

DWPF Melter #2 Prototype Bus Bar Test Report (U)

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1.0 ABSTRACT

Characterization and performance testing of a prototype DWPF Melter #2 Dome Heater Bus Bar are described. The prototype bus bar was designed to address the design features of the existing system which may have contributed to water leaks on Melter #1. Performance testing of the prototype revealed significant improvement over the existing design in reduction of both bus bar and heater connection maximum temperature, while characterization revealed a few minor design and manufacturing flaws in the bar. The prototype is recommended as an improvement over the existing design. Recommendations are also made in the area of quality control to ensure that critical design requirements are met.

2.0 INTRODUCTION

Some of the copper tubing attached to the Defense Waste Processing Facility (DWPF) Melter #1, Dome Heater Bus Bars has developed leaks. Thermal modeling of the existing Dome Heater Bus Bars (see Figure 2-1) indicates that there is significant heat generation in the Inconel terminals of the heaters.[1] Thermal stress/cycling created by this heating may have contributed to the leaks in the tubing on Melter #1. The DWPF Melter #2 has been constructed and is currently being readied for installation in DWPF when Melter #1 reaches the end of its life. A modification necessary to prevent recurrence of the cooling water leaks is desired prior to installation of Melter #2 in DWPF. A timely, yet proven, solution is required due to Melter #1 having exceeded its original design life, and the importance of reliable operation of this critical and remotely-accessed system that precludes repair of the bus bar once installed.

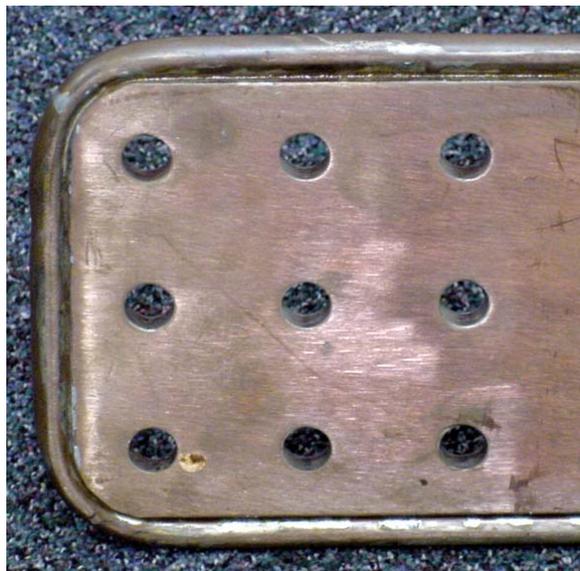


Figure 2-1

Close-up of Existing Bus Bar Heater End

Two solutions to the problem appeared feasible: either modify the Dome Heaters to replace the Inconel material that was the cause of the heat generation, or modify the

Dome Heater Bus Bars so that they could more adequately handle the heat load. Modification of the dome heaters on the DWPF Melter #2 was determined to be impractical due to their limited accessibility. HLW/DWPF/TTR-00-0025 was approved on May 4, 2000, requesting that Savannah River Technology Center-Engineered Equipment and Systems (SRTC-EES) develop a new Dome Heater Bus Bar design, fabricate a prototype, and test it to verify design acceptability. EES Job Number 22787 was assigned to this effort. A bus bar with an internal cooling water passage based on a DWPF Engineering concept was designed and fabricated previous to depletion of the funds provided under the original TTR. The TTR was revised on December 8, 2000, deleting requirements for thermal modeling and authorizing the additional funding necessary to complete the requested testing. This report describes the design of the prototype bus bar, its fabrication, and testing. Based on the testing program, additional design recommendations are also presented. All testing activities were performed in accordance with Manual E7 as a Baseline R&D Activity per L1 Procedure 7.10.

The prototype bus bar is a 3/4" x 8" C110 copper bar approximately 18 inches in length with an internal cooling water passage (see Figure 2-2). The bus bar was manufactured by Watteredge-Uniflex of Avon Lake, Ohio (a national manufacturer specializing in bus bars and other high-current-carrying components) per their standard practice for the fabrication of internally cooled bus bars, and EES drawing number EES-22787-R3-001.[2] The prototype bus bar was purchased under Purchase Order number AC14343A, placed on August 23, 2000. Included as part of the bus bar design is the connection detail for the bus-to-transformer and the bus-to-heater connection points. This detail was altered from the existing design to provide a more reliable connection, given the cyclic loading of the system as current to the Dome Heaters is varied to control vapor space temperature.

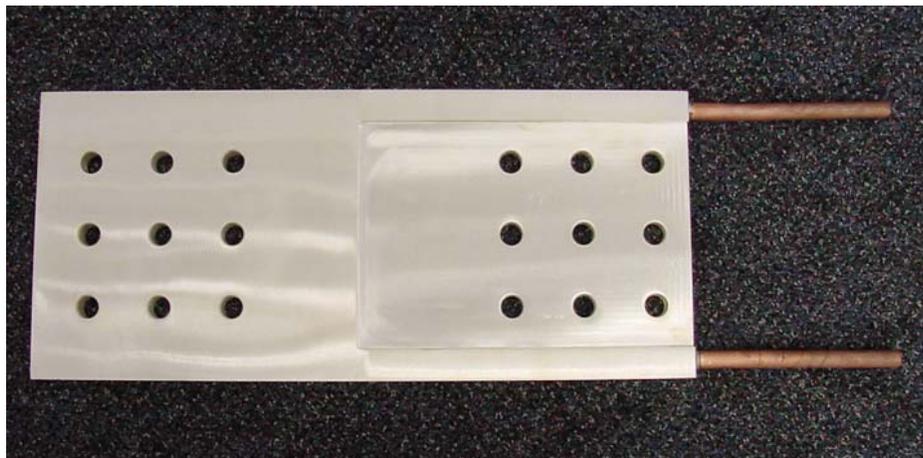


Figure 2-2
Prototype Bus Bar

3.0 METHODS

Testing of the prototype bus bar was performed according to Special Procedure FP-870, DWPF Melter #2 Prototype Bus Bar Test Procedure[3], and the Task Technical/QA Plan (TTQAP) for the DWPF Melter #2 Prototype Bus Bar Testing, EES 22787-TTQAP.[5]

The purpose of the test procedure was to document the as-built characteristics of the prototype bus bar; verify that the new design can be installed between the existing Melter #2 Dome Heaters and Transformers; and compare the performance, under load, of the prototype to the existing bus bar design.

