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Ten Year Operating Test Results and Post-Test Analysis of a 1/10 Segment Stirling Sodium Heat Pipe

Phase III Final Report

John H. Rosenfeld, Kenneth G. Minnerly, and Christopher M. Dyson
Thermacore, Inc., Lancaster, Pennsylvania

July 2012

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1.0 Introduction

Stirling heat engines are being developed for electrical power generation on manned and unmanned earth orbital and planetary missions and also for terrestrial applications for utility and remote power generation. Dish Stirling solar systems and nuclear reactor Stirling systems are two promising applications of Stirling engine technology. Sources of thermal energy used to drive the Stirling engine typically have non-uniform temperatures and heat fluxes. Liquid metal heat pipe receivers are often used as heat transformers to uniformly deliver thermal energy at high temperatures to the heater heads of these Stirling engines. The use of heat pipe receivers can greatly enhance system efficiency and potential life span.

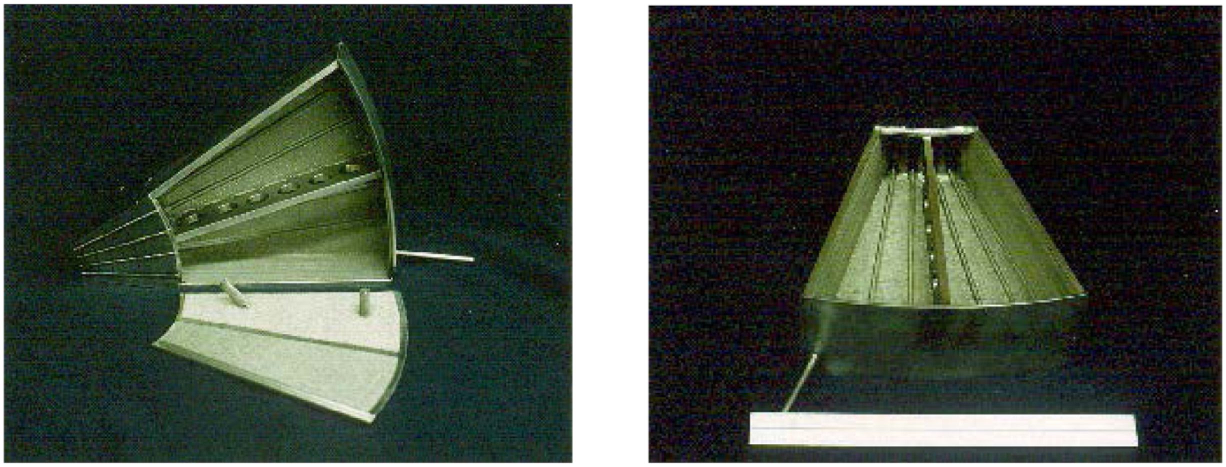
One issue raised during the design phase of heat pipe receivers is the potential solubility corrosion of the heater head section by the liquid metal working fluid. Stainless steels and nickel-based super-alloys are standard materials of construction for high temperature heat pipes and heater heads operating in the temperature range 823 to 1073 K. At these operating temperatures, some components of these materials are appreciably soluble in working fluids such as sodium, potassium, and NaK. Over a typical life span of 7 to 10 yr, essentially pure working fluid condensate will condense on the heater head surfaces. The condensate will leach the soluble components of the heater head material and transport them to the evaporator section of the heat pipe. When the working fluid is evaporated again, the soluble materials are precipitated and essentially pure working fluid is returned to the condenser section to leach more material. The condensation heat flux for a Stirling heater head is typically 20 to 25 W/cm^2. This corresponds to approximately 760,000 L of sodium per year, condensing on a heater head for a 33% efficient 25 kWe Stirling engine.

Thermacore was awarded Phase I and Phase II SBIR programs to investigate solubility corrosion and to develop coatings that would essentially eliminate the solubility corrosion potential. A complete description of the work performed and the conclusions reached can be found in the Final Report for Contract Number NAS3–26925. The final task of the program was to fabricate a 1/10th segment of the current Stirling Space Power Converter (SSPC) utilizing the coatings and coating processes developed during the program. This heat pipe would then be life tested for up to 10 yr by Thermacore as Phase III.

Unfortunately, the heat pipe intended for life testing had several weld failures after charging and processing. Because this pipe was no longer available, Thermacore and NASA acquired the original 1/10th segment heat pipe from Mechanical Technology Incorporated (MTI) for the Phase III effort. The 1/10th segment heat pipe, fabricated by Thermacore for the SSPC project under MTI Subcontract No. 003–05034, was returned to Thermacore for testing on this program.

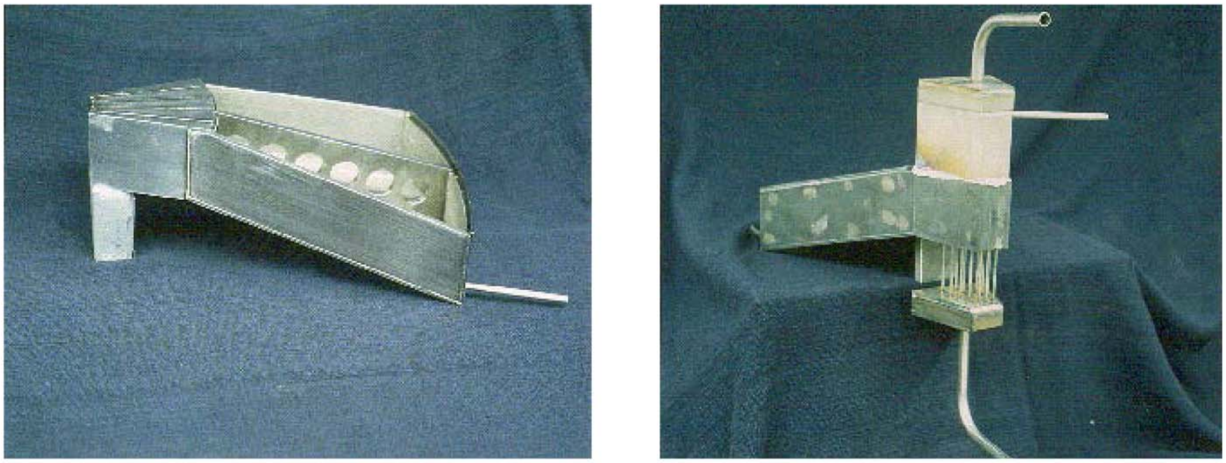
2.0 Heat Pipe Description

The SSPC starfish heater consists of fifty radial fins with 38 one-millimeter diameter gas passages in each fin. The helium working fluid in the converter flows through the gas passages while the sodium in the heat pipe condenses on the outside of each fin. The annular heat pipe is attached to the outer radius of the starfish heater. The 1/10th segment is a 36° slice of the overall heater and heat pipe. The 38 small diameter helium gas passages are replaced with five larger diameter passages to allow for installation of a calorimeter to remove and measure the heat flow. Several photographs of the 1/10th segment are shown in Figure 1. The design specifications for this heat pipe are shown in Table 1.



1/10th Segment Heat Pipe, Top Plate Removed.

1/10th Segment Heat Pipe Wick Structure.



1/10th Segment Heat Pipe, Operating Orientation.

1/10th Segment Heat Pipe w/Gas-gap Calorimeter.

Figure 1.—1/10th segment heat pipe.

TABLE 1.—DESIGN SPECIFICATIONS FOR THE TENTH SEGMENT HEAT PIPE

Parameter	Specification
Operating temperature	1023 K (750 °C)
Working fluid and fluid charge	100 g, high purity sodium
Calorimetric heat transport	4500 W
Condenser surface heat flux	20 W/cm^2
Envelope and fill tube material	In 718 envelope; 316L SS fill tube
Wick structure material	316L SS; two layers 100 mesh screen
Arteries	Four; 0.318 cm (0.125 in.) inner diameter
Artery material	316L SS; 325 mesh screen
Coating	None

3.0 Description of Test Setup

Figure 2 is a photograph of the 1/10th segment life test setup. The heat pipe is heated primarily by radiation from 12 silicon carbide heating elements. In order to minimize heat loss, the heating elements are surrounded by a 9-in.-thick graded insulation package. The insulation package is formed to fit and support the heat pipe/calorimeter package. The power is controlled with a phase angle power controller in conjunction with a PID temperature controller. The Silicon Carbide heating elements operate in series at a relatively low voltage, approximately 30 V. A 10 kVA step down transformer is used to reduce the primary 208 to 35V.

The desired operating temperature is set on the PID temperature controller. The input signal to the temperature controller is the heat pipe vapor space temperature (Type K thermocouple). The temperature controller sends a control signal to the phase angle power controller to increase or decrease power to maintain the heat pipe at the set point. The temperature controller also has a latching, over temperature alarm feature. In addition, the temperature controller has a second control feature that is being used to energize the hour meter when the temperature is within 5° of the set point.

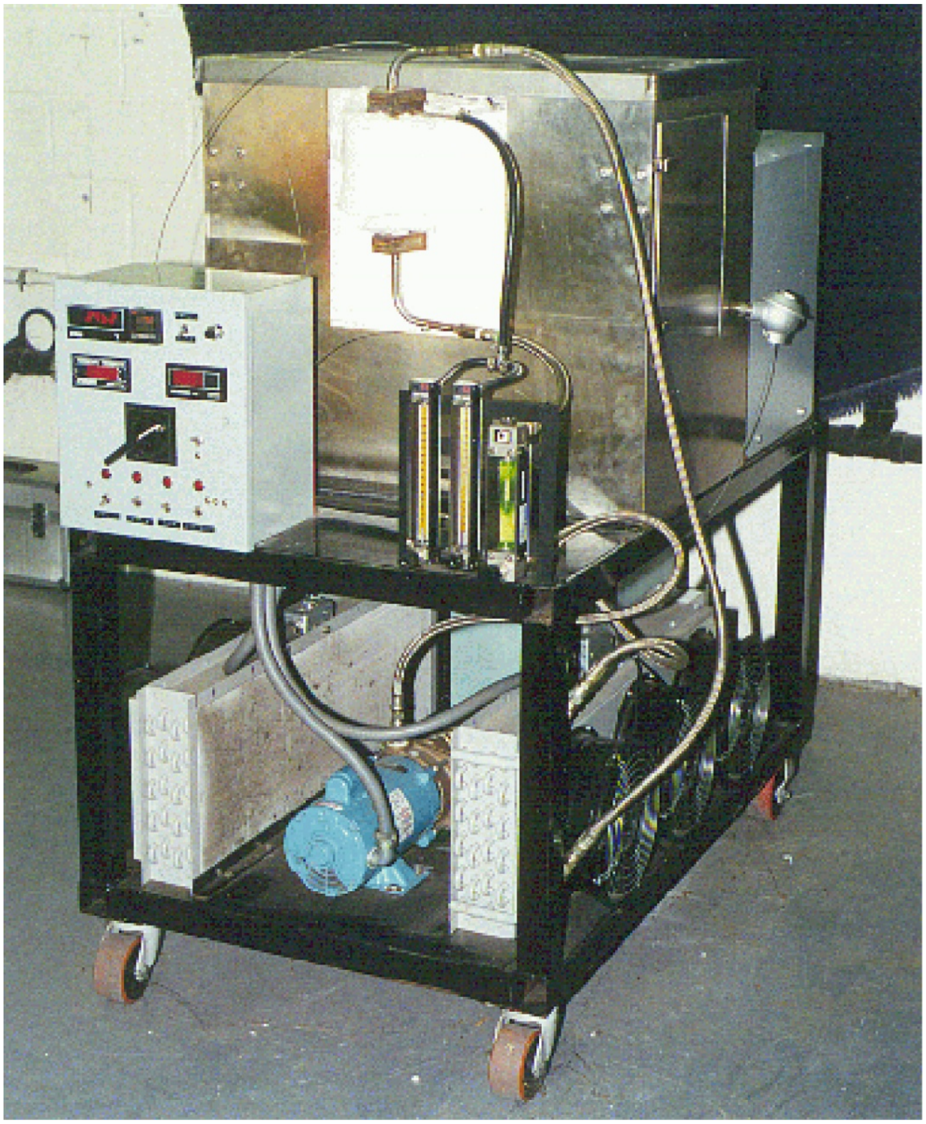


Figure 2.—Photograph of 1/10th segment life test setup.

The power that the heat pipe transfers is extracted and measured using a gas gap calorimeter. The gas gap calorimeter consists of small diameter water tubes that are inserted into the heater head gas passage holes. The gap between the heater head holes and the water tubes outer diameter is filled with a mixture of helium and nitrogen gas. This arrangement results in the calorimeter water tube, a gas gap, and the heat pipe wall.

Operation of the gas gap calorimeter is best understood by tracing the flow of thermal energy from the heat pipe wall to the water in the water tubes. The sodium vapor generated in the evaporator section of the heat pipe condenses on the Starfish heater head webs releasing its latent heat of vaporization. The thermal energy is transferred through the thickness of the heater head web by conduction. Next, the energy is transferred across the gas-gap by radiation and by conduction through the gas. By controlling the fraction of nitrogen, a low thermal conductivity gas, and the fraction of helium, a high thermal conductivity gas, in the gas gap, the resistance to conduction across the gap can be modulated. The heat is then transferred through the water tube wall by conduction and transferred by convection to the water flowing through the water tubes. The temperature rise of the water flowing through the tubes and the flow rate are used to calculate the heat pipe power throughput.

In this setup, the coolant is now distilled water. The coolant is pumped from a tank under the test setup, through a 50 μm filter, into the calorimeter. The coolant exiting the calorimeter then flows through two liquid-to-air heat exchangers, which are also mounted under the test setup. Therefore, the throughput power is ultimately rejected to the room air.

4.0 Work Status

During the final period of performance (March 31, 2009 through June 1, 2010), life testing of the 1/10th segment heat pipe was completed. There were several interruptions in the testing during this period, which were due to maintenance requirements on the support loop equipment or due to facility power failures. The heat pipe has held up well through these situations. A summary of the interruptions is provided below.

The first shutdown during the reporting period occurred on March 27, 2009, due to a clogged calorimeter. Scale deposits were found inside the tubes. The calorimeter was rebuilt, the system was flushed, the meters were calibrated, and the unit was restarted on June 4, 2009. On August 24, 2009, the unit was again shut down to clean a clogged calorimeter. The calorimeter was cleaned, and the unit was restarted on September 15, 2009. The calorimeter again showed signs of scale clogging on October 29, 2009 and the unit was shut down for maintenance. The tubes were replaced, and the unit was returned to service on November 16, 2009.

The unit operated without interruption until March 12, 2010, when a brief potage was required to replace the silicon carbide heaters. The unit was restarted on March 15, 2010. The unit was then operated with no interruptions until June 1, 2010, when it was decided to terminate the life test. The unit had been operated at 700 °C for over 10 yr at that date.

The heat pipe appeared to be operating normally at the test termination date. The life test unit has successfully operated for 87,783 hr. Work was then completed to remove sodium samples for post-test analysis at to complete metallographic examination of the envelope and wick material. The results of this work are described in the following section of the report.

5.0 Life Test Data

The life test setup is checked nearly every working day to make sure that the system is functional (pumps and fans are on, heaters are on, and He/N_2 are flowing). The operating parameters are checked in detail on a weekly basis and recorded in a laboratory notebook (Table 2). If the system requires modification, such as adjusting the helium /nitrogen flow rates to keep the power at 4500 W, all measurements are made and recorded before corrective action is taken.

