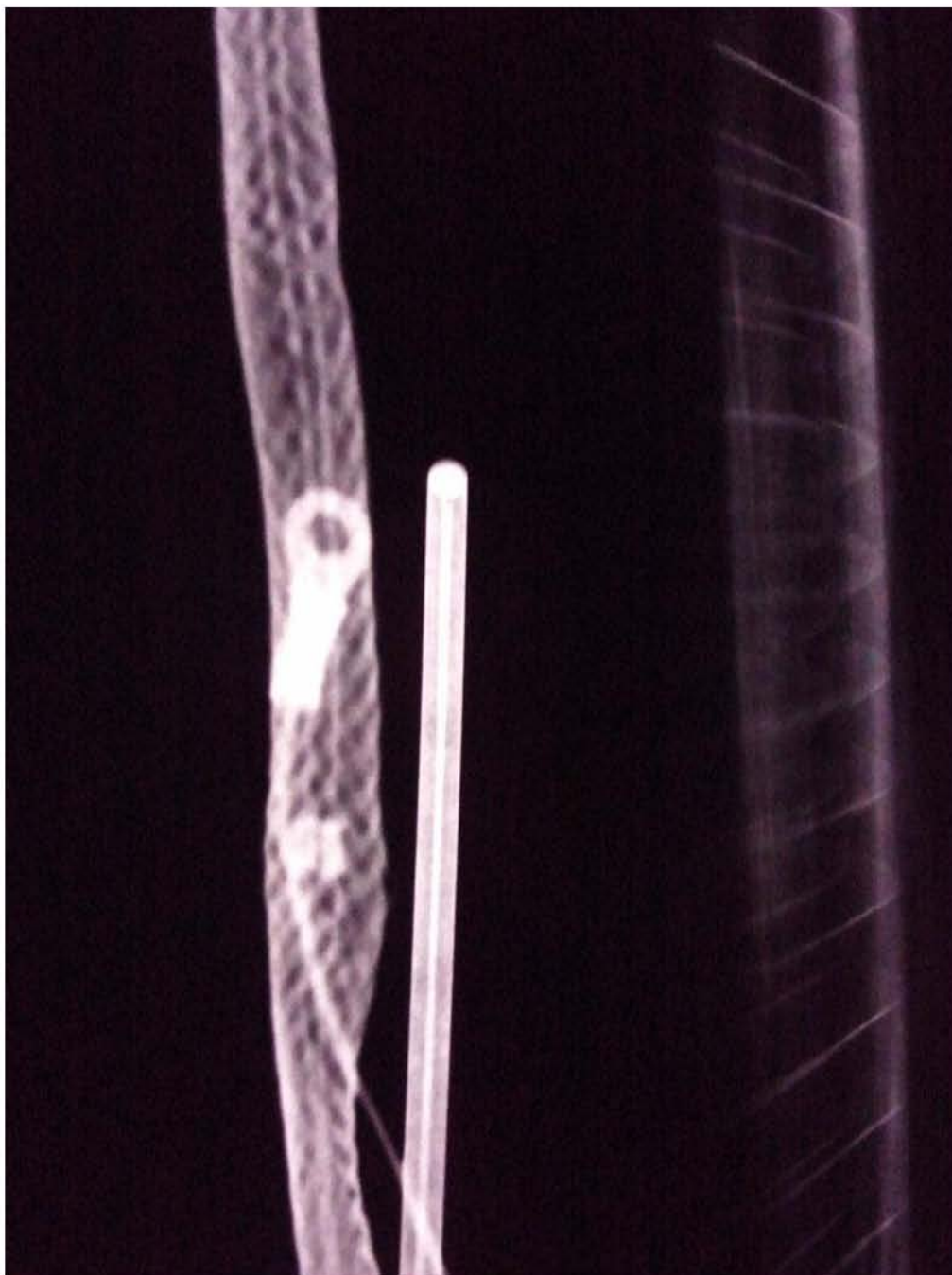


Figure E.97.—Grounding connection for Bulk Fluid Heater 3.