3.1 Dimensional Measurements

Dimensional measurements were conducted in the 717-A Dimensional Inspection Facility to quantify the as-built characteristics of the bus bar and compare this condition to the design drawing. The following attributes were measured: slot width (dimension A, Figure 3-1), bar thickness at each end (dimensions B and C, Figure 3-1), flatness of the bottom and top surface of the bar (areas D and E, Figure 3-1). In addition the position of slot A was also determined.

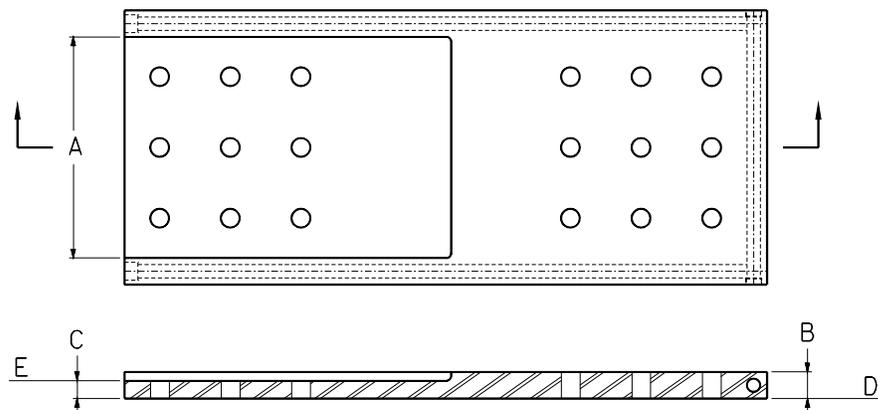


Figure 3-1
Dimensional Measurement Locations

All measurements were made in accordance with the standard practices and procedures of the Dimensional Inspection Facility. The following Measuring and Test Equipment (M&TE) were used: Starrett coordinate measuring machine (QV7CM001), digital caliper (QV7DC003), and RTH Surtronic 4 (QV7SF004).

3.2 Pressure Test

A hydrostatic pressure test was conducted by IES personnel in the 723-A High Pressure Lab per Proof/Leak Test Procedure, Manual L9.4, Procedure 8303. The pressure test requirements were specified in accordance with the requirements of ASME B31.3 piping code for a category D fluid. The design temperature of 120 °C and design pressure of 60 psig yielded a required minimum test pressure of 112 psig at room temperature in accordance with Paragraph 345.4 of the code. The bus bar was sealed on one end, filled with water, and vented; it was then pressurized and held for a minimum of ten minutes. The following M&TE were used: pressure gauge (3-1101) and thermometer (EA-1047).

3.3 Coolant Loop Characterization

Measurements were made to determine the relationship between flow and pressure drop through both the prototype and the existing bus bar designs. The

two sets of data allowed comparison of the two designs. The test configuration is shown in Figure 3-2, and the following M&TE were used: flow meter (TR-20270) and pressure gage (TR-03604) with 4-20 mA output to remote indicator (3-2745). Differential pressure data was collected for a range of flows from 0.5 to 2 gpm.

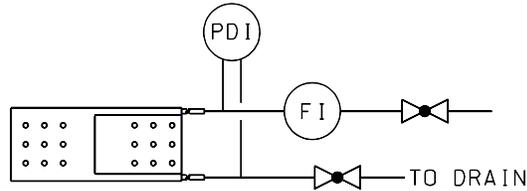


Figure 3-2
 Coolant Loop Test Configuration

3.4 Load Tests

The two bus bars were operated in parallel at three current levels so that bus bar temperature, temperature distribution, and cooling water temperature differential could be compared. The test configuration is shown schematically in Figure 3-3, and Figure 3-4. The M&TE used in the test are listed in Table 3-A. In the test configuration three separate resistor sections were employed to close the secondary circuit. There were two Inconel sections (designated R1 A and B) to simulate the Dome Heater Stabs and an aluminum shunt resistor to close the circuit. The Inconel “heaters” were sized based on previous thermal analysis[1] to produce the same I^2R heating effect as the heater stabs in the actual melter assembly. The shunt resistor was designed to provide the proper resistance in the secondary for the power supply while providing sufficient surface area to convectively shed its own I^2R heating.