TABLE 2.—LIFE TEST SETUP OPERATING PARAMETERS

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Coolant quality F.P. (°C)	Elect. power (W)	N_2 flow	He flow	Hour meter
09/23/96	698	1119	38	28	4		5014	1	8	649
10/01/96	699	1122	32	23	4		4994	15	13	807
10/04/96	698	1119	33	24	4		4850	15	16	887
10/11/96	698	1105	33	24	4		5020	15	17	1055
10/18/96	699	1125	33	24	4		4925	13	15	1223
10/25/96	699	1109	33	22	4			23		1384
11/01/96	698	1095	35	25	4	–43	4700	23	50	1558
11/08/96	700	1074	39	32	4		4400	20	55	1726
11/15/96	699	1079	29	21	4		4500	15	55	1891
11/22/96	699	1047	28	21	4		4200	15	55	2064
11/27/96	700	1061	23	14	4		4300	15	70	2180
12/06/96	749	1071	31	24	4	–43	3600	15	65	2392
12/13/96	747	1038	35	29	4		3400	10	62	2561
12/20/96	749	984	22	16	4		2700	20	0	2735
12/27/96	749	982	29	23	4		2500	20	0	2903
01/03/97	749	1039	31	38	4	<–43	3600	0	55	3071
01/10/97	Off for repair									

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Coolant	Elect. power (W)	N_2 flow	He flow	Hour meter
01/17/97	Startup										
01/18/97	612	1164	18	13	4	5299	DI Water	5500	60	0	3185
01/20/97	700	1240	29	22	4	7419	DI Water	6500	50	0	3232
01/24/97	699	1237	28	22	4	6359	DI Water	5990	50	0	3329
02/03/97	698	1210	29	23	4	6359	DI Water	5900	50	0	3563
02/10/97	700	1214	22	16	4	6359	DI Water	6000	50	0	3730
02/18/97	699	1208	28	23	4	5299	DI Water	5900	50	0	3923
02/21/97	698	1209	31	25	4	6359	DI Water	5900	50	0	3995
02/28/97	701	1203	34	28	4	6359	DI Water	5900	50	0	4162
03/11/97	697	1202	36	30	4	6359	DI Water	5900	50	0	4428
03/14/97	699	1209	20	15	4	5299	DI Water	5900	50	0	4498
03/20/97	699	1208	22	16	4	6359	DI Water	5900	50	0	4666
03/28/97	698	1209	26	21	4	5299	DI Water	5900	50	0	4835
04/07/97	697	1203	32	26	4	6359	DI Water	5900	50	0	5074
04/11/97	698	1209	28	21	4	7418	DI Water	5900	50	0	5177
04/18/97	699	1206	25.3	20.1	4.0	5511	DI Water	5800	50	0	5264
05/05/97	699	1203	27.6	22.3	4.0	5617	DI Water	5800	50	0	5673
05/09/97	700	1203	32.2	26.6	4.0	5935	DI Water	5800	50	0	5775
05/19/97	697	1199	31.1	25.6	4.0	5829	DI Water	5800	50	0	6009
05/23/97	698	1201	29.2	24.0	4.0	5511	DI Water	5800	50	0	6105
05/30/97	698	1200	32.0	26.3	4.0	6041	DI Water	5800	50	0	6272
06/06/97	698	1204	33.4	27.7	4.0	6041	----------	5800	50	0	6441
06/13/97	696	1203	42.2	36.4	4.0	6147	DI Water	5800	50	0	6607
06/20/97	698	1204	36.7	31.6	4.0	5405	DI Water	6000	50	0	6773

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Coolant	Elect. power (W)	N_2 flow	He flow	Hour meter
06/27/97	698	1208	42.5	37.5	4.0	5299	DI Water	6000	50	0	6947
07/07/97	698	1208	36.2	31.1	4.0	5405	DI Water	5800	50	0	7181
07/15/97	698	1207	38.9	33.7	4.0	5511	DI Water	5800	50	0	7373
08/02/97	697	1205	44.8	39.7	4.0	5404	DI Water	5900	50	0	7787
08/08/97	698	1210	39.6	34.4	4.0	5511	DI Water	5800	50	0	7952
08/18/97	698	1212	34.3	28.9	4.0	5723	DI Water	5800	50	0	8190
08/22/97	697	1210	38.3	32.5	4.0	6147	DI Water	5600	50	0	8288
09/02/97	700	1224	43.6	38.2	4.0	5723	DI Water	7200	50	0	8556
09/05/97	699	1202	33.8	28.6	4.0	5511	DI Water	7500	50	0	8623
09/12/97	698	1212	35.4	30.4	4.0	5299	DI Water	5900	50	0	8790
09/23/97	699	1214	32.6	27.6	4.0	5299	DI Water	5800	50	0	9060
09/26/97	699	1216	29.4	24.1	4.0	5617	DI Water	6000	50	0	9123
10/03/97	698	1235	30.3	24.4	4.0	6253	DI Water	6200	50	0	9292
10/10/97	698	1230	40.9	34.9	4.0	6359	DI Water	6100	50	0	9464
10/17/97	700	1236	26.0	20.1	4.0	6253	DI Water	6300	50	0	9627
10/28/97	700	1235	27.2	21.3	4.0	6253	DI Water	6100	50	0	9892
11/1/97	698	1232	34.6	28.6	4.0	6359	DI Water	6300	50	0	9968
11/7/97	699	1233	29.0	23.5	4.0	5829	DI Water	6000	50	0	10,209
11/17/97	699	1234	26.1	20.1	4.0	6359	DI Water	6200	50	0	10,546
11/24/97	700	1235	25.5	19.0	4.0	6889	DI Water	6100	50	0	10,830
12/6/97	700	1233	23.6	17.8	4.0	6147	DI Water	6200	50	0	10,971
12/12/97	700	1231	35.3	29.6	4.0	6041	DI Water	5900	50	0	11,142
12/19/97	698	1232	37.3	31.5	4.0	6147	DI Water	5900	50	0	11,211
12/23/97	Off for repair. Calorimeter leak.										
2/2/98	Calorimeter fixed. Unit back on.										
2/6/98	699	1215	24.9	19.6	4.0	5617	DI Water	6000	50	0	11,235
2/16/98	700	1208	23.3	17.2	4.0	6465	DI Water	5700	50	0	11,475
2/24/98	700	1207	26.0	20.5	4.0	5829	DI Water	5760	50	0	11,643
2/27/98	699	1208	26.8	21.0	4.0	6146	DI Water	5600	50	0	11,715
3/6/98	699	1189	29.1	23.8	4.0	5617	DI Water	5500	50	0	11,890
3/13/98	Off for repair. Wire failure. Also one calorimeter tube leaked.										
4-6-98	Fixed. Unit back on.										
4/10/98	698	1204	27.2	22.2	4.0	5299	DI Water	5600	50	0	12,042
4/17/98	698	1200	35.9	31.0	4.0	5193	DI Water	5500	50	0	12,210
4/24/98	697	1165	30.7	26.0	4.0	4981	DI Water	5300	50	0	12,377
5/1/98	697	1169	33.1	28.4	4.0	4981	DI Water	5300	50	0	12,545
5/8/98	700	1149	31.5	27.3	4.0	4451	DI Water	4900	55	0	12,714
5/15/98	699	1140	32.3	27.4	4.0	5193	DI Water	4800	55	0	12,880
5/26/98	698	1116	33.3	29.3	4.0	4239	DI Water	4500	55	0	13,145
5/29/98	697	1089	41.7	37.6	4.0	4345	DI Water	4700	55	0	13,222
6/1/98	Off for repair										
8/15/98	Replaced calorimeter. Replaced 6 silicon carbide heaters. Cleaned fluid system. Replaced DI water with distilled water. Installed 50 micron filter. Repairs complete. Unit back on.										

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
8/15/98	700	1253	44.1	39.0	4.0	5405	6300	46	Distilled Water	50	13,337
8/21/98	700	1258	33.7	27.9	4.0	6115	6300	46	Distilled Water	50	13,463
8/28/98	700	1258	42.4	36.3	4.0	6432	6200	48	Distilled Water	50	13,631
9/8/98	700	1258	39.8	34.2	4.0	5904	6200	50	Distilled Water	50	13,902
9/25/98	700	1259	39.2	33.5	4.0	6010	6300	51	Distilled Water	50	14,309
10/1/98	700	1260	38.2	32.6	4.0	5904	6280	50	Distilled Water	50	14,454
10/9/98	699	1263	34.4	28.6	4.0	6115	6290	51	Distilled Water	50	14,638
10/16/98	700	1265	35.4	30.0	4.0	5694	6200	51	Distilled Water	50	14,812
10/27/98	700	1266	31.6	25.8	4.0	6115	6290	51	Distilled Water	50	15,072
11/3/98	700	1266	29.4	23.7	4.0	6010	6210	50	Distilled Water	50	15,246
11/16/98	700	1263	29.0	23.3	4.0	6010	6250	50	Distilled Water	50	16,184
12/15/98	685	1247	23.9	18.5	4.0	5694	5925	50	Distilled Water	50	16,471
1/2/99	Water line in the life test room developed a leak and flooded the room. Electricity to the room was shut off.										
1/4/99	Water line was repaired. Electricity to the life test room was turned on.										
1/5/99	New silicon carbide heaters were ordered. Life test should resume by February 1, 1999.										
2/26/99	12 silicon carbide heaters replaced and life test resumed.										
2/26/99	700	1248	37.8	32.4	4.0	5694	6450	40	Distilled Water	50	16,471
3/1/99	Heater leads replaced.										
3/4/99	Power failure. Life test restarted.										
3/15/99	700	1258	32.2	26.7	4.25	6161	6685	42	Distilled Water	50	16,735
3/22/99	700	1251	31.1	25.5	4.0	5904	6175	40	Distilled Water	50	16,903
3/29/99	700	1256	37.5	32.3	4.0	5483	6300	41	Distilled Water	50	17,071
4/5/99	700	1250	36.6	30.4	4.0	6537	6300	42	Distilled Water	50	17,239
4/12/99	700	1257	33.4	27.6	4.0	6115	6300	43	Distilled Water	50	17,407
4/19/99	700	1253	34.4	28.6	4.2	6421	6300	43	Distilled Water	50	17,575
4/26/99	700	1250	34.4	27.6	4.2	7528	6300	43	Distilled Water	50	17,743
5/03/99	700	1251	43.3	37.6	4.3	6461	6350	43	Distilled Water	50	17,911
5/10/99	700	1253	38.8	33.3	4.3	6234	6350	43	Distilled Water	50	18,079

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
5/17/99	700	1250	42.5	36.8	4.0	6010	6360	43	Distilled Water	50	18,247
5/20/99	Power failure. Life test restarted.										
5/24/99	700	1266	40.9	35.1	4.3	6574	6700	44	Distilled Water	50	18,415
6/1/99	700	1265	50.1	43.5	3.8	6611	6700	45	Distilled Water	50	18,583
6/2/99	Power failed. Life test restarted.										
6/7/99	700	1265	44.8	39.1	4.3	6421	6600	45	Distilled Water	50	18,751
6/14/99	700	1258	44.8	39.0	4.2	6421	6600	48	Distilled Water	50	18,919
6/21/99	700	1263	39.7	33.7	4.1	6484	6600	48	Distilled Water	50	19,087
6/28/99	700	1264	50.9	44.7	4.1	6700	6600	48	Distilled Water	50	19,255
7/5/99	700	1268	48.4	42.5	4.1	6376	6600	48	Distilled Water	50	19,423
7/12/99	700	1268	41.5	35.4	4.3	6914	6600	49	Distilled Water	50	19,591
7/19/99	700	1267	52.4	46.2	4.0	6537	6700	49	Distilled Water	50	19,759
7/21/99	Shut down due to water leak.										
7/23/99	Life test restarted.										
7/26/99	700	1256	47.8	42.1	4.3	6461	6600	49	Distilled Water	50	19,879
8/1/99	700	1258	43.7	37.6	4.3	6914	6600	49	Distilled Water	50	20,047
8/9/99	700	1261	39.9	34.3	4.3	6341	6670	49	Distilled Water	50	20,215
8/14/99	Power Failure										
8/16/99	Life test restarted										
8/23/99	700	1261	39.9	34.3	4.3	6341	6670	50	Distilled Water	50	20,503
8/23/99	Shut down due to thermocouple failure.										
8/25/99	Life test restarted.										
8/25/99	700		42.5	35.6	4.3	7813	6630	50	Distilled Water	50	20,503
8/30/99	668		35.0	29.5	4.5	6518	6200	50	Distilled Water	50	20,623
9/6/99	700		42.5	35.6	4.3	7813	6630	60	Distilled Water	50	20,791
9/7/99	Shut down due to power failure.										
9/20/99	Chamber thermocouple was replaced. Life test restarted.										
9/27/99	671		36.7	31.3	4.5	6399	6200	90	Distilled Water	50	20,959
10/4/99	670	1250	38.5	33.3	4.5	6162	6100	102		50	21,127
10/11/99	653	1239	38.2	35.1	4.3	3510	6000	102		50	21,295
10/18/99	655	1242	37.4	31.9	4.3	6228	6000	102		50	21,463
10/25/99	655	1242	37.4	31.9	4.3	6228	6000	102		50	21,631
10/25/99	Life test stopped due to power failure. Two heaters were broken in half.										
01/08/00	All heaters, connectors, and spray clips were replaced. Water cartridge filter was replaced. Life test restarted										

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
01/17/00	700	1314	33.3	27.2	4.5	7229	6300	42		50	21,799
01/24/00	700	1310	36.7	30.4	4.5	7466	6500	44		50	21,967
01/30/00	700	1312	37.4	31.2	4.5	7347	6300	44		50	22,135
02/07/00	700	1304	37.6	31.5	4.5	7229	6500	46		50	22,303
02/14/00	700	1304	41.6	35.3	4.3	7134	6500	46		50	22,471
02/21/00	700	1308	38.1	32.3	4.5	6873	6600	46		50	22,639
02/28/00	700	1309	31.1	37.1	4.5	7110	6500	46		50	22,807
03/06/00	700	1312	36.6	30.7	4.5	6992	6500	46		50	22,975
03/13/00	700	1310	31.7	25.9	4.5	6873	6450	46		50	23,143
03/20/00	700	1308	30.1	24.1	4.5	7110	6500	45		50	23,311
03/27/00	700	1304	34.4	28.5	4.5	6992	6600	47		50	23,479
04/03/00	700	1307	36.5	30.2	4.5	7466	6500	47		50	23,647
04/07/00	Life test stopped because fuse box was burnt and a heater was broken.										
04/25/00	Fuse box was replaced along with connectors, heater, and wiring. Life test restarted.										
04/25/00	700	1266	36.5	30.1	4.5	7584	6500	47		50	23,743
05/01/00	700	1290	35.8	29.7	4.5	7229	6500	45		50	23,887
05/08/00	700	1287	45.2	39.1	4.5	7229	6400	46		50	24,055
05/15/00	700	1294	34.8	29.0	4.5	6873	6400	46		50	24,223
05/22/00	700	1293	40.3	34.2	4.5	7229	6500	47	Distilled Water	50	24,391
05/29/00	700	1290	40.2	34.1	4.3	6907	6400	48		50	24,727
06/05/00	689	1280	40.2	34.1	4.3	6907	6300	75		50	24,727
06/05/00	Shut down to replace two heaters, and restarted the same day.										
06/12/00	700	1268	47.3	41.2	4.3	6907	6300	48		50	24,887
06/19/00	700	1268	41.8	35.7	4.3	6907	6300	50		50	25,055
06/26/00	700	1268	41.8	35.7	4.3	6907	6300	50		50	25,223
07/05/00	700	1268	41.8	35.7	4.3	6907	6300	50		50	25,391
07/10/00	690	1255	46.1	40.4	4.3	6454	6800	70		50	25,559
07/17/00	620	1239	40.1	34.5	4.3	6341	5900	90		50	25,727
07/24/00	664	1233	42.3	36.8	4.5	7110	5882	100		50	25,895
07/31/00	640	1192	45.5	40.0	4.5	6518	5395	100		50	26,063
08/07/00	625	1182	46.6	41.5	4.3	5775	5270	102		50	26,231
08/14/00	630	1195	39.6	34.3	4.5	6281	5300	102		50	26,399
08/21/00	630	1184	35.2	29.5	4.3	6454	5300	102		50	26,567
08/28/00	600	1120	38.8	34.2	4.5	5451	4670	102		50	26,735
09/05/00	Shut down due to power failure. Restarted.										
09/06/00	510	1043	31.0	27.0	4.5	4740	3980	102		50	27,071
09/11/00	500	1030	36.5	32.6	4.5	4622	3830	102		50	27,239
09/18/00	498	1027	34.0	30.4	4.5	4266	3815	102		50	27,407
09/25/00	492	1020	31.9	28.4	4.5	4148	3790	102	Distilled Water	50	27,575
10/02/00	491	1011	31.3	27.6	4.5	4385	3660	102		50	27,743
10/08/00	484	1007	23.7	20.1	4.5	4266	3650	102		50	27,911
10/08/00	Life test shut down due to heater degradation										
04/03/01	After a new agreement with NASA, life test restarted.										
04/04/01	700		23.7	20.1	4.5	4266	5800	39	DI Water	50	27,911
04/09/01	700		33.8	28.1	4.5	6755	6100	40	DI Water	50	28,055
04/16/01	700		32.3	26.6	4.5	6755	6080	41	DI Water	50	28,223
04/23/01	700		39.5	33.7	4.5	6873	6300	42	DI Water	50	28,391