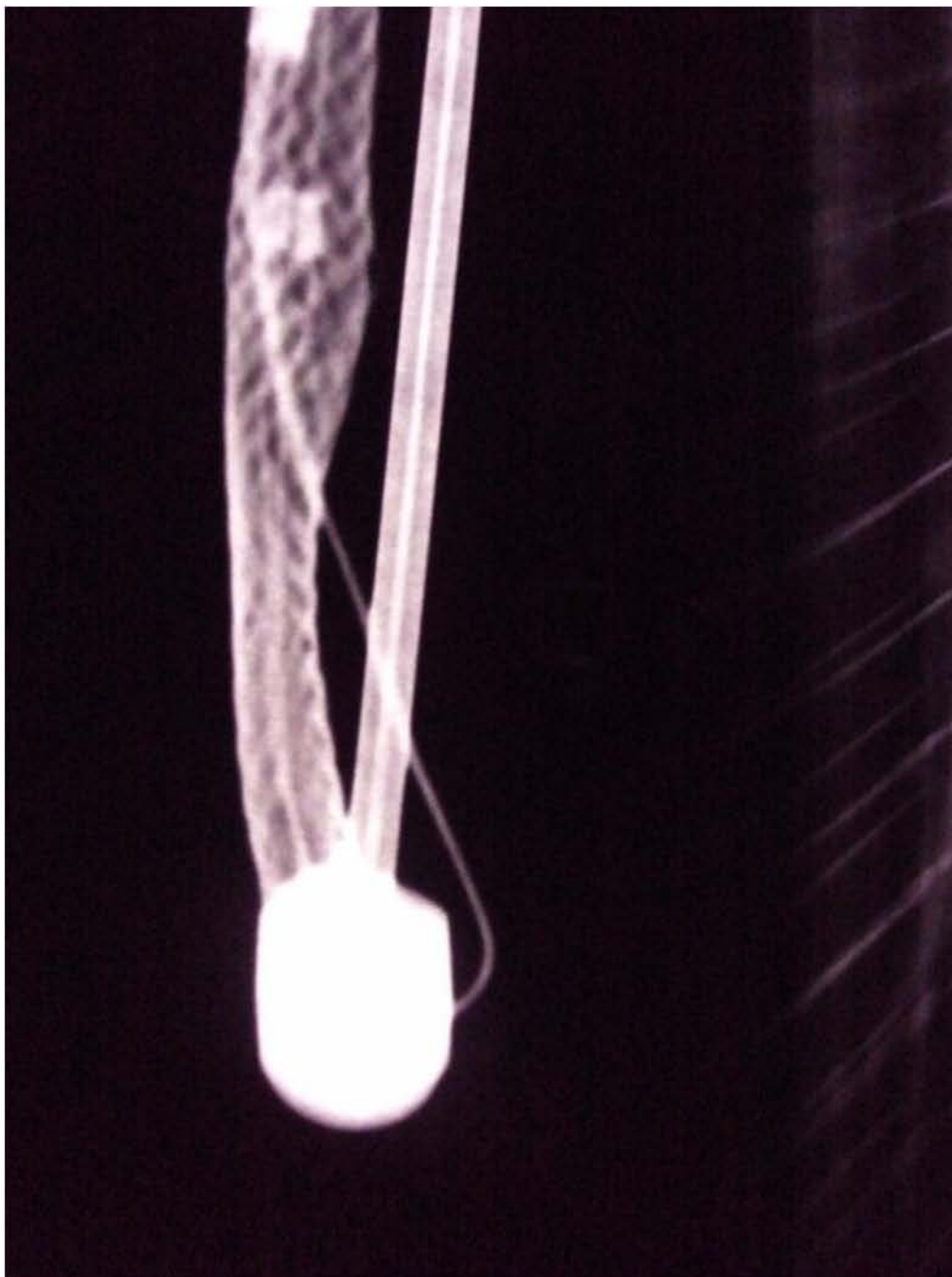


Figure E.98.—Power connection to heating element for Bulk Fluid Heater 3.

Appendix F.—Approvals

Prepared by:	<u>/s/ Wendell H. Booth</u> Wendell H. Booth ZIN Technologies, Inc. BXF Lead Electrical Engineer	Date:	<u>04/05/12</u>
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Reviewed by:	<u>/s/ Jim Bruewer</u> Jim Bruewer ZIN Technologies, Inc. Manufacturing Manager	Date:	<u>04/06/12</u>
Reviewed by:	<u>/s/ Debra R. Lyden</u> Debra R. Lyden ZIN Technologies, Inc. Quality/Safety Manager	Date:	<u>04/06/12</u>

Approvals.—Continued

Approved by:	<u>/s/ Raymond K. Pavlik</u> Raymond K. Pavlik ZIN Technologies, Inc. BXF Project Lead	Date:	<u>04/06/12</u>
Accepted by:	<u>/s/ William A. Sheredy</u> William A. Sheredy NASA Glenn Research Center BXF Project Manager	Date:	<u>04/11/12</u>

Appendix G.—Revisions

[illegible]

Reference

1. “Rainey, K. N. and You, S. M., “Boiling heat transfer phenomena from microporous and porous surfaces in saturated FC-72,” *International Journal of Heat and Mass Transfer*, Vol. 40, pp. 4437–4447, 1997,