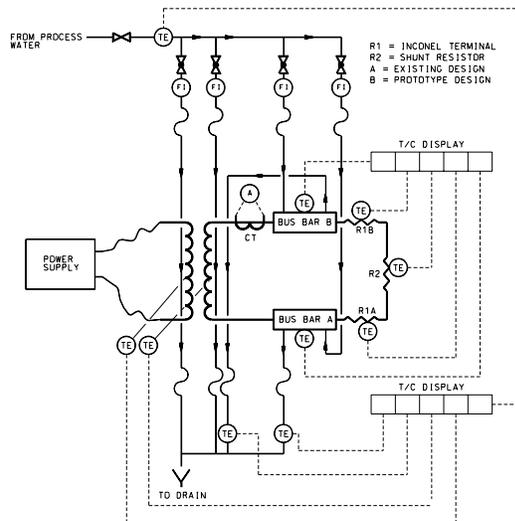


Figure 3-3
 Load Test Schematic

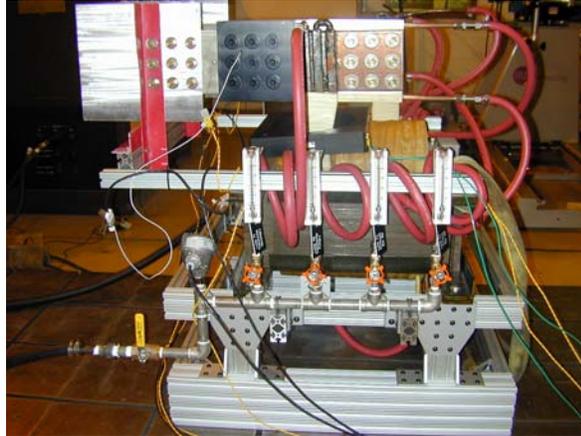


Figure 3-4
 Load Test Apparatus

Power was controlled on the primary side of the dome heater transformer to obtain the required secondary current. The secondary current was directly measured to establish the test point. Three different secondary current levels were specified for testing: 2600, 3800, and 5000 amps. For each of these three test conditions all four cooling loops were supplied with 45 to 55 psi process water and adjusted to 1.5 gpm nominal flow. The test current was maintained while bus temperature was measured to determine a steady state point. The test procedure defined steady state as a change in temperature of less than two degrees Celsius over a ten-minute interval. Due to the rapid rate at which the bars reached steady state, this definition was adjusted during the test so that in all cases a temperature difference of 0.5 degrees Celsius or less over the ten-minute period was achieved. Temperatures were recorded for each bus bar, all three resistor sections, and the bus bar cooling loops inlet and outlets at five-minute or smaller intervals, beginning at system power-up. When the steady state condition was reached, both bus bar temperatures were recorded, as well as the actual secondary current and the actual cooling loop flow rates. A thermal image of each bus bar was also recorded, as well as one for each Inconel resistor/connector. These same measurements were also taken for a fourth test condition. The secondary current was adjusted to 3800 amps, and the cooling water flow to each of the bus bars was reduced to approximately one half of the nominal value.

Table 3-A
 Load Test Instrumentation List

Instrument	Location	M&TE Number
Bus Bar Temperature Elements (TE's)	Prototype (B)	3-3048
	Existing (A)	3-3047
Resistor TE's	Aluminum Shunt (R2)	3-3038
	Inconel at Existing Bus (R1A)	3-3039
	Inconel at Prototype Bus (R1B)	3-3046

AC Ammeter	Transformer Secondary	3-3099-1
Current Transformer	Transformer Secondary	3-3099
Cooling Loop Flow Indicators (FI's)	Transformer Secondary	3-3013
	Transformer Primary	3-3016
	Prototype Bus Bar	3-3014
	Existing Bus Bar	3-3015
Cooling Loop TE's	Inlet	3-3108
	Prototype Outlet	3-3113
	Existing Outlet	3-3112

3.5 Melter #2 Fit Test

The bus bar fit test was conducted in the 717-F mock-up facility on the actual DWPF Melter #2 assembly. A dummy bus bar was used in this test in lieu of the prototype bus bar. The dummy bar was manufactured to the same design drawing as the prototype bus bar, except that no internal cooling channels were provided, the tubing sections were not present, and the milled slot was lengthened 1 inch. See Section 4.5 for more detail on the slot dimension change. A single Dome Heater bus bar was removed and the dummy bus bar installed in its place. The dummy was bolted to the Transformer Stab and the alignment at the Dome Heater connection was checked.

3.6 Destructive Measurements

Destructive tests were conducted by the SRTC Materials Consultation Group. A number of changes were made to the destructive measurement test plan as shown in the test procedure, FP-870. Plating thickness measurements were made using the Nikon measuring microscope, M&TE ES-79, which was calibrated using a 0.01mm (0.00035 inch) stage micrometer standard, M&TE #3-1592, with an uncertainty of 0.0025 mm. The weld depth was not measured because the part was not welded as called for on the design drawing, but silver soldered instead. Five measurements were made of the plating thickness for each of the six samples. The sampling plan was altered to add additional samples covering the extra plug that was welded into the bus bar during cooling passage repairs and the tubing connection on the bar that was provided by the manufacturer.

Samples were removed from the bus bar according to the sampling plan shown in Figure 3-5. These samples were prepared and micrographs were recorded of the silver soldered or welded areas while the plating thickness was measured on half of the remaining samples in accordance with the test procedure FP-870.

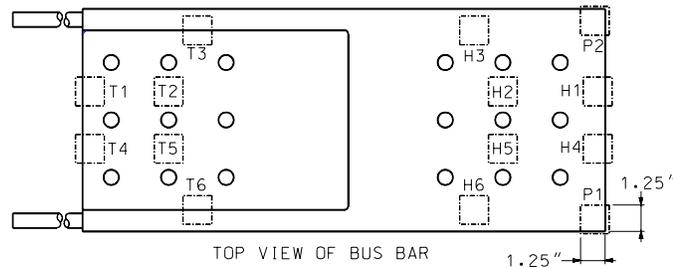


Figure 3-5
Bus Bar Sample Location Plan

4.0 RESULTS

The detailed results of all tests are documented in notebook WSRC-NB-2000-00266, DWPF Melter #2 Bus Bar Testing[4], as either the original data or as an attached copy of an original test report.

4.1 Dimensional Measurements

The dimensional inspection results were compiled in inspection report number 2000-IR-06-7066. All attributes were found to be within the tolerances specified on drawing EES-22787-R3-001. During testing it was discovered that the tolerance for dimension C (see Figure 3-1) on drawing EES-22787-R3-001 did not match the required tolerance listed in the Task Acceptance Criteria section of the TTQAP (EES-22787-TTQAP) for this test program, nor did it match the tolerance for dimension B. To address this conflict, drawing EES-22787-R3-001 was revised to match the TTQAP and reissued as Revision B.