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
04/30/01	700	1275	30.8	24.9	4.5	6992	6250	42	DI Water	50	28,559
05/07/01	700	1279	29.6	23.7	4.5	6992	6500	44	DI Water	50	28,727
05/14/01	700	1287	36.4	30.2	4.5	7347	6200	43	DI Water	50	28,895
05/21/01	700	1285	34.9	29.0	4.5	6992	6400	44	DI Water	50	29,063
05/28/01	700	1282	46.1	40.0	4.5	7229	6400	44	DI Water	50	29,231
06/04/01	700	1284	41.3	35.3	4.5	7110	6300	44	DI Water	50	29,399
06/11/01	700	1284	41.3	35.3	4.5	7110	6300	44	DI Water	50	29,567
06/18/01	700	1283	47.0	41.1	4.5	6992	6300	44	DI Water	50	29,735
06/25/01	700	1285	40.1	34.4	4.5	6755	6350	45	DI Water	50	29,903
07/02/01	700	1283	32.0	26.0	4.5	7110	6500	46	DI Water	50	30,071
07/04/01	Shutdown due to power failure. Restarted on 07/05/01 at 7 A.M.										
07/05/01	700	1283	32.0	26.0	4.5	7110	6500	46	DI Water	50	
07/09/01	700	1285	40.1	34.4	4.5	6755	6500	46	DI Water	50	30,239
07/10/01	Shut down due to power failure. Power supply leads were burnt and the insulators were broken.										
07/23/01	Parts replaced and testing restarted.										
07/23/01	700	1277	46.0	40.0	4.5	7110	6100	43	DI Water	50	
07/30/01	700	1282	35.0	29.0	4.5	7110	6200	44	DI Water	50	30,407
08/06/01	700	1282	39.0	33.0	4.4	6952	6100	44	DI Water	50	30,575
08/13/01	700	1282	39.0	33.0	4.5	7110	6250	45	DI Water	50	30,743
08/20/01	Shut down due to power failure. Restarted										
08/20/01	682	1264	36.0	30.0	4.5	7110	6000		DI Water	50	30,911
08/21/01	700	1278	36.0	30.0	4.5	7110	6300	46	DI Water	50	
08/27/01	700	1288	38.0	32.0	4.5	7110	6300	47	DI Water	50	31,079
09/04/01	685	1268	38.0	32.0	4.5	7110	6100	50	DI Water	50	31,247
09/04/01 (Reset)	700	1282	38.0	32.0	4.5	7110	6350	50	DI Water	50	
09/10/01	700	1284	39.0	33.0	4.5	7110	6150	50	DI Water	50	31,415
09/17/01	700	1280	29.0	23.0	4.5	7110	6350	56	DI Water	50	31,583
09/24/01	589	1163	40.0	36.0	4.5	4740	5001	58	DI Water	50	31,751
10/01/01	600	1173	40.0	36.0	4.5	4740	5170	60	DI Water	50	31,919
10/08/01	595	1169	33.0	28.0	4.5	7115	5100	70	DI Water	50	32,087
10/15/01	597	1175	35	30	4.5	7100	5150	70	DI Water	50	32,255
10/22/01	584	1163	31	26	4.5	7100	5050	70	DI Water	50	32,423
10/29/01	579	1165	16	11	4.5	7100	5050	70	DI Water	50	32,591
10/29/01	Testing shut down to rebuild furnace. Heater elements were broken.										
11/09/01	Furnace rebuilt with all new heaters, connectors; replaced water filter, replaced Vapor Temp. T.C., restarted.										
11/10/01	Calorimeter assembly—two .125 dia. Tubes cracked and leaking water. Shut down Life Test.										
02/21/02	New Calorimeter assembly welded together and installed. Restarted 02/21/02.										
02/25/02	700	1230	31.3	25.9	4.5	6400	5600	45	DI Water	50	32,687
03/04/02	700	1226	32.7	26.8	4.5	7000	5600	44	DI Water	50	32,855
03/11/02	700	1224	33.7	27.6	4.5	7200	5700	45	DI Water	50	33,023
03/18/02	700	1230	34.6	28.8	4.5	6800	5800	45	DI Water	50	33,191
03/25/02	700	1232	36.5	31.1	4.5	6400	5700	45	DI Water	50	33,359
04/01/02	700	1228	38.6	32.1	4.5	7700	5900	45	DI Water	50	33,527
04/08/02	700	1230	35.0	29.0	4.5	7100	5900	46	DI Water	50	33,695
04/15/02	700	1231	36.5	30.8	4.5	6700	5700	47	DI Water	50	33,863
04/22/02	700	1230	35.1	29.5	4.5	6500	6000	50	DI Water	50	34,031
04/29/02	700	1231	37.5	32.2	4.5	6200	5700	46	DI Water	50	34,199
05/06/02	700	1231	37.4	32.2	4.5	6100	5800	47	DI Water	50	34,367

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05/13/02	700	1232	39.0	33.5	4.5	6500	6000	47	DI Water	50	34,535
05/20/02	700	1233	35.5	29.7	4.5	6800	5800	48	DI Water	50	34,703
05/28/02	700	1236	40.6	35.5	4.5	6100	5750	47	DI Water	50	34,895
05/31/02	700	1232	41.5	35.6	4.5	7000	5800	47	DI water	50	34,967
05/31/02											Shut-down
10/02/02											Re-start
10/07/02	700	1220	35.7	30.7	4.5	5900	5700	54	“	50	35,111
10/14/02	700	1225	29.1	23.7	4.5	6400	5680	54	“	50	35,279
10/21/02	700	1225	35.6	30.7	4.5	5800	5700	54	“	50	35,447
10/28/02	697	1220	31.1	26.0	4.5	6050	5675	50	“	50	35,615
10/28/02											Shut-down
10/31/02											Re-start
11/04/02	700	1214	35.5	30.2	4.4	6150	5500	48	“	50	35,663
11/11/02	700	1216	38.9	33.5	4.4	6300	5500	46	“	50	35,831
11/18/02	690	1206	32.9	27.5	4.4	6300	5300	50	“	50	35,999
11/25/02	700	1215	34.5	29.2	4.4	6150	5800	50	“	50	36,167
12/02/02	700	1215	32.8	27.3	4.4	6400	5850	53	“	50	36,335
12/09/02	700	1218	36.1	30.6	4.4	6400	5850	50	“	50	36,503
12/16/02	700	1221	35.9	30.6	4.4	6150	5560	50	“	50	36,671
12/23/02	696	1216	35.0	29.6	4.4	6300	5580	50	“	50	36,839
12/30/02	700	1222	32.8	27.4	4.4	6300	5500	52	“	50	37,007
01/06/03	700	1220	33.9	28.4	4.4	6400	5600	53	“	50	37,175
01/13/03	700	1223	30.7	25.4	4.4	6150	5650	53	“	50	37,343
1/20/03	700	1225	32.4	26.9	4.4	6400	5750	54	Water	50	37,511
1/27/03	700	1224	28.2	22.8	4.4	6300	5650	55	“	50	37,679
2/03/03	700	1222	33.5	28.1	4.4	6300	5660	56	“	50	37,847
2/10/03	700	1227	32.5	27.2	4.4	6150	5600	55	“	50	38,015
2/17/03	699	1222	31.8	26.4	4.4	6000	5625	56	“	50	38,183
2/24/03	701	1221	30.1	24.8	4.4	6150	5750	60	“	50	38,351
3/03/03											38,519
3/10/03	700	1225	33.1	27.7	4.4	6000	5550	56	“	50	38,687
3/17/03	700	1226	38.3	32.8	4.4	6400	5650	55	“	50	38,855
3/24/03	700	1225	37.6	32.2	4.4	6000	5550	55	“	50	39,023
3/31/03	700	1226	34.8	29.5	4.4	5890	5500	56	“	50	39,191
4/07/03	700	1226	34.8	29.5	4.4	5890	5500	58	“	50	39,359
4/07/03											Power failure /
4/07/03											Restart
4/14/03	700	1228	38.3	32.9	4.3	5860	5680	56	“	50	39,527
4/17/03											Power failure
4/21/03											Restart
4/28/03	700	1229	38.7	33.5	4.3	5640	5400	55	“	50	39,735
5/05/03	700	1229	38.5	33.1	4.3	5860	5300	55	“	50	39,903
5/12/03	632	1159	39.6	34.8	4.3	5200	4935	60	“	50	40,071
5/12/03						Heater replacement				%	Shut-down
5/13/03											Re-start

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5/19/03	700	1230	38.3	33.0	4.3	5750	5750	52	Water	50	40,215
5/27/03	700	1223	39.6	34.2	4.3	5860	5700	52	“	50	40,383
6/02/03	700	1233	37.6	32.2	4.3	5860	5700	53	“	50	40,551
6/09/03	700	1227	39.2	33.9	4.3	5750	5700	52	“	50	40,719
6/10/03						Power lead failure					Shut down
6/20/03											Re-start
6/23/03	683	1223	39.3	34.1	4.3	5640	5800	56	“	50	40,800
6/30/03	700	1238	38.2	32.7	4.3	5960	5700	50	“	50	40,968
7/06/03						Building power failed					Shut down
7/07/03											Re-start
7/07/03	700	1236	38.2	32.7	4.3	5960	5700	50	“	50	41,128
7/14/03	700	1235	37.3	31.8	4.3	5960	5600	56	“	50	41,296
7/21/03	700	1238	43.3	38.0	4.3	5750	5750	52	“	50	41,464
7/28/03	700	1236	42.3	37.0	4.3	5750	5650	51	“	50	41,632
8/04/03	700	1235	42.1	36.6	4.3	5960	5750	52	“	50	41,800
8/11/03	700	1240	44.7	39.1	4.3	6070	5800	52	“	50	41,968
8/16/03						Power failure					Shut down
8/18/03											Re-start
8/25/03	700	1235	42.0	36.5	4.3	5960	5750	52	Water	50%	42,280
8/29/03						Power failure					Shut down
9/02/03											Re-start
9/08/03	700	1238	39.7	34.2	4.3	5960	6000	60	“	50	42,553
9/15/03	700	1244	41.5	36.1	4.3	5860	6180	58	“	50	42,721
9/22/03	700	1240	39.7	34.2	4.4	6100	6000	60	“	50	42,887
9/24/03						Calorimeter clogged up					Shut down
11/10/03						Flushed calorimeter					Re-start
11/17/03	700	1235	39.6	34.5	4.5	5785	5950	54	“	50	43,104
11/24/03	696	1225	40.1	34.9	4.3	5960	5725	54	“	50	43,272
12/01/03	697	1221	39.0	33.7	4.5	6010	5675	54	“	50	43,440
12/08/03	692	1216	37.3	32.7	4.5	6350	5650	54	“	50	43,608
12/15/03	696	1219	37.4	32.1	4.5	6010	5650	54	“	50	43,776
12/22/03	695	1215	38.3	33.0	4.5	6010	5625	54	“	50	43,944
12/29/03	691	1214	38.8	33.8	4.5	5670	5600	54	“	50	44,112
1/05/04	695	1215	38.2	33.1	4.5	5780	5600	54	“	50	44,280
1/12/04	699	1215	36.8	31.7	4.5	5780	5600	54	“	50	44,448
1/19/04	702	1217	35.4	30.3	4.5	5780	5650	54	“	50	44,516
1/26/04	704	1217	33.4	28.5	4.5	5560	5600	54	“	50	44,684
2/02/04	703	1210	33.6	29.1	4.5	5100	5560	54	“	50	44,852
2/07/04	714	1218	35.6	29.2	4.5	7260 [?]	5650	54	Water	50%	45,020
2/16/04	705	1209	35.0	30.1	4.5	5560	5650	54	“	50	45,188
2/23/04	703	1211	38.1	33.0	4.5	5780	5650	54	“	50	45,356
3/01/04	685	1200	40.0	34.9	4.5	5780	5500	54	“	50	45,524
3/04/04						Install new controller					

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3/08/04	700	1237	42.1	36.6	4.5	6100 [?]	5900		“	50	45,712
3/15/04	700	1240	42.4	37.3	4.5	5780	5700		“	50	45,880
3/22/04	700	1239	37.4	31.8	4.5	6210	6200		“	50	46,048
3/29/04	700	1238	37.8	31.0	4.5	7540 [?]	6150		“	50	46,216
4/05/04	700	1246	37.3	32.0	4.5	5877 [?]	5750		“	50	46,384
4/12/04	700	1246	42.1	35.5	4.5	7318 [?]	5600		“	50	46,552
4/17/04	700	1242	46.6	39.8	4.4	7372 [?]	5700		“	50	46,770
4/26/04	700	1256	36.2	30.6	4.4	6071	5900		“	50	46,888
5/03/04	700	1256	36.3	29.1	4.4	7806 [?]	5850		“	50	47,056
5/10/04	700	1254	44.9	39.6	4.4	5746	6050		“	50	47,224
5/17/04	700	1254	44.5	37.6	4.4	7481 [?]	6050		“	50	47,392
5/24/04	700	1256	48.6	43.1	4.4	5963	5775		“	50	47,560
6/01/04	700	1260	40.1	32.8	4.5	8094 [?]	5750		“	50	47,728
6/07/04	700	1260	39.4	33.7	4.5	6320 [?]	5700		“	50	47,896
6/14/04	700	1259	43.6	36.6	4.5	7761 [?]	6000		“	50	48,064
6/21/04						Power failure 6/20			Water		48,232
7/12/04						Replaced breaker	50amp main				
7/19/04	700	1247	40.0	34.3	4.5	6320 [?]	5850		“	50	48,400
7/26/04	700	1248	40.5	34.3	4.5	6874 [?]	5850		“	50	48,568
7/26/04						Shutdown System			Heaters Replaced Replacement		
8/26/04						Restart System			New water		
8/27/04	700	OUT	40.9	35.6	4.5	5876	6100		“	50	48,592
8/30/04	700	OUT	39.9	34.9	4.5	5543	6150		“	50	48,664
9/06/04	700	1241	38.2	33.5	4.5	5210	6000		“	50	48,872
9/13/04	700	1241	41.4	35.2	4.5	6873 [?]	5875		“	50	49,040
9/20/04	700	1241	36.7	31.5	4.5	5764	5850		“	50	49,208
9/27/04	700	1237	38.9	34.1	4.5	5321	5900		“	50	49,376
10/04/04	700	1237	38.9	34.1	4.5	5321	5900		“	50	49,544
10/11/04	700	1242	37.2	31.7	4.5	6097 [?]	5862		“	50	49,712
10/15/04						Calorimeter clogged					
12/08/04		Restart				Calorimeter Rebuild					49,712
12/08/04	700	1240	38.4	33.4	4.5	5543	6100		“‘	50	49,712
12/13/04						Bld. Power Failure					49,760
12/14/04						Restart system				50	49,760
12/20/04	699	1203	30.3	25.6	4.5	5210	5850		“	50	49,904
1/03/05	698	1203	40.8	36.0	4.5	5321	5860		Water	50	50,240
1/10/05	702	1205	38.0	33.4	4.5	5099	5860		“	50	50,408
1/17/05	702	1205	37.3	32.5	4.5	5321	5830		“	50	50,576
1/24/05	707	1210	38.0	33.1	4.5	5432	5874		“	50	50,744
1/31/05	697	1197	41.4	36.6	4.5	5321	5725		“	50	50,912
2/07/05	695	1197	40.8	36.1	4.5	5684	5765		“	50	51,080