In general, dimensional measurements showed that the size tolerances in the manufactured part were within the same order of magnitude as those provided in the design drawing. However, the flatness of the bus bar was much better than required. Measured flatness was within a 0.0004-inch tolerance zone in the worst case, while the requirement was a 0.010-inch zone.

4.2 Pressure Test

The High Pressure Lab reported the results of pressure testing of the prototype bus bar on IES Proof/Leak Test Data Sheet, SRT-IES-2000-494. The actual test pressure achieved was 120.3 psig and no visible leaks were detected during the ten-minute observation period.

4.3 Coolant Loop Characterization

Coolant loop pressure differential data was collected for the prototype bus design; initially however, the full range of flow could not be reached as flows in excess of 1.5 gpm exceeded the 100 in-H₂O range of the pressure gage. Pressure drop calculations performed to select the range of the test instrumentation indicated that the pressure drop should not exceed 64 in-H₂O. An investigation of the cause

of the excessive pressure drop was initiated, and resulted in an examination of the interior of the bus bar with a video probe. This investigation revealed that the cross bore in the bar did not completely penetrate one of the longitudinal bores.

A repair of the prototype bus bar was completed by drilling into the cross-bore in the bus bar. The bus bar was entered in the side where the flow restriction was present and the cross-bore was opened up to its full diameter. The hole in the bus bar was sealed by press fitting a plug into the hole and welding over the plug to reseal the bar. Flow testing was then completed using the repaired prototype and an existing design bus bar.

The differential pressure data gathered were plotted versus flow and a second order polynomial equation was generated for each of the bus bars. These graphs are shown below in Figures 4-1 and 4-2. The differential pressure in the two bus bars can be compared at a flow rate of 1.5 gpm using these characteristic equations. The results of this comparison show that pressure drop through the prototype bus bar is 42.8% greater than that through the existing bar. The total pressure drop in the prototype is 23.7 in-H₂O or 0.86 psi versus 16.6 in-H₂O or 0.60 psi in the existing design. Although the percentage difference appears large, the actual losses are small and amount to less than 5% of the total system pressure loss. The water temperature varied during the tests from 70.7 °F during the tests with the existing bar to 63.3 °F during the prototype tests. This variation would cause a 14% difference in Reynolds number; therefore, a difference in friction factors of about 1.3% between the two tests would reduce the reported percentage difference in pressure differential by the same 1.3%.

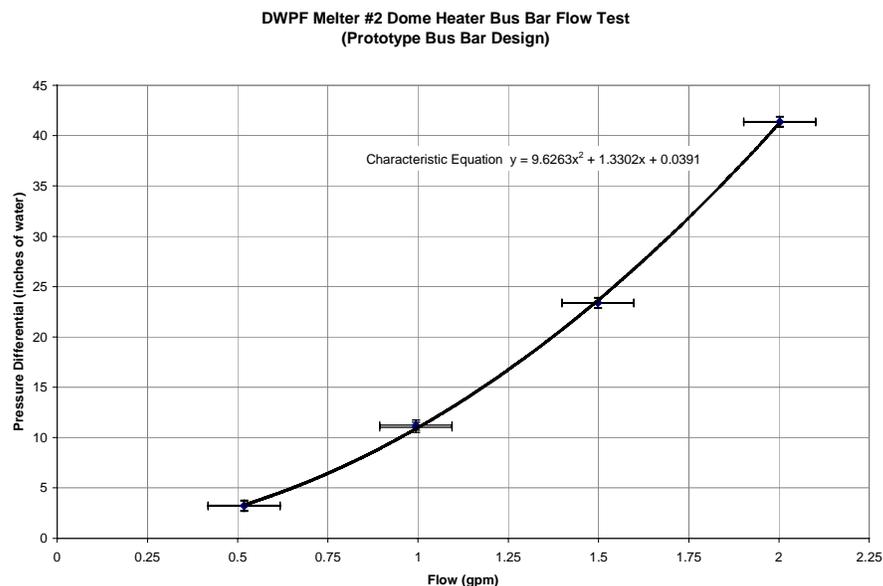


Figure 4-1
Prototype Bus Bar Flow Test Results

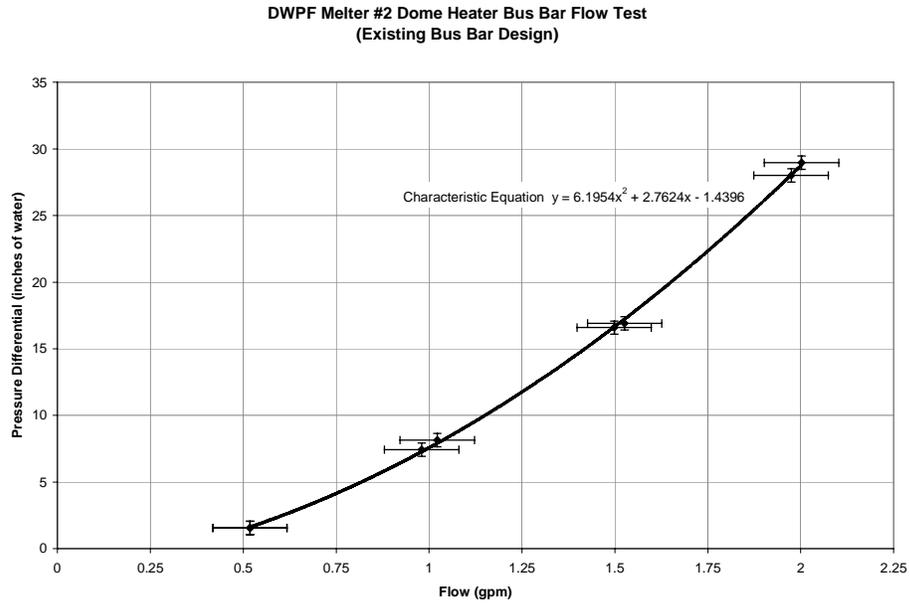


Figure 4-2
 Existing Bus Bar Flow Test Results

4.4 Load Tests

Load testing of the two bus bars showed that discrete surface temperatures on the existing design bus bar exceeded those on the prototype bus bar from 19 to 43 percent over the range of currents tested. Inconel heater temperatures were 27 to 44 percent higher with the existing bus bar design. Temperature and cooling flow data for each of the four test conditions are shown in Table 4-A.