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
2/14/05	701	1200	39.3	34.6	4.5	5684	5680		“	50	51,248
2/21/05	700	1200	34.1	29.2	4.5	5925 [?]	5725		“	50	51,416
2/28/05	700	1191	37.9	32.2	4.5	6892 [?]	5750		“	50	51,584
3/07/05	700	1196	38.3	33.2	4.5	6287	5800		“	50	51,752
3/14/05	700	1198	33.5	28.7	4.5	5917	5840		“	50	51,920
3/21/05	700	1198	36.9	32.0	4.5	6040 [?]	5880		“	50	52,088
3/28/05	700	1197	39.4	34.9	4.5	5547	5850		“	50	52,256
4/04/05	700	1197	37.1	32.7	4.5	5423	5855		“	50	52,424
4/11/05	700	1198	39.1	34.6	4.5	5423	5875		“	50	52,592
4/18/05	700	1197	39.8	35.3	4.5	5423	5800		“	50	52,760
4/25/05	700	1198	38.1	33.7	4.5	5302	5800		“	50	52,928
5/02/05	700	1198	38.2	33.8	4.5	5302	5850		“	50	53,096
5/09/05	700	1198	38.0	33.6	4.5	5302	5860		“	50	53,264
5/16/05	700	1198	40.0	35.3	4.5	5663	5870		“	50	53,432
5/23/05	700	1198	38.5	34.1	4.5	5302	5850		“	50	53,600
5/30/05	700	1198	42.1	37.6	4.5	5422	5800		“	50	53,768
6/06/05	700	1198	43.6	39.1	4.5	5422	5825		“	50	53,936
6/13/05					6/12	POWER FAILURE	7:45P.M.				
6/13/05	700	1198	38.5	34.1	4.5	5302	5850		“	50	54,092
6/20/05	700	1198	42.6	37.8	4.5	5784	5700		“	50	54,260
6/27/05	700	1198	43.7	38.9	4.5	5784	5745		“	50	54,428
6/28/05						POWER FAILURE					
7/5/05			RE-START			METERS CAL.					54,428
7/11/05	700	1198	41.9	37.1	4.5	5784	5890		“	50	54,596
7/18/05	700	1198	44.2	39.7	4.5	5423	5850		“	50	54,764
7/25/05	700	1198	42.7	38.2	4.5	5423	5870		“	50	54,932
8/01/05	700	1199	42.0	37.5	4.5	5423	5870		DI Water	50	55,100
8/08/05	700	1198	43.1	38.5	4.5	5544	5870		“	50	55,268
8/15/05	700	1199	44.2	39.6	4.5	5544	5850		“	50	55,436
8/22/05	700	1199	42.9	38.2	4.5	5665	5890		“	50	55,604
8/29/05	700	1199	43.9	39.2	4.5	5665	5850		“	50	55,772
9/05/05	700	1200	42.2	37.6	4.5	5544	5876		“	50	55,940
9/12/05	700	1200	42.8	38.2	4.5	5544	5720		“	50	56,108
9/19/05	700	1200	43.2	38.9	4.5	5182	5750		““‘	50	56,276
9/26/05	700	1199	41.6	36.9	4.5	5664	5750		“	50	56,444
10/03/05	700	1198	43.3	38.7	4.5	5543	5780		“	50	56,612
10/10/05	700	1184	42.3	37.8	4.5	5422	5500		“	50	56,780
10/17/05	700	1184	39.3	34.8	4.5	5422	5500		“	50	56,984
10/24/05	700	1184	41.6	37.2	4.5	5301	5480		“	50	57,116
10/31/05	700	1185	40.5	36.1	4.5	5301	5490		“	50	57,284
11/07/05	700	1186	39.7	35.3	4.5	5301	5550		“	50	57,452
11/14/05	700	1186	41.3	36.9	4.5	5301	5530		“	50	57,620
11/21/05	700	1186	41.1	36.6	4.5	5421	5550		“	50	57,788
11/28/05	700	1185	41.7	37.3	4.5	5301	5550		“	50	57,956
12/05/05	700	1183	36.0	31.4	4.5	5542	5550		DI Water	50	58,124
12/12/05	700	1165	38.6	34.4	4.5	5060	5150		“	50	58,292

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
12/19/05	700	1165	38.2	33.9	4.5	5180	5150		“	50	58,460
12/23/05	700	1165	41.7	37.7	4.5	4818	5150		“	50	58,556
12/23/0512:00pm						SHUT DOWN					
12/28/05						Heater replacement					
12/28/052:00pm	700	1157	40.3	36.2	4.5	4938	5920	Restart system	“	50	58,556
01/03/06	700	1157	38.2	34.1	4.5	4938	5150		“	50	58,700
01/09/06	700	1157	38.1	34.0	4.5	4938	5150		“	50	58,868
01/16/06	700	1157	30.8	26.6	4.5	5058	5270		“	50	59,036
01/23/06	700	1155	37.6	32.9	4.5	5660	5200		“	50	59,204
01/30/06	700	1155	41.3	37.4	4.5	4697	5200		“	50	59,372
02/06/06	700	1155	39.2	34.6	4.5	5540	5200		“	50	59,540
02/13/06	700	1153	36.9	32.3	4.5	5540	5150		“	50	59,708
02/20/06	700	1153	37.2	32.6	4.5	5540	5150		“	50	59,826
02/27/06	700	1151	36.2	31.7	4.5	5420	5065		“	50	60,044
03/06/06	700	1151	36.2	31.7	4.5	5420	5065		“	50	60,212
03/13/06	700	1151	40.6	36.1	4.5	5420	5065		“	50	60,380
03/20/06	700	1145	39.6	34.9	4.5	5660	5000		DI Water	50	60,548
03/27/06	700	1136	38.5	34.1	4.5	4940	4800		“	50	60,716
04/03/06	700	1136	38.7	34.3	4.5	4940	4800		“	50	60,884
04/05/06	700	1136	34.1	29.6	4.5	5420	4825		“	50	60,932
04/05/06						Shutdown to rebuild the calorimeter					
05/23/06 restart	700	1214	47.2	41.6	4.5	6300	6025		“	50	60,932
05/28/06						Shutdown; damaged power cables					61,004
06/01/06restarted											
06/05/06	553	1052	40.7	36.6	4.5	4940	4225		“	50	61,124
06/12/06						Brief power failure; restart					
06/19/06	700	1207	46.6	40.5	4.5	7345	5840		“	50	61,436
06/26/06	700	1207	44.7	39.2	4.5	6620	5825		“	50	61,604
07/01/06						Power failure					
07/05/06						restart					61,700
07/10/06	700	1207	44.4	38.8	4.5	6740	5830		“	50	61,820
07/17/06	700	1207	45.0	40.3	4.5	5660	5850		“	50	61,988
07/19/06						Power failed (& restart)					
07/20/06	694	1207	44.6	38.8	4.5	6980	5875		“	50	62,060
07/20/06						Shutdown to replace heaters.					
07/25/06						Startup.					
07/31/06	700	1205	43.7	38.3	4.5	6500	5875		DI Water	50	62,204

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08/07/06	700	1207	44.3	38.6	4.5	6860	5875		“	50	62,372
08/08/06						Power failed w/damage to wiring					
09/06/06						Repaired and restarted					
09/10/06						Power failed					
09/11/06 restarted.	700	1203	39.3	33.8	4.5	6620	5880		“	50	62,492
09/18/06	700	1205	42.9	37.3	4.5	6740	5750		“	50	62,660
09/25/06	700	1203	45.8	40.3	4.5	6620	5700		“	50	62,828
09/28/06						Power failed & restarted.					
10/02/06	700	1208	39.7	33.9	4.5	6980	5775		“	50	62,980
10/09/06	700	1203	41.7	36.2	4.5	6620	5700		“	50	63,148
10/16/06	700	1202	42.4	37.0	4.5	6500	5700		“	50	63,316
10/23/06	700	1202	45.2	39.5	4.5	6860	5565		“	50	63,484
10/30/06	700	1230	43.6	37.8	4.5	6980Power failed & restarted.	5710		“	50	63,628
11/05/06						Power failed & restarted					
11/07/06	700	1202	41.3	35.5	4.5	6980	5700		“	50	63,748
11/13/06	700	1203	42.4	36.7	4.5	6860	5650		DI Water	50	63,892
11/20/06	700	1205	39.1	33.3	4.5	6980	5600		“	50	64,060
11/27/06	700	1203	41.8	36.1	4.5	6860	5600		“	50	64,228
12/04/06	700	1204	37.2	31.6	4.5	6740	5600		“	50	64,396
12/11/06	700	1204	38.8	33.2	4.5	6740	5600		“	50	64,564
12/18/06	700	1204	40.7	34.9	4.5	6980	5600		“	50	64,732
12/22/06	700	1202	41.3	35.5	4.5	6980	5600		“	50	64,828
12/22/06						Shutdown for repairs.					
12/27/06	700	1200	35.6	30.6	4.5	6020	5600		“	50	64,828
01/02/07 Restart.	700	1194	39.9	34.4	4.5	6620	5940		“	50	64,948
01/08/07	700	1198	40.4	34.8	4.5	6740	6020		“	50	65,092
01/15/07	700	1194	39.9	34.4	4.5	6620	5850		“	50	65,260
01/22/07	700	1196	37.4	31.9	4.5	6620	5875		“	50	65,428
01/27/07						Power failed.					
01/29/07						Restarted.					
01/30/07	670	1089	30.0	25.7	4.5	5175	4170		“	50	65,548
02/05/07	531	1014	14.6	10.6	4.5	4810	3775		“	50	65,716
02/12/07	565	1040	41.7	37.9	4.5	4570	3925		“	50	65,884
02/19/07	563	1026	38.6	35.1	4.5	4210	3760		DI Water	50	66,052
02/26/07	573	1034	40.9	37.1	4.5	4570	3830		“	50	66,220
03/06/07						Shutdown to repair calorimeter.					66,418
05/23/07	Calorimeter “total rebuilt” with 304 SS only. Empty DI water, cleanout, recharge, replace water filter, 20 micron 10” long. Retighten all connections. Clean heat exchanger fins.										
5/23/07	700	1231	45.1	39.1	4.5	7216	7150		DI Water	50	66,418

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5/24/07	700	1229	45.4	39.0	4.5	7697	6330		“	50	66,442
5/25/07	700	1231	45.7	39.1	4.5	7937	6400		“	50	66,466
5/29/07	700	1229	46.0	39.5	4.5	7817	6400		“	50	66,562
6/4/07	700	1223	49.2	42.6	4.0	7937	6190		“	50	66,706
6/6/07	700	1224	49.8	43.5	4.0	7576	6350		“	50	66,754
Shut down due to power upgrade											
6/7/07	700	1224	49.8	43.5	4.0	7576	6350		DI Water	50	66,778
6/11/07	700	1224	47.2	40.8	4.5	7697	6300		“	50	66,874
6/18/07	700	1220	50.7	44.3	4.0	7697	6150		“	50	67,039
6/25/07	700	1220	51.1	45.9	4.3	6254	6150		“	50	67,207
6/29/07	700	1220	50.8	45.5	4.0	6374	6170		“	50	67,299
7/9/07	700	1218	51.3	44.4	4.0	8298	6070		“	50	67,587
7/16/07	700	1220	49.9	44.0	4.0	7096	6200		“	50	67,755
7/23/07	700	1219	49.3	43.3	4.0	7216	6200		DI Water	50	67,923
7/30/07	700	1221	49.8	43.9	4.0	7096	6250		“	50	68,091
8/6/07	700	1219	51.7	45.9	4.0	6975	6250		“	50	68,259
8/13/07	700	1219	50.6	45.3	4.0	6374	6250		“	50	68,427
8/20/07	700	1219	48.9	42.8	4.3	7336	6280		“	50	68,595
8/27/07	Replaced two TCs in heat pipe. Replace electrical cable to furnace heaters. Replace water filter and drain DI water. Clean fin side of heat exchangers. Startup at 10:00 A.M.										
8/28/07	700	1218	45.6	39.7	4.3	7096	6325		DI Water	50	68,619
9/4/07	700	1220	49.5	44.3	4.3	6254	6200		“	50	68,787
9/10/07	700	1222	51.3	45.3	4.3	7216	6350		“	50	68,955
9/17/07	700	1219	50.2	44.4	4.3	6975	6150		“	50	69,123
9/24/07	700	1223	45.7	39.7	4.3	7216	6250		“	50	69,459
10/1/07	700	1222	51.3	46.2	4.3	6133	6300		“	50	69,627
10/8/07	700	1221	52.0	46.4	4.3	6735	6225		“	50	69,795
10/15/07	700	1221	50.3	44.9	4.3	6494	6250		“	50	69,963
10/22/07	700	1219	50.6	44.4	4.3	7456	6150		“	50	70,131
10/29/07	700	1218	48.8	42.9	4.0	7096	6125		“	50	70,299
11/5/07	700	1218	49.3	43.4	4.3	7096	6100		“	50	70,467
11/12/07	700	1219	50.3	44.4	4.3	7096	6160		“	50	70,635
11/19/07	700	1219	45.2	39.1	4.3	7336	6150		DI Water	50	70,803
11/26/07	700	1221	45.6	39.7	4.5	7096	6270		“	50	70,971
12/3/07	700	1220	46.3	40.2	4.3	7336	6200		“	50	71,139
12/10/07	700	1220	44.8	38.9	4.3	7096	6200		“	50	71,307
12/17/07	700	1217	45.8	39.9	4.3	7096	6100		“	50	71,475
12/24/07	Power interruption. All system off. Replaced heaters, connectors, repaired electrical feed cable. Drain DI water tank and clean it. Replace water filter. Add “bleed off” DI water line. Clean and vacuum fin side of heat exchanger										
12/28/07	700	1205	44.3	38.5	4.5	6975	6650		“	50	71,475
1/2/08	700	1204	44.2	38.2	4.3	7216	5830		“	50	71,595
1/7/08	700	1207	47.6	41.7	4.3	7096	5900		“	50	71,715
1/14/08	700	1207	43.9	38.1	4.3	6975	5875		“	50	71,883
1/21/08	700	1207	37.6	31.7	4.3	7095	5910		“	50	72,051
1/28/08	700	1207	45.6	39.7	4.3	7095	5860		“	50	72,219
2/4/08	700	1208	45.7	39.8	4.3	7095	5800		“	50	72,387
2/11/08	700	1206	37.7	31.8	4.3	7095	5810		“	50	72,555
2/18/08	700	1208	43.5	37.7	4.3	6975	5875		“	50	72,723
2/25/08	700	1206	43.6	37.8	4.3	6975	5850		“	50	72,891

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3/3/08	700	1205	39.8	34.0	4.3	6975	5850		“	50	73,059
3/10/08	700	1206	39.8	34.0	4.3	6975	5850		“	50	73,227
3/17/08	700	1193	41.8	36.2	4.3	6734	5560			50	73,395
	Total	rebuild	Calorimeter,	flush	tank,	calibrate	meters				
4/14/08						RESTART SYSTEM					
4/15/08	700	1223	48.5	42.1	4.3	7695	6125			50	73,419
4/21/08	700	1221	43.3	36.9	4.3	7695	6065			50	73,563
4/25/08	700	890	OFF	OFF	OFF	BROKEN WATER	LINE			50	73,659
5/6/08						RESTART SYSTEM					
5/7/08	700	1221	50.8	44.6	4.3	7455	6200			50	73,683
5/12/08	700	1220	43.8	37.3	4.3	7816	6050			50	73,743
5/19/08	700	1220	44.8	38.6	4.3	7455	6100			50	73,911
5/26/08	700	1219	49.4	43.2	4.3	7455	6000			50	74,079
6/2/08	700	1220	47.2	40.8	4.3	7695	6000			50	74,247
6/9/08	700	1218	45.8	39.5	4.3	7575	5950			50	74,415
6/16/08	700	1216	46.4	40.5	4.3	7094	5950			50	74,583
6/23/08	700	1215	50.1	44.3	4.0	6974	5870			50	74,751
6/24/08						POWER FAILURE					
6/30/08	700	1215	45.9	39.7	4.3	7455	5875			50	74,919
7/7/08	700	1215	43.3	36.9	4.3	7695	5875			50	75,087
7/14/08	700	1215	45.1	39.0	4.3	7334	5875			50	75,255
7/21/08						POWER FAILURE			1:00 p.m. restart		
7/21/08	700	1210	45.6	39.8	4.3	6973	5970			50	75,423
7/22/08						Calorimeter clogged					
9/4/08						RESTART SYSTEM					
9/5/08	609	1130	39.8	35.7	4.5	4929	5120			50	75,423
9/8/08	700	1222	41.0	35.8	4.5	6251	6050			50	75,495
9/15/08	700	1217	42.7	37.5	4.5	6251	5900			50	75,663
9/22/08	700	1217	40.9	35.9	4.5	6010	5925			50	75,831
9/26/08	700	1216	43.6	38.5	4.5	6130	5885			50	75,927
9/26/08						Replaced Heaters					
9/27/08						RESTART SYSTEM					
9/29/08	700	1225	43.2	37.6	4.5	6731	6500			50	75,927
10/6/08	700	1228	40.2	34.8	4.5	6491	6510			50	76,095
10/13/08	700	1228	39.1	33.8	4.5	6371	6410			50	76,263
10/20/08	700	1228	38.4	33.1	4.5	6371	6450			50	76,431
10/27/08	700	1228	39.3	34.1	4.5	6251	6370			50	76,599
11/3/08	700	1226	40.1	34.9	4.5	6251	6260			50	76,767
11/4/08						Replaced Power leads	Restart system				

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
11/10/08	700	1224	40.6	35.5	4.5	6131	6320			50	76,935
11/17/08	700	1226	38.8	33.6	4.5	6251	6360			50	77,103
11/24/08	700	1225	42.2	36.2	4.5	7213	6350			50	77,271
12/1/08	700	1208	40.8	35.7	4.5	6131	6300			50	77,439
12/2/08						Calorimeter clogged					
12/2/08						Restart System					
12/8/08	700	1227	38.7	34.2	4.5	5410	6425			50	77,595
12/9/08	700	1238	44.1	39.4	4.5	5650	6650			50	77,619
12/15/08	700	1234	44.9	40.8	4.5	4929	6450			50	77,763
12/18/08						Replaced Power leads	Restart system				
12/22/08	700	1235	41.1	37.1	4.5	4809	6485			50	77,931
12/29/08	700	1237	39.1	34.8	4.5	5170	6540			50	78,099
12/31/08					Bld.	Power failure					78,147
1/5/09						Restart System					
1/12/09	700	1240	36.4	31.9	4.5	5410	6560			50	78,315
1/19/09	700	1235	40.1	36.1	4.5	4809	6460			50	78,483
1/26/09	700	1237	37.3	33.1	4.5	5049	6500			50	78,651
2/2/09	700	1235	39.9	35.5	4.5	5289	6500			50	78,819
2/9/09	700	1234	39.9	35.5	4.5	5289	6500			50	78,987
2/16/09	700	1238	40.4	35.8	4.5	5529	6550			50	79,155
2/23/09	700	1238	38.2	33.7	4.5	5409	6600			50	79,323
3/02/09	700	1235	38.2	33.6	4.5	5529	6580			50	79,491
3/09/09	700	1235	44.8	40.2	4.5	5529	6350			50	79,659
3/16/09	700	1233	41.3	37.0	4.5	5169	6430			50	79,827
3/23/09	700	1230	40.1	35.6	4.5	5409	6400			50	79,995
3/27/09	700	1226	43.2	38.9	4.5	5649	6100			50	80,091
3/27/09						Shutdown. calorimeter clogged.					
6/4/09						System Restart after Refurbish-ment					
6/4/09	700	1242	43.9	39.4	4.5	5297	6560			50	80,091
6/08/09	700	1244	47.3	41.7	4.5	6592	6620			50	80,187
6/15/09	700	1236	42.1	36.8	4.5	6238	6550			50	80,373
6/22/09						Power failure					
6/22/09						System Restart					80,541
6/29/09	700	1234	44.2	38.6	4.5	6592	6445			50	80,709
07/06/09	700	1228	41.5	36.5	4.5	5885	6528			50	80,877
07/13/09	700	1224	40.8	35.4	4.5	6356	6300			50	81,045
07/20/09	700	1225	41.4	36.1	4.5	6238	6375			50	81,213
07/27/09	700	1225	42.8	37.4	4.5	6356	6175			50	81,381
08/03/09	700	1225	42.8	37.4	4.5	6356	6175			50	81,549
08/10/09	700	1230	44.4	38.8	4.5	6592	6250			50	81,717

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
08/17/09	700	1230	44.4	38.8	4.5	6592	6275			50	81,885
08/24/09	700	1224	43.2	37.9	4.5	6238	6175			50	82,053
08/24/09						Shutdown, Calorimeter Clogged					
09/15/09						System Restart after Refurbishment					
09/15/09	700	1228	39.2	34.6	4.5	5349	6275			50	82,056
09/21/09	700	1212	40.9	35.3	4.5	6512	6225			50	82,197
09/28/09	700	1208	39.6	34	4.5	6512	6150			50	82,365
10/05/09	700	1205	39.4	33.9	4.5	6396	6100			50	82,533
10/12/09	700	1205	38.2	32.8	4.5	6279	6125			50	82,701
10/19/09	700	1205	39.8	34.4	4.5	6279	5900			50	82,869
10/26/09	700	1200	44.3	39.2	4.5	5930	5825			50	83,037
10/29/09	700	1189	44.8	39.4	4.5	6279	5700			50	83,109
10/29/09						Shutdown, Calorimeter Clogged					
11/16/09						System Restart after Refurbishment					83,109
11/23/09	700	1167	38.9	33.8	4.5	5930	5700			50	83,227
11/30/09	700	1160	41.6	35.3	4.5	7326	5500			50	83,445
12/07/09	700	1154	36.9	31.7	4.5	6047	5450			50	83,613
12/14/09	700	1154	41.6	36.6	4.5	5814	5450			50	83,781
12/21/09	700	1154	38	32.8	4.5	6047	5450			50	83,949
12/28/09	700	1154	36.4	31.7	4.5	5465	5400			50	84,117
01/04/10	700	1160	38.7	33.7	4.5	5814	5450			50	84,285
01/11/10	700	1160	39.8	34.7	4.5	5930	5470			50	84,453
01/18/10	700	1158	40.8	36	4.5	5582	5400			50	84,621
01/25/10	700	1158	41.3	36.6	4.5	5465	5400			50	84,789
02/01/10	700	1158	37.1	32.3	4.5	5582	5400			50	94,957
02/08/10	700	1157	37.7	32.7	4.5	5814	5375			50	85,125
02/15/10	700	1150	40.9	36.1	4.5	5582	5225			50	85,293
02/22/10	700	1155	43.1	38.4	4.5	5465	5300			50	85,461
03/01/10	700	1143	40.3	35.5	4.5	5582	5155			50	85,629
03/08/10	700	1144	41.4	36.5	4.5	5698	5175			50	85,797
03/12/10	700	1148	40.7	35.8	4.5	5698	5250			50	85,901
03/12/10						Shutdown, Heater Replacement					
03/15/10						Restart after Heater Replacement					
03/22/10	700	1169	43.9	39.4	4.5	5233	5575			50	86,079
03/29/10	700	1173	43.6	38.6	4.5	5814	5500			50	86,247
04/05/10	700	1176	42.9	38.2	4.5	5465	5550			50	86,415
04/12/10	700	1180	40.7	36	4.5	5465	5500			50	86,583

Date	Vapor temp. (°C)	Heater temp. (°C)	Coolant temp. out (°C)	Coolant temp. in (°C)	Flow rate (GPM)	Calorimeter power (W)	Elect. Power (W)	Percent of full power	Coolant	N_2 flow	Hour meter
04/19/10	700	1182	37.4	32.9	4.5	5233	5725			50	86,751
04/26/10	700	1179	41.3	36	4.5	6163	5400			50	86,919
05/03/10	700	1181	44.1	39.2	4.5	5698	5725			50	87,087
05/10/10	700	1181	40.5	35.7	4.5	5582	5575			50	87,255
05/17/10	700	1181	41.4	36.8	4.5	5349	5525			50	87,423
05/24/10	700	1181	41.5	36.8	4.5	5465	5715			50	87,591
06/01/10	700	1181	40.9	36.1	4.5	5582	5600			50	87,783
06/01/10						Shutdown after Test Completion					

6.0 Post Operational Analysis Results

This section of the paper describes the post-test analysis of the sodium and the heat pipe envelope. The goal of this task was to measure and evaluate changes to the sodium chemistry and envelope metallurgy incurred during the long term operation of the heat pipe. Figure 3 shows the heat pipe at the end of life testing.

6.1 Post-Test Analysis of the Working Fluid Chemistry

At the conclusion of testing, a sodium sample was removed from the heat pipe for analysis. After removal from the support test stand, the two heat pipe fill tubes were torch heated to drive liquid sodium out of them. The heat pipe was then placed in an argon-filled glove box, and the fill tubes were cut off. A clean stainless steel vessel with a 1/4 in. connecting tube was welded onto one of the fill tubes on the heat pipe. A tube section with a vacuum valve was welded onto the other fill tube. The heat pipe with these vessels attached to the fill ports is shown in Figure 4. The heat pipe was then heated as shown in Figure 5, and about 10 g of sodium were pushed into the collection vessel under argon pressure. The collection vessel was then placed in an argon glove box, and a solution was prepared by dissolving 1 g in deionized water in a glass Pyrex (Corning, Incorporated, Corning, NY) beaker. The sodium hydroxide solution was then diluted to 500 ml. The resulting solution was acidified to a pH 2.0 using nitric acid, as determined by pH paper.

A sample of the sodium was also collected from the source vessel, to compare the initial composition with the composition after ten years of operation. This sample was similarly prepared. Lastly, a sample of the de-ionized water was collected to confirm that no contamination occurred due to impurities in the water.

The aqueous sample was placed into a Nalgene bottle and sent to Lehigh Testing Laboratories for chemical analysis. The sodium solution was scanned from ~160 to ~ 800 nm with a Spectro CIROS, side-on plasma, inductively coupled plasma atomic emission spectrometer (ICP–AES) equipped with a CCD detector. A background blank of 2,000 mg/L sodium solution from a traceable stock solution was also scanned; this sample was also acidified with nitric acid. Element peaks above the background scan were noted and a method was generated for these elements, which were then quantified using the same ICP–AES. Calibration curves for each of the elements determined were constructed using traceable standards, which included a matrix of 2,000 mg/L sodium based upon the sample preparation specifications. A comparison of the sodium peaks (standard, blank and sample) suggests that the value has good integrity. Thus, a sample concentration of 1g/500 ml or 2,000 mg/L was used to quantify the elemental concentration data. In other words, the solution concentration in ppm is equal to the concentrations of other elements found in the sodium sample.

Figure 3.—Heat pipe at the end of life testing.

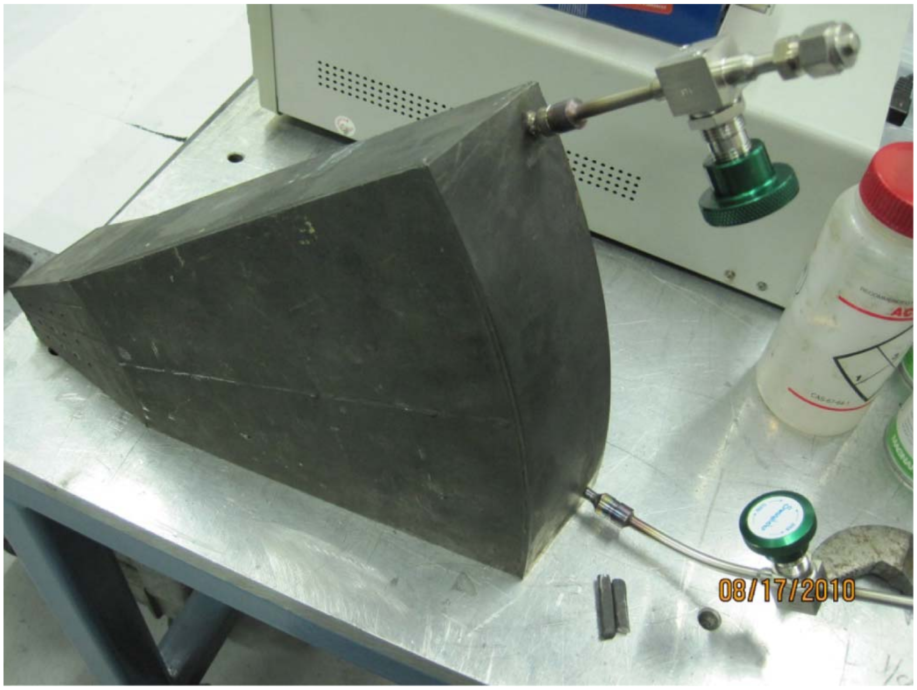


Figure 4.—Vessels attached to heat pipe fill ports.

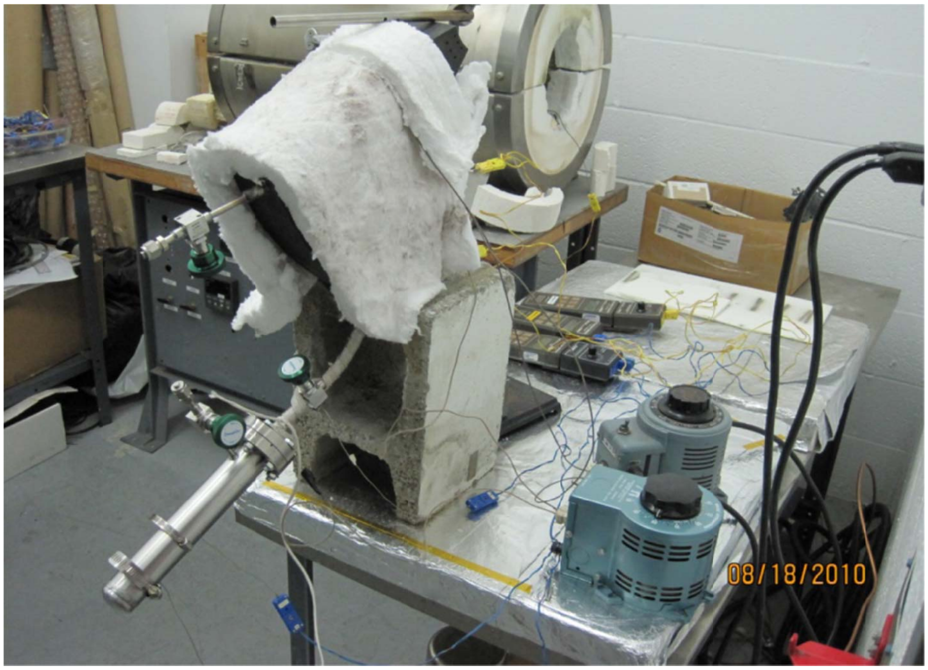


Figure 5.—Heating and draining the sodium from the heat pipe.