Table 4-A
 Load Testing Temperature and Flow Data

Bus Bar	Bus Surface Temp. (°C)	Inconel Surface Temp. (°C)	Cooling Flow (gpm)	Cooling Delta (°C)
2600 A Secondary Current				
Prototype	21.7	135.4	1.5	0.67
Existing	25.9	171.4	1.5	0.79
3700 A Secondary Current				
Prototype	24.6	246.0	1.4	1.17
Existing	32.9	320.4	1.5	1.70
4900 A Secondary Current				
Prototype	29.2	354.7	1.4	2.40
Existing	41.9	502.0	1.5	3.08
3900 A Secondary Current				
Prototype	28.7	250.1	0.71	2.60
Existing	37.2	360.2	0.75	3.42

The most marked difference between the two bus bars occurred at the 5000 amp nominal secondary current test and these results are depicted below in Figures 4-3 through 4-5. As previously depicted in Figure 3-3, A is used to identify the existing design bus while B identifies the prototype. The resistors, R1 and R2, are also as shown in Figure 3-3 and represent the Inconel Terminal and the aluminum shunt resistor respectively.

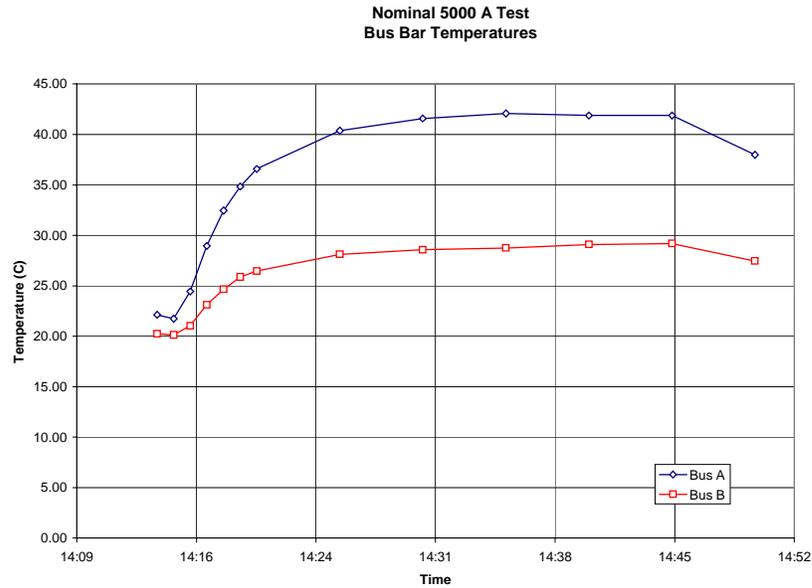


Figure 4-3
 Bus Surface Temperature vs Time for 5000 A Nominal Current

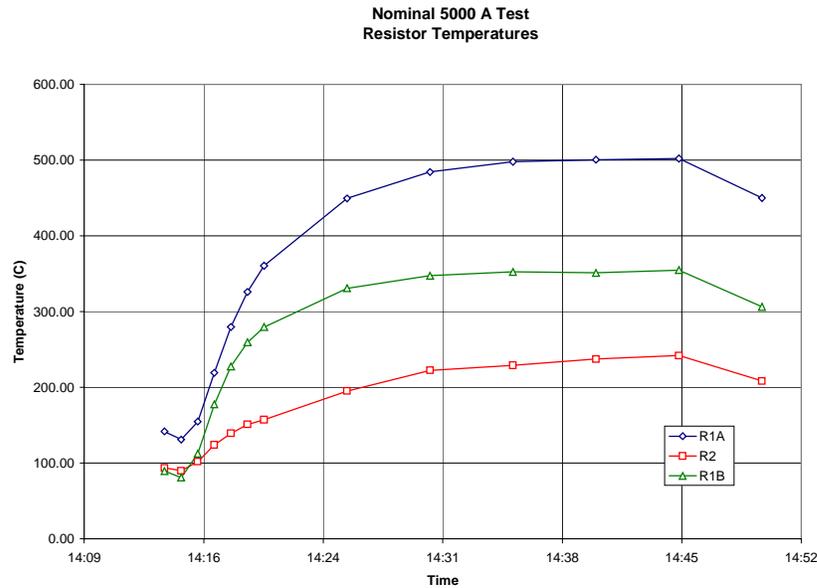


Figure 4-4
 Resistor Surface Temperature vs Time for 5000 A Nominal Current

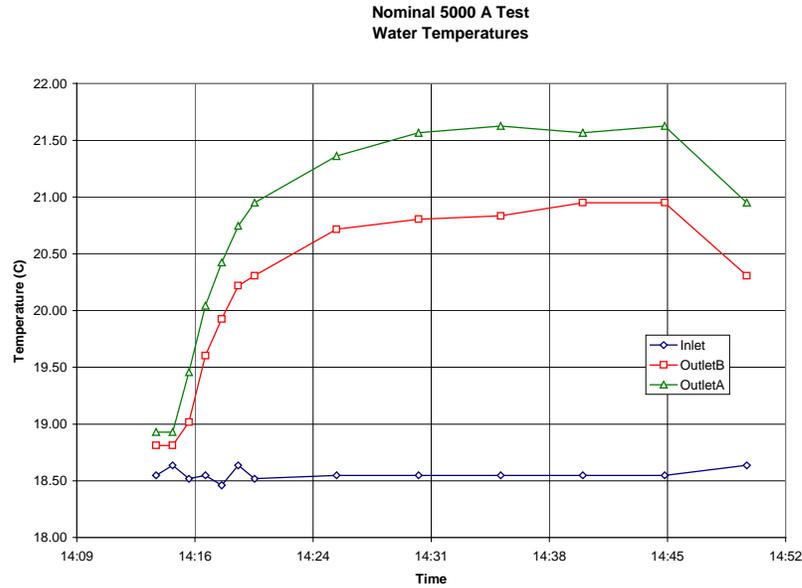


Figure 4-5
 Cooling Water Temperature vs Time for 5000 A Nominal Current

In all four tests cases the thermal energy carried from the system by the cooling water was greater in the case of the existing design bus bar. The familiar relation $q = \dot{m}c_p\Delta t$ was used to make this comparison and at first the result seemed incongruous since the existing design bus bar was operating at a higher temperature. However, when the electrical resistance of the two bars is compared it can be shown that the resistance of the existing bus bar is 40% greater than the prototype and therefore produces 40% more I^2R heating. The greater