TABLE 3.—SODIUM COMPOSITION ANALYSIS

Element	Source sodium, ppm	After 10 yr, ppm	De-ionized water source, ppm
Boron	41	713	0.1
Magnesium	5	15	<0.0001
Aluminum	26	286	<0.02
Silicon	<14	7171	0.03
Potassium	430	177	<0.04
Calcium	25	86	<0.0004
Chromium	4	39	0.01
Manganese	1	4	<0.0007
Iron	14	198	0.06
Copper	84	98	<0.002
Zinc	37	78	0.004
Strontium	0.5	0.6	<0.0002
Barium	48	949	<0.002
Phosphorous	22	<1	<0.04
Nickel	114	<1	<0.01
Lithium	0	18	0
Zirconium	0	5	0

6.1.1 Sodium Analysis Results

Fifteen trace elements were found in the initial sodium composition, compared to seventeen that were found present in the composition after 10 yr of operation. Table 3 shows the complete sodium analysis results. The de-ionized water was determined to be essentially free of trace metal contaminants, which verifies the accuracy of the results. The largest changes to the sodium composition included increased dissolution of boron, aluminum, silicon, iron, and barium. The source of these elements would be the Inconel and stainless steel vessel materials in contact with the sodium. A decrease in the potassium and nickel concentration was also measured.

Review of the Inconel alloy composition shows that boron, manganese, iron, chromium, silicon, and aluminum may have dissolved into the sodium from the envelope inner surface. Similarly, iron, chromium, manganese, and silicon are present as alloying elements in the 316 stainless steel screen wick material. The envelope and wick materials can account for all of the trace element increases except barium. It is possible that barium is present in small concentrations in either the wick or wall material, or that the sodium sample removed from the heat pipe had barium concentrated in the excess fluid charge, because as a heavy element it would have settled to the bottom of the vessel from where the sample was removed.

6.2 Post-Test Analysis of the Envelope and Wick Materials

Several sections of the heat pipe envelope were selected from which to remove samples for analysis. The heat pipe was first cut into two pieces; smaller samples were then removed from the halves. A wire electron discharge machining (EDM) approach was used to remove the test samples. Figure 6 shows the two sections of the heat pipe after the samples were removed. The outer surface of the envelope retained a natural dark oxide coating.

The sample analysis was performed by the NASA Glenn Research Center (GRC). Each envelope/ wick sample was then prepared for analysis. The individual samples were sectioned using a high speed silicon carbide cut-off wheel. Samples were then nickel-plated, mounted, and polished. Figures 7 to 16 show an example of the preparation steps.

A total of 6 envelope/wick samples were removed for analysis. Sample regions included envelope samples taken from the heat pipe evaporator, adiabatic, and condenser regions. For some samples, a single wire EDM cut removed two samples, i.e., the lower side (evaporator) sample and an upper (adiabatic) sample. These were designated A and B, respectively. Table 4 describes the location of each sample. Smaller samples were sectioned using high speed silicon carbide cut-off wheels for metallography and electron microscopy analysis. Samples were nickel-plated, mounted, and polished. Figures 7 to 16 show the sample preparation steps.

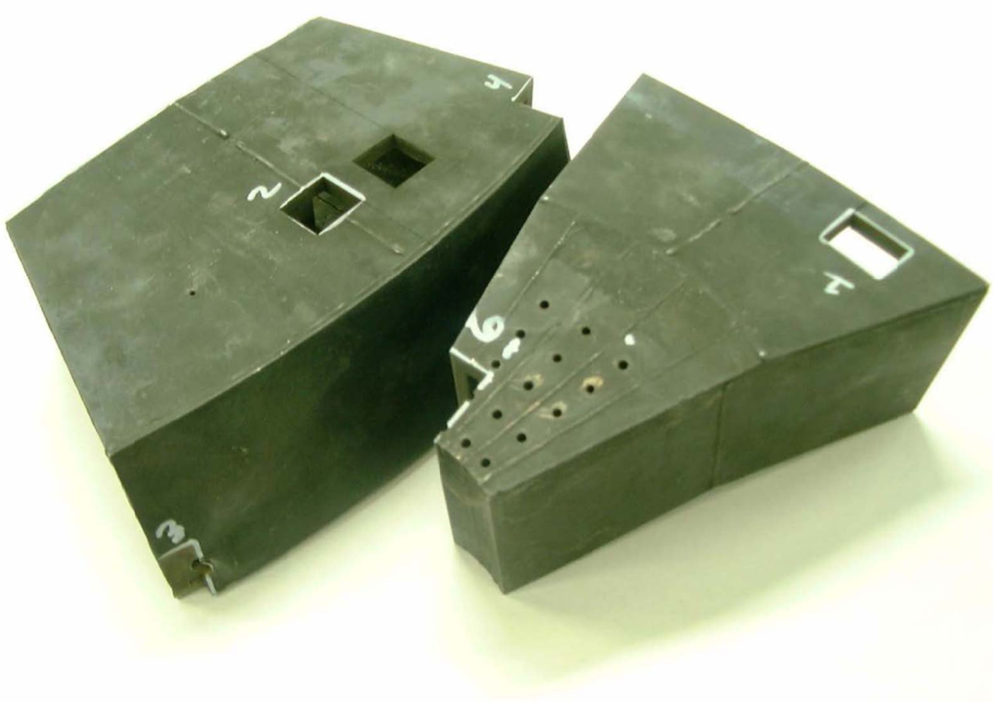


Figure 6.—Sectioned halves of the heat pipe.

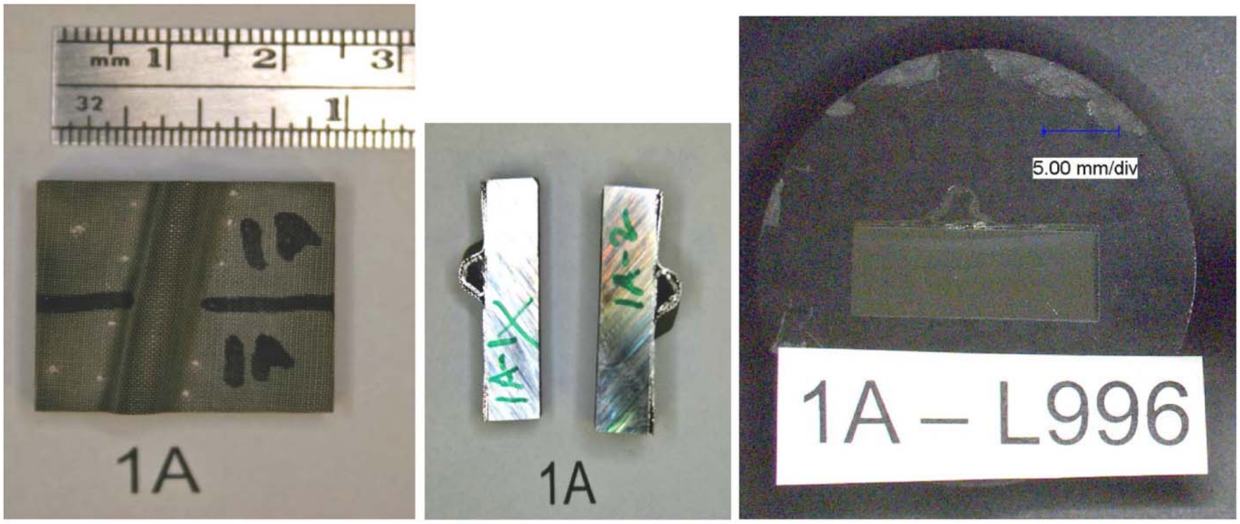


Figure 7.—Sample preparation steps for 1A.

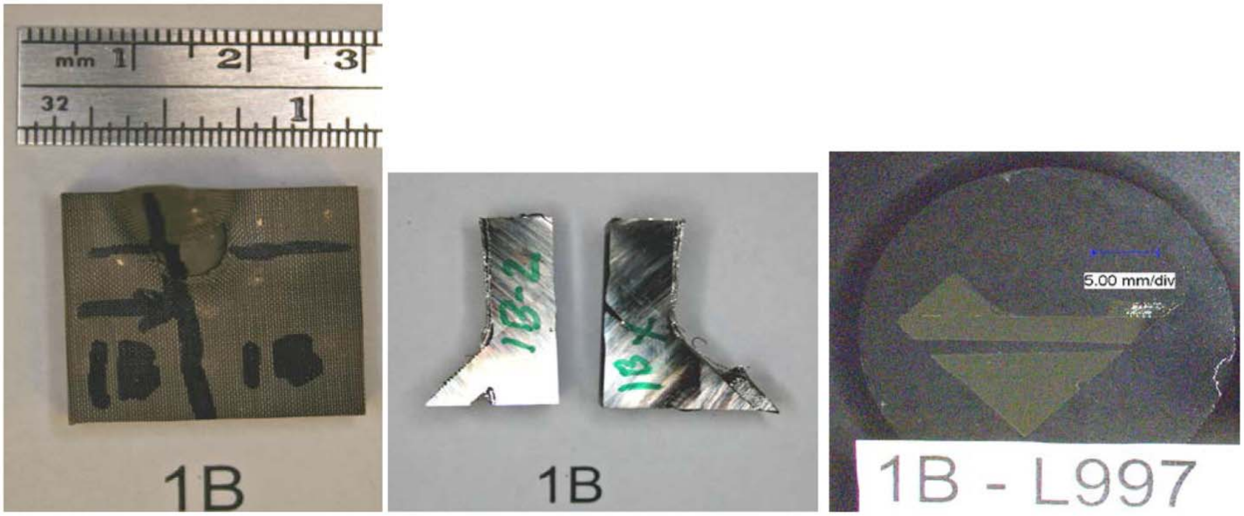


Figure 8.—Sample preparation steps for 1B.

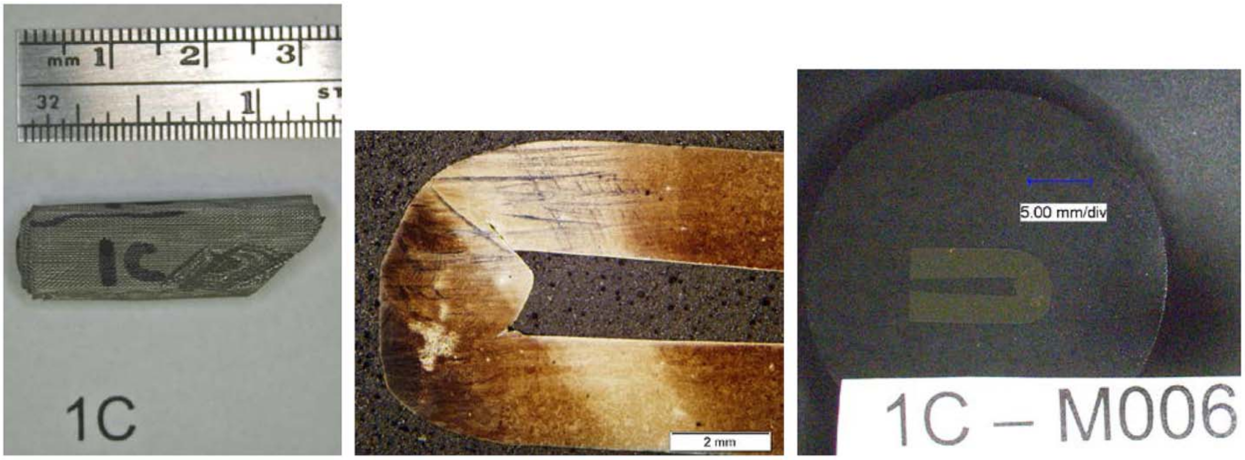


Figure 9.—Sample preparation steps for 1C.

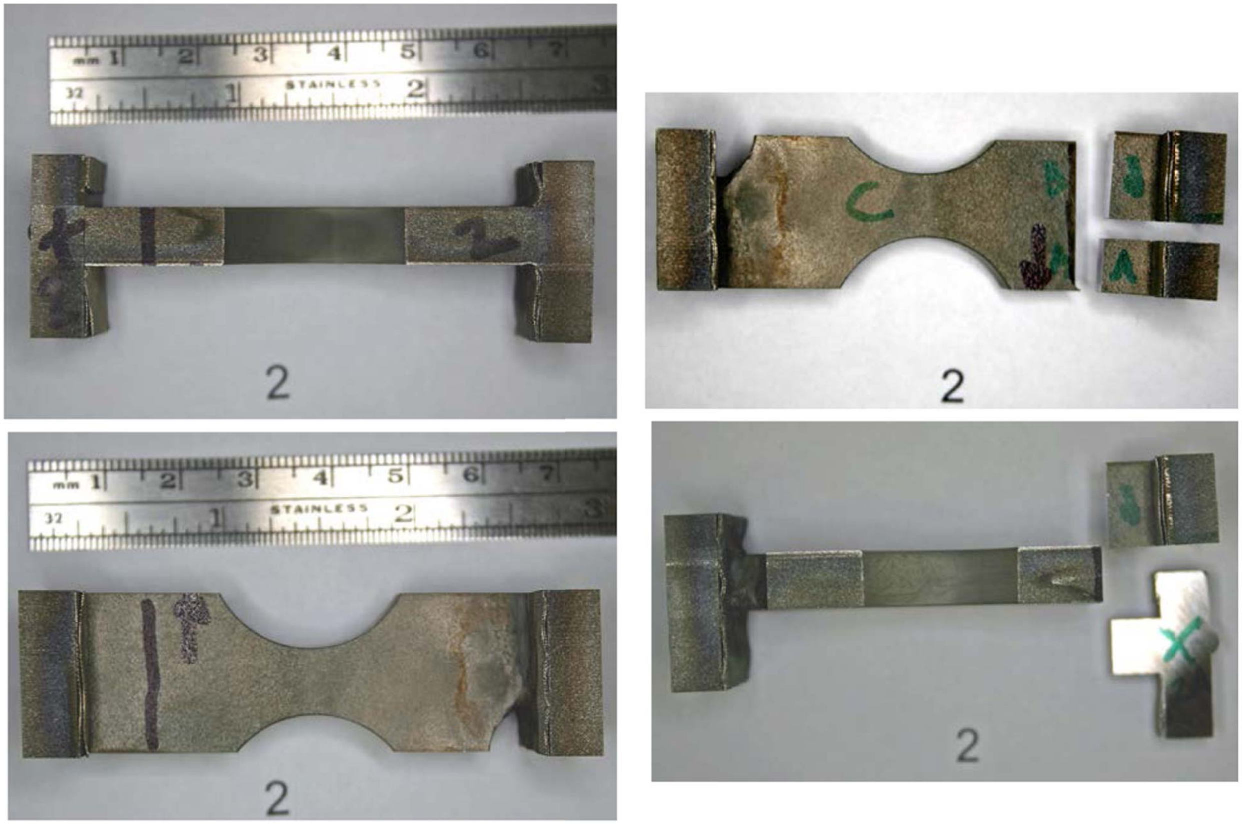


Figure 10.—Sample preparation steps for 2.

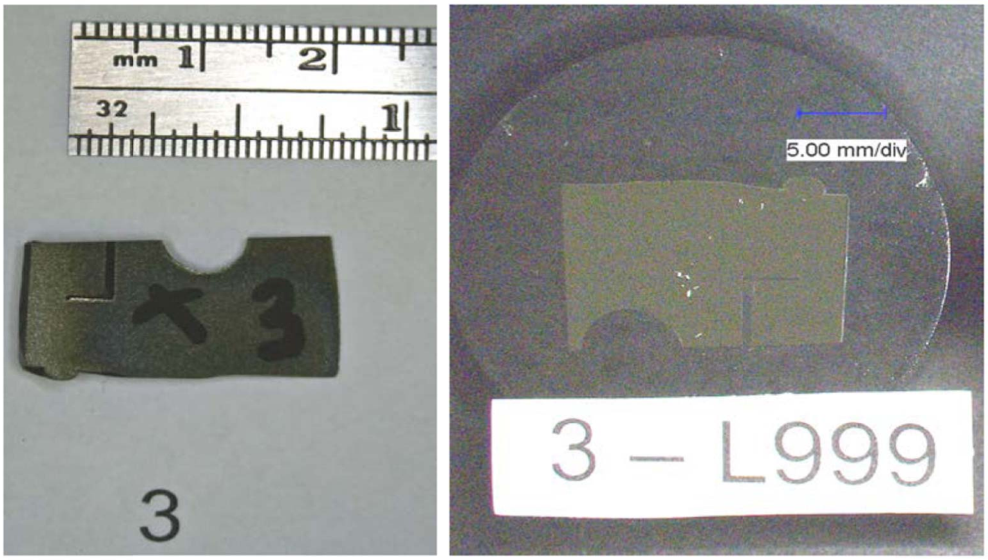


Figure 11.—Sample preparation steps for 3.