resistance in the existing bus bar design is due to its smaller cross sectional area. Because of the increased resistance more energy is required to be dissipated by the cooling water in the existing bus compared to the prototype bus to maintain the energy balance of the two systems.

Thermal profiles of the bus bars generated with the infrared camera produced fair images depicting the thermal gradient in the bus bars at each of the test points. However, the extreme heat from the Inconel resistor in the view of the camera appears to have biased the recorded temperatures. Using these thermal images a plot of the bus bar surface temperature along the length of the bar under four test conditions was generated. This plot is shown in Figure 4-6. Note that the close proximity of the Inconel resistor to the leading edge of the bus bar makes the determination of the maximum bus bar temperature difficult and for this reason the maximum temperatures are somewhat suspect. This is especially true of the maximum temperature presented for the prototype bar at the 4900 amp test point as this point does not follow the trends of the other curves. These curves suggest that the temperature delta between the two bus designs remains fairly constant along the length of the bar, at least over the first 5.5 inches measured.

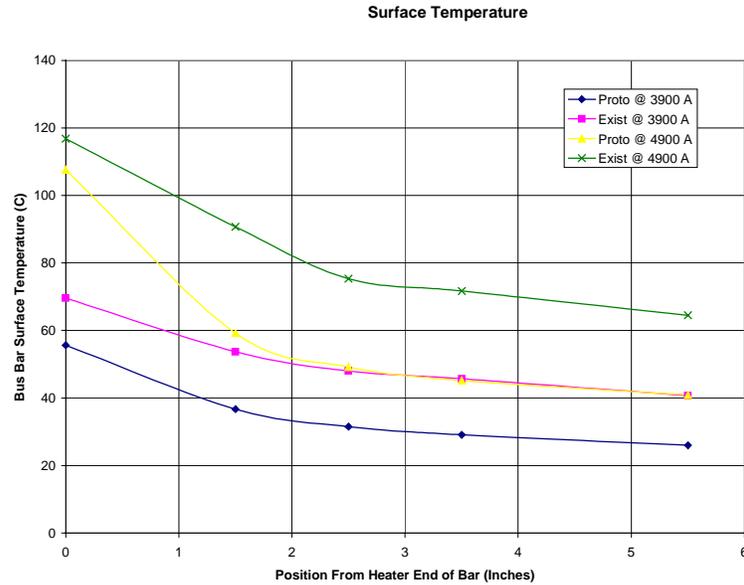


Figure 4-6
 Bus Bar Surface Temperature vs Position

The temperature profiles for the 2600 and 4900 amp test conditions are shown in Figures 4-7 through 4-10. The profiles are consistent between the two current levels with only a change in scale. There are only slight “hot” indications of the bolt locations and this is at least partly due to the fact that the bolts protrude above the bus surface and are thus able to reflect the radiant energy of the Inconel resistor.