Figure 12.—Sample preparation steps for 4.

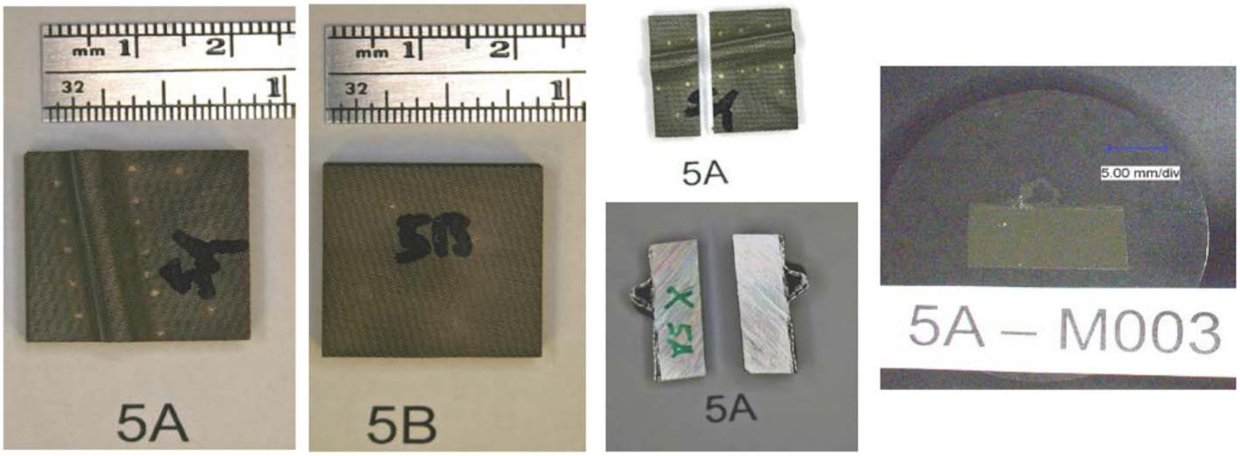


Figure 13.—Sample preparation steps for 5A–5B.

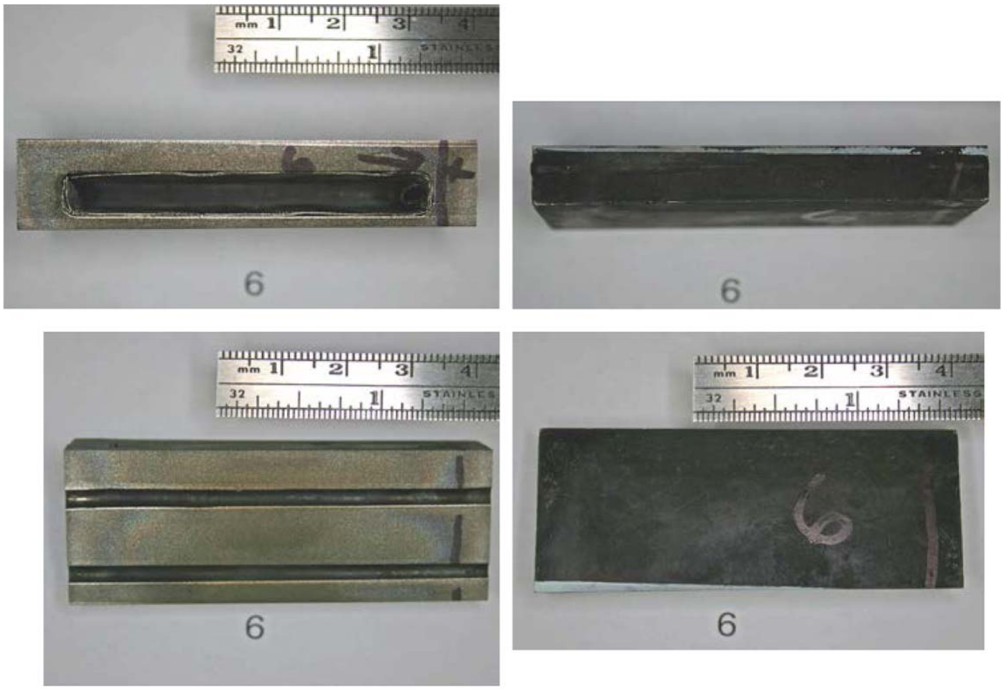


Figure 14.—Sample preparation steps for 6.

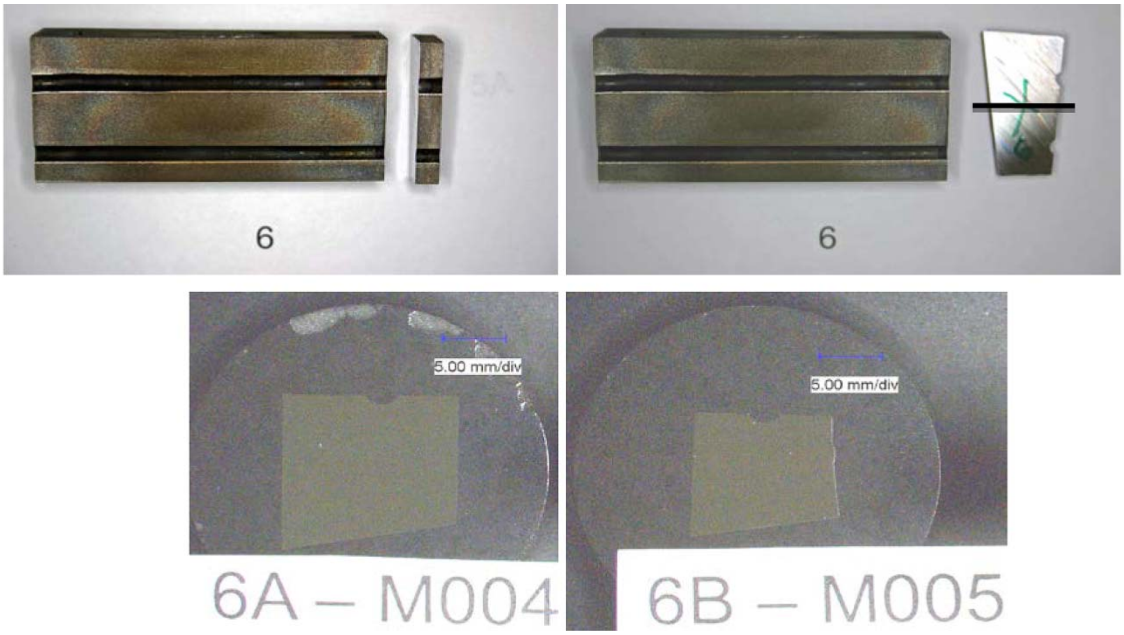
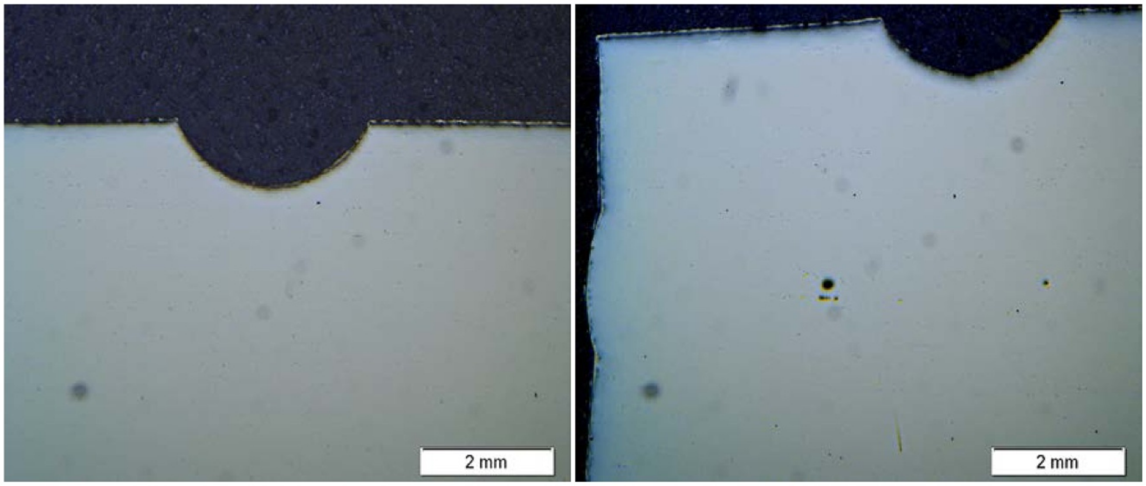


Figure 15.—Sample preparation steps for 6A–6B.



Sample 6A

Sample 6B

Figure 16.—Additional sample preparation steps for 6A–6B.

TABLE 4.—HEAT PIPE ENVELOPE/WICK SAMPLE DESCRIPTIONS

Sample number	Location on heat pipe	Specific features comments
1A	Evaporator	Screen wick/screen artery
1B	Adiabatic	Screen wick
2A	Evaporator/adiabatic	Internal support divider/weld joint
2B	Evaporator/adiabatic	Internal support divider/weld joint
3	Fill tube	Fill tube
4	Corner/adiabatic	Corner with other fill tube
5A	Evaporator	Screen wick/screen artery
5B	Adiabatic	Screen wick
6	Condenser	Screen wick/artery

6.3 Heat Pipe Evaporator Region Envelope

Electron microprobe microstructural analysis was done on evaporator Samples 1A and 5A. The electron microprobe images are shown in Figures 17 to 19, 25, and 26. A microprobe wavelength dispersive spectroscopy (WDS) quantitative line scan of major elements for each side of Sample 1A and 5A are shown in Figures 20 to 22, 27, and 28. The analysis of the inner surface of the envelope in the heat pipe evaporator section showed about 30 µm near the interface that was significantly affected (Fig. 19). Figure 20 shows microprobe WDS quantitative line scan of major elements found in test Sample 1A near the sodium (inner) surface. The principal effect was a loss of nickel from this layer. Microprobe WDS maps show that other elements were present in increased concentration, including niobium, iron, silicon, and titanium (Figs. 23 and 24). Sample 5A showed similar result (Fig. 27). Microprobe analysis also showed an increase in nickel and a decrease in molybdenum and iron near the outer surface of the envelope wall, in a region about 100 µm in thickness. This surface was exposed to air and to direct radiation from the silicon carbide heaters during the life test. Most of the envelope thickness was not substantially affected by the test.

Because nickel was apparently removed from the inner envelope surface in the evaporator region, an effort was made to determine if nickel was transported by the sodium to other regions of the heat pipe. No evidence of nickel deposition was observed in any sample; in fact, nickel removal to a 30 µm depth was typically observed near the inner envelope surface in all of the analyzed samples. This result suggests that the nickel migrated deeper into the envelope, and that diffusion from the inner surface toward the outer surface was the predominant method of transport. The outer surface of the heat pipe envelope was covered with a dark oxide that typically forms from long exposure to air at high temperature.

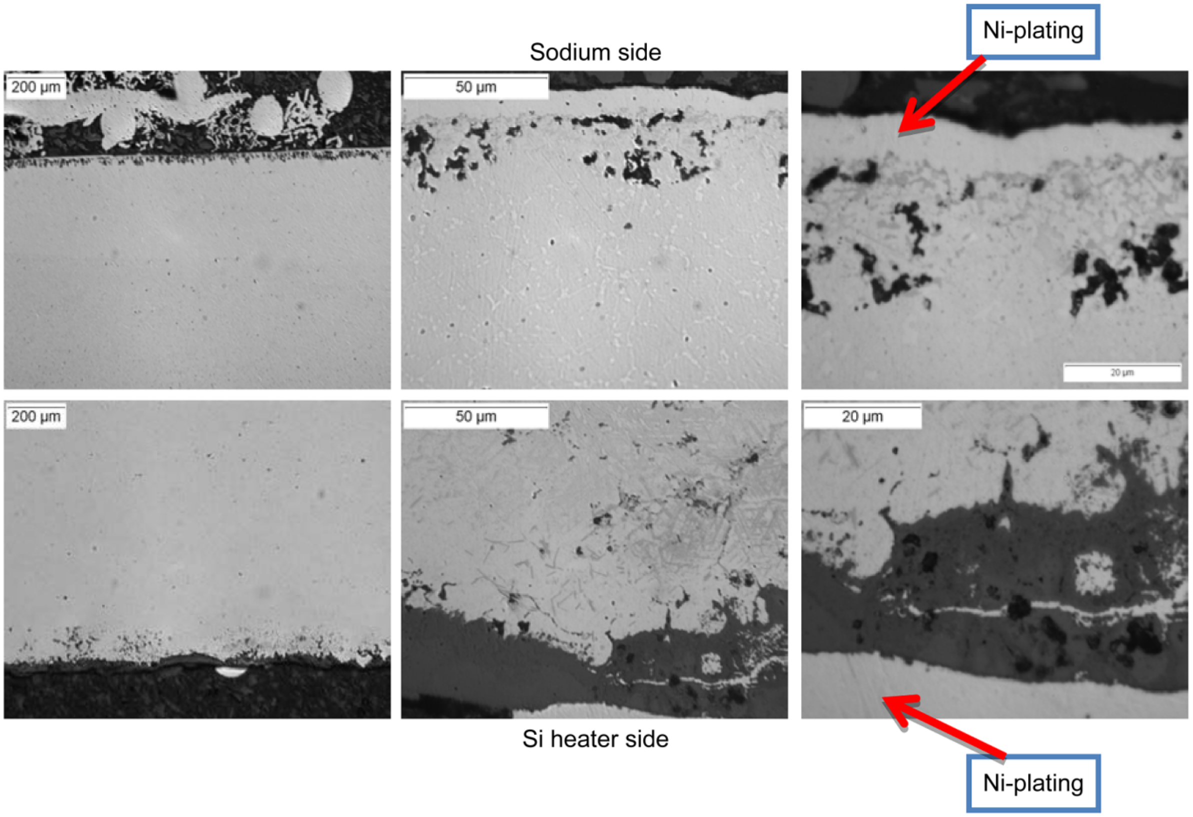
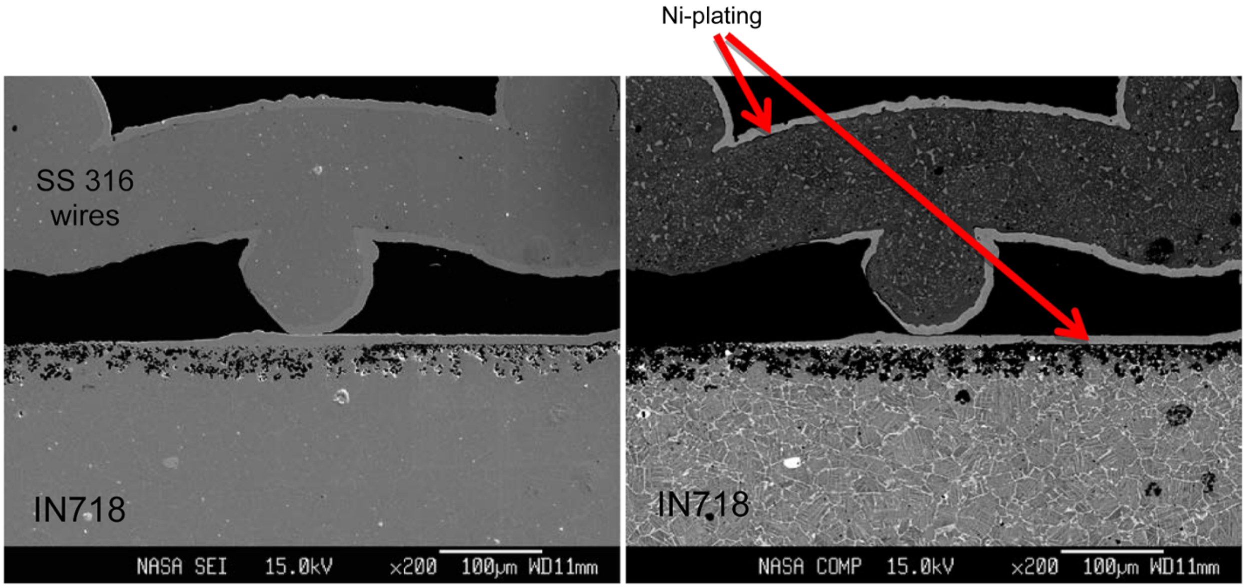