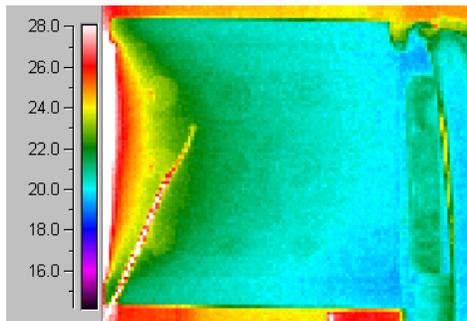


Figure 4-7
 Prototype at 2600 A

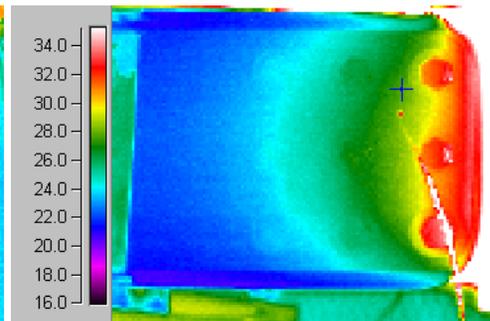


Figure 4-8
 Existing at 2600 A

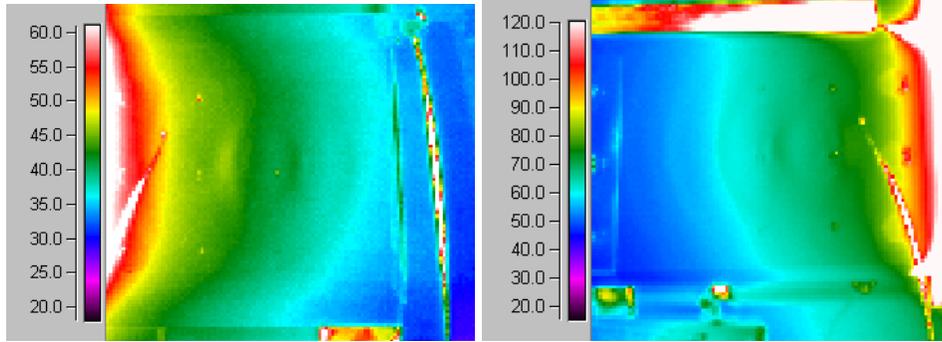


Figure 4-9
Prototype at 4900 A

Figure 4-10
Existing at 4900 A

The profiles produced are in good agreement with the profiles generated from a previous finite element analysis of the system[1]. One difference apparent when the images of the existing bus are compared with the corresponding profile generated by modeling is the inflection of the thermal profile at the rounded corners on the leading edge of the bar. The profile generated through modeling of the existing design at a 5000 amp load is shown in Figure 4-11.

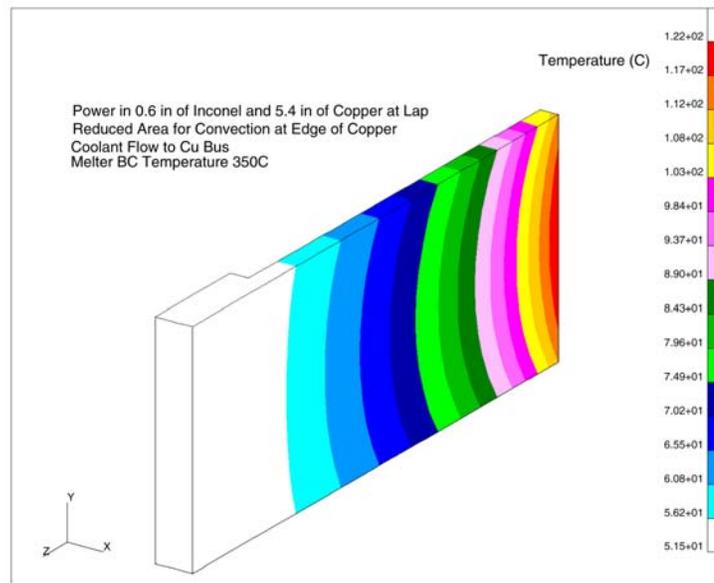


Figure 4-11
Temperature Profile Produced by Thermal Model[1]

The intense heat generated in the Inconel resistor is evident in the discoloration that can be seen in the post-test picture (see Figure 4-12). This heat-affected zone extends for approximately 2.5 inches along the resistor, and provides some indication of the current path through the Inconel with respect to the copper and aluminum attachments.



Figure 4-12
Heat-effected Zone in Inconel Resistor

4.5 Melter #2 Fit Test

After removal of an existing bus bar for work not related to this testing, the dummy bus bar was fit into Melter #2 without removal of other components. The transformer end of the bus bar was easily bolted in place; however, at the Dome Heater end the hole patterns did not line up. An offset of approximately 1/2 inch was noted between the two hole patterns. This misalignment was investigated to determine the source of the problem. The hole patterns of the dummy and the existing bus bar were compared and they were found to match. Construction personnel were then interviewed to determine if any "spring" was present in the assembly when the existing bus bar was removed for this test. The personnel indicated that there was "spring" in the system and that the last two bolts had to be driven out of the assembly. In fact, the Construction personnel indicated that the system had to be pulled together at assembly. Based on this information this test is considered successful, especially since the new bus bar will be able to be installed on the Melter #2 without disturbing the existing assembly other than removal of the existing bus bars.

Previous to fit testing, an interference with the existing transformer assembly was noted when the prototype bar was assembled on the load test apparatus. An interference of approximately 0.75 inch was noted between the slot in the bar and the transformer connector. System design drawings were reviewed and they also showed a 0.75-inch interference. To correct this problem an additional one inch was milled from the slot in the bus bar. The dummy bus bar that was used in the Melter #2 fit test was fabricated to the new dimensions.

4.6 Destructive Measurements

Destructive measurement of the bus bar revealed a minimum silver plating thickness of 0.0002 inches in the proximity of the center of the transformer end of the bus bar and a maximum of 0.0003 inches along the edges. See Table 4-B for a complete listing of the average plating thickness values for each of the samples.

The average plating thickness reported by the manufacturer was 0.0003 inches. This reported value appears to be on the high side given the values determined during destructive measurements; however, the design minimum of 0.0002 inches was met. It should also be noted that the destructive measurements were of necessity made on a used bar, as shown in Figure 4-13, and some degradation of the coating may have occurred. No peeling or delamination of the coating was observed during measurements conducted with the measuring microscope at a magnification of 40x.

Table 4-B
 Average Plating Thickness Measurements

Sample Designation (See Figure 3-5)	Surface	Average Plating Thickness (Inches)
T1	Bottom	0.00025
T2	Bottom	0.00020
T3	Bottom	0.00030
H1	Top	0.00030
H2	Top	0.00025
H3	Top	0.00025



Figure 4-13
 Prototype Bus Bar Condition Previous to Destructive Testing

Sectioning of the plugged regions of the bus bar revealed a number of findings. The most important of these was that the plug installed by the manufacturer was silver soldered in place as opposed to welded, as called for on the design drawing. The two plugged regions are shown in Figures 4-14 and 4-15. Both joints were leak tight under pressure and at full design current. Review of the plugged areas also revealed that the manufacturer installed the plug opposite the location called for on the design drawing. (This was also noted when the bus bar was examined by video probe.) Also, the source of the flow restriction in the bus bar that was observed during the flow tests can be seen in the sample from the repaired corner of the bar. This sample is shown in Figure 4-16. It is clear from observing the

original holes in the bar (the holes which pass across the edge of the sample) that the end of one bore (the cross bore) barely penetrated the side of the other.

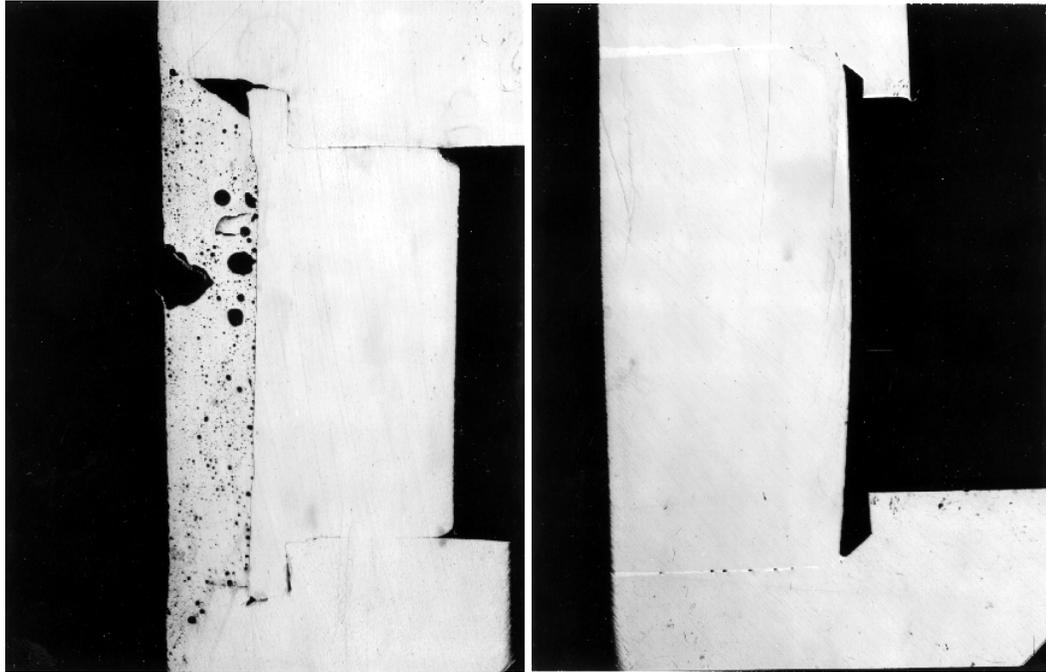


Figure 4-14
Welded Bus Bar Plug Section

Figure 4-15
Silver Soldered Bus Bar Plug Section

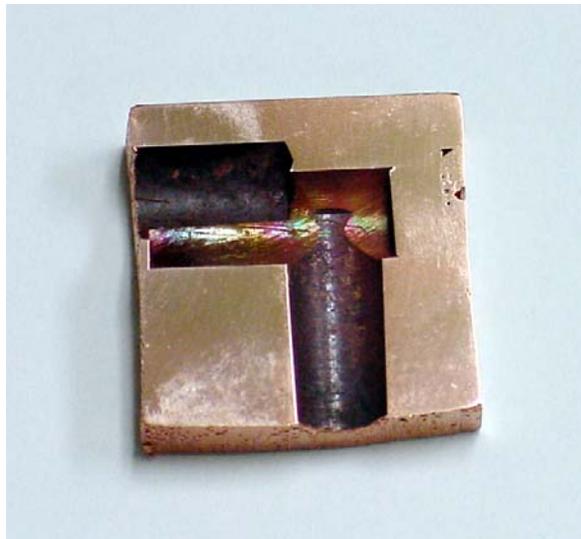


Figure 4-16
Repaired Corner of Bus Bar
(Shown in section)

The tubing connections to the bus bar were also examined and appeared as expected based on the design drawing for the part. The silver soldered tubing connection is shown in section view in Figure 4-17.



Figure 4-17
Bus Bar Tubing Connection Section

5.0 DISCUSSION

The design of the prototype bus bar was based on the concept of a solid bar with a single internal cooling passage, and no alternate designs such as laminated bars or bars with multiple cooling passages were considered. The design elements of the prototype bar which were considered included the following: physical size required to fit the existing system while accommodating the internal cooling passage, method of plugging the bar where required to produce the internal passage, method of attaching the tubing stubs to the bar, plating requirements, and the connection detail. All of these design elements are captured on the design drawing for the part; however, certain additional recommendations are made in the following section.

6.0 RECOMMENDATIONS

The prototype bus bar is recommended as a replacement to the existing design for Melter #2. The prototype performed markedly better during testing at load, and produced lower overall temperatures in the bus bar and in the Inconel heater/resistor. An increase in cooling loop pressure drop can be expected by the introduction of the prototype design into the system; however, this increase is small compared to the overall system losses.

A number of potential modifications or changes to the prototype design were noted during testing. These changes, based on the completed test program, are not included in revision B of the development drawing, EES-22787-R3-001; however, they should be evaluated for inclusion in the record drawing. The slot length in the bus bar must be increased by 1-inch to a total of 10.25 inches to address the interference observed during assembly. The tolerance on this dimension remains the same. The cross-bored hole in the bus bar should be completely bored through and then plugged on each side. This change will allow better inspection of the interconnections in the cooling passage. The bus bar should be flow-tested before being introduced to service to assure that no flow restrictions are present in the bar. The introduction of foreign material or the improper installation of the plugs in the cross-bore could cause these flow restrictions. The depth of the two long bores in the bus bar should be increased to 17.92 inches with the

tolerance remaining the same. This will ensure that the ends of the long bored holes are at least at a depth equal to the centerline of the cross bore if the tolerance on the position of the cross-bore and the length of the bar remain the same.

The amount of “spring” in the existing bus bar assemblies would seem to suggest that drilling the mounting holes for the bus bars at assembly would be advantageous and this is recommended. If drilling these holes at assembly is considered difficult, then the diameter of the mounting holes should be increased to that on the existing bus bars.

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8.0 REFERENCES

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