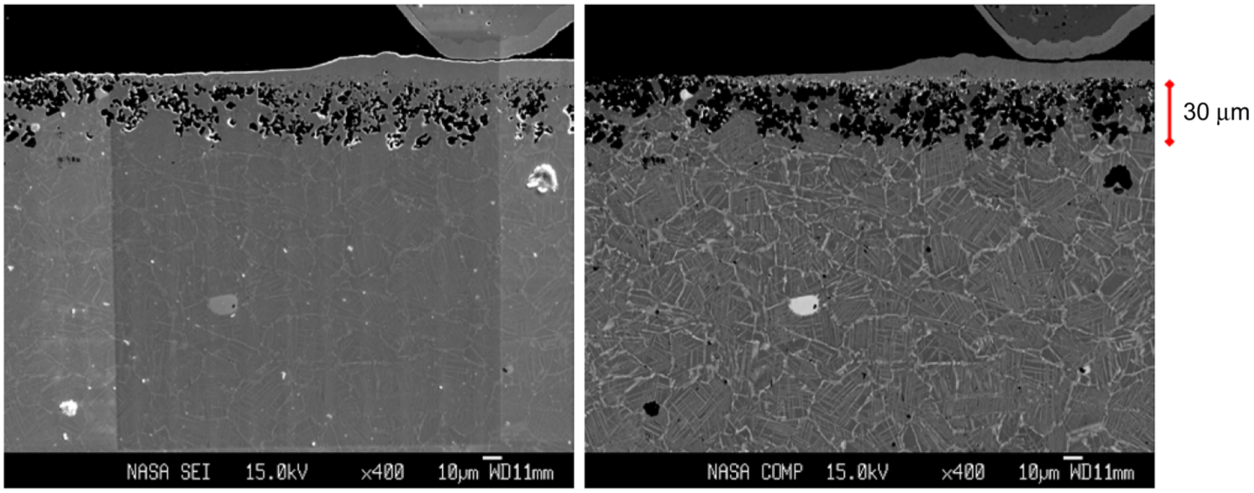
Figure 17.—Sample 1A.



Secondary electron image

Back-scattered electron image

Figure 18.—Electron microprobe images of the sodium (inner) side of Sample 1A.



Secondary electron image

Back-scattered electron image

Figure 19.—Electron microprobe images showing the 30 µm affected region observed on the sodium (inner) side of Sample 1A.

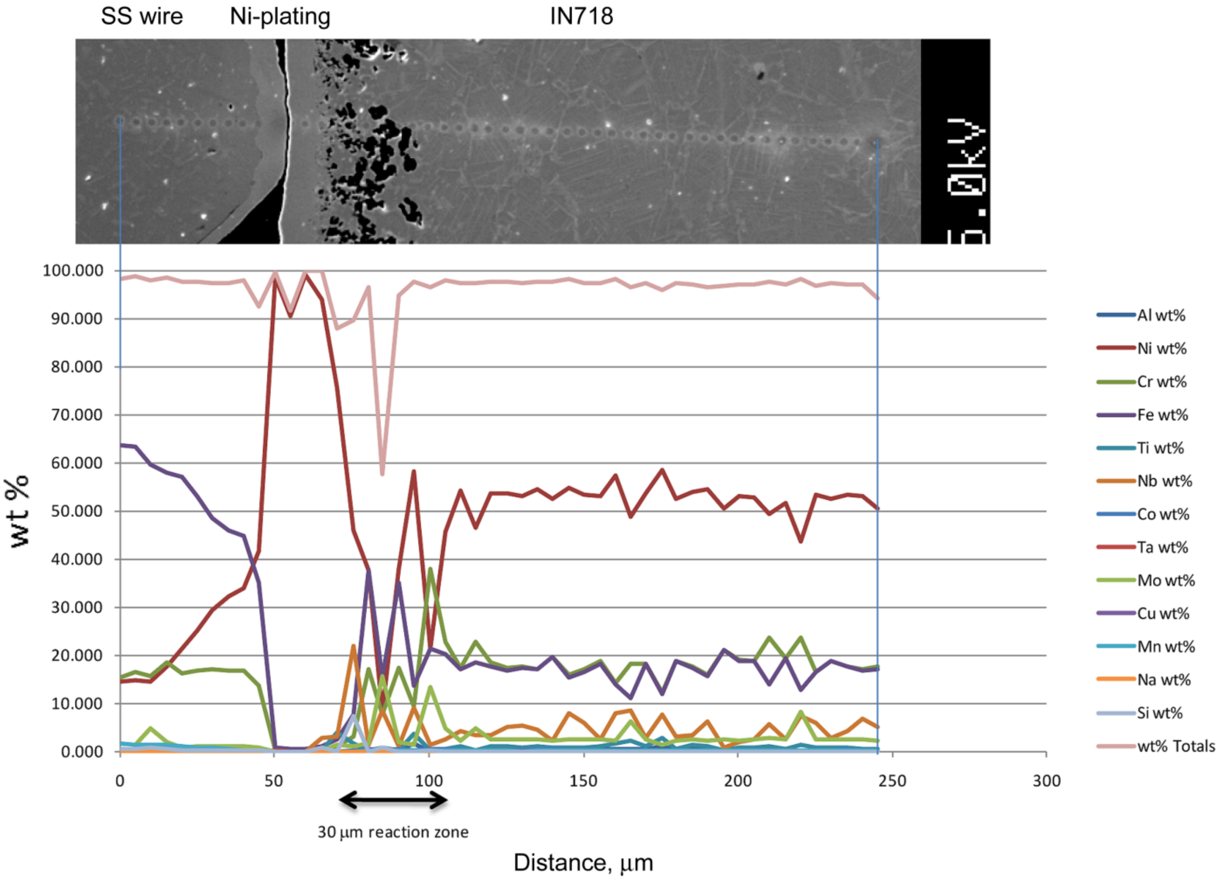


Figure 20.—Electron microprobe image and wavelength dispersive spectroscopy (WDS) quantitative line scan of major elements for test Sample 1A near the sodium (inner) surface.

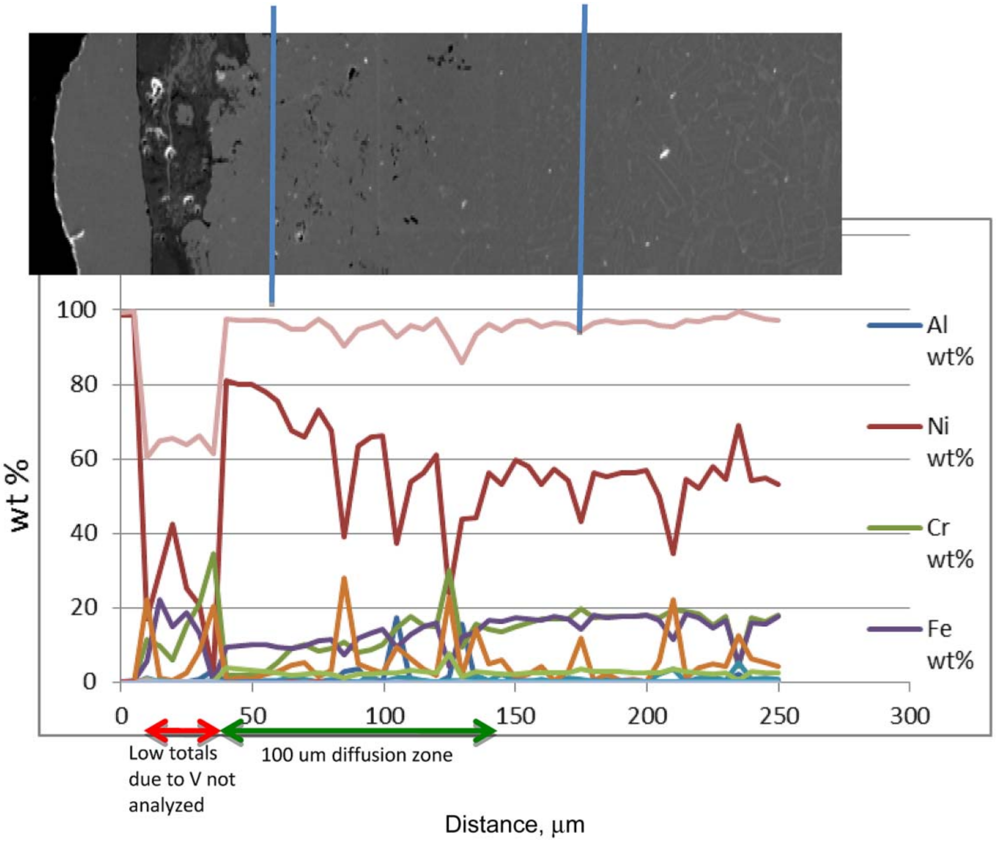


Figure 21.—Electron microprobe image and wavelength dispersive spectroscopy (WDS) quantitative line scan of major elements for test Sample 1A near the SiC (outer) surface.

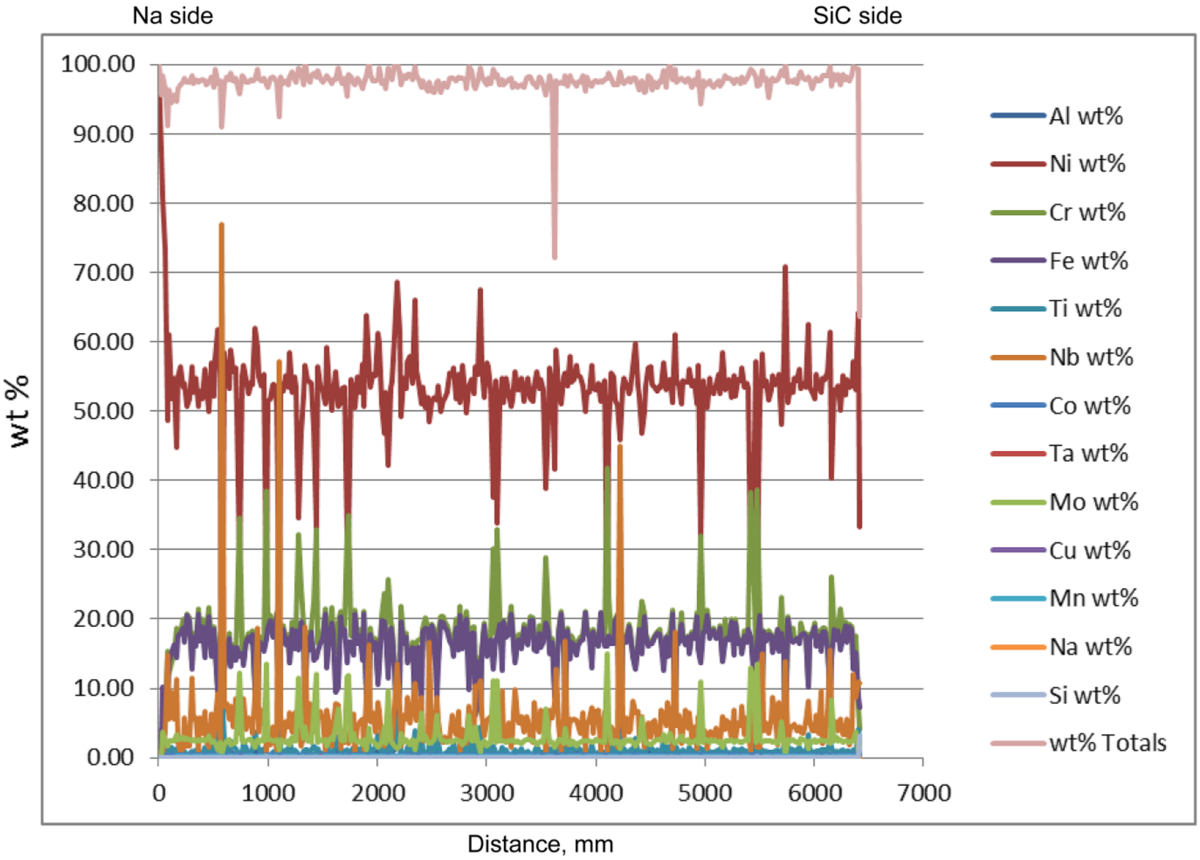
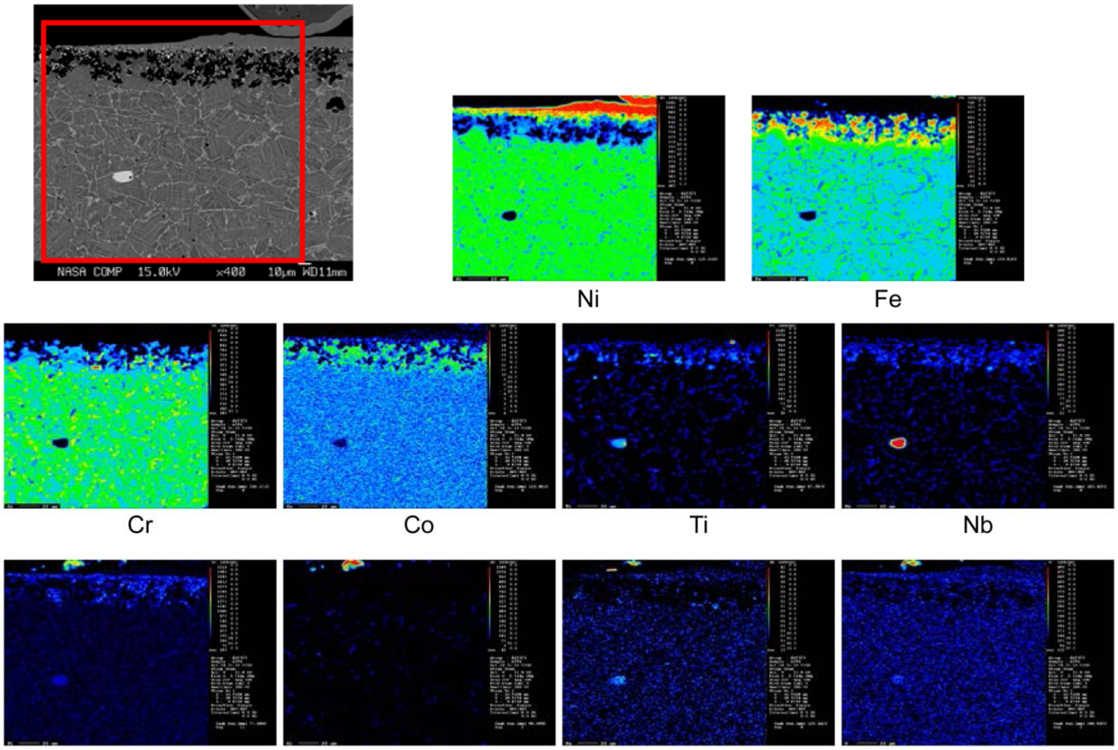


Figure 22.—Wavelength dispersive spectroscopy (WDS) quantitative line scan of major elements for the entire thickness of test Sample 1A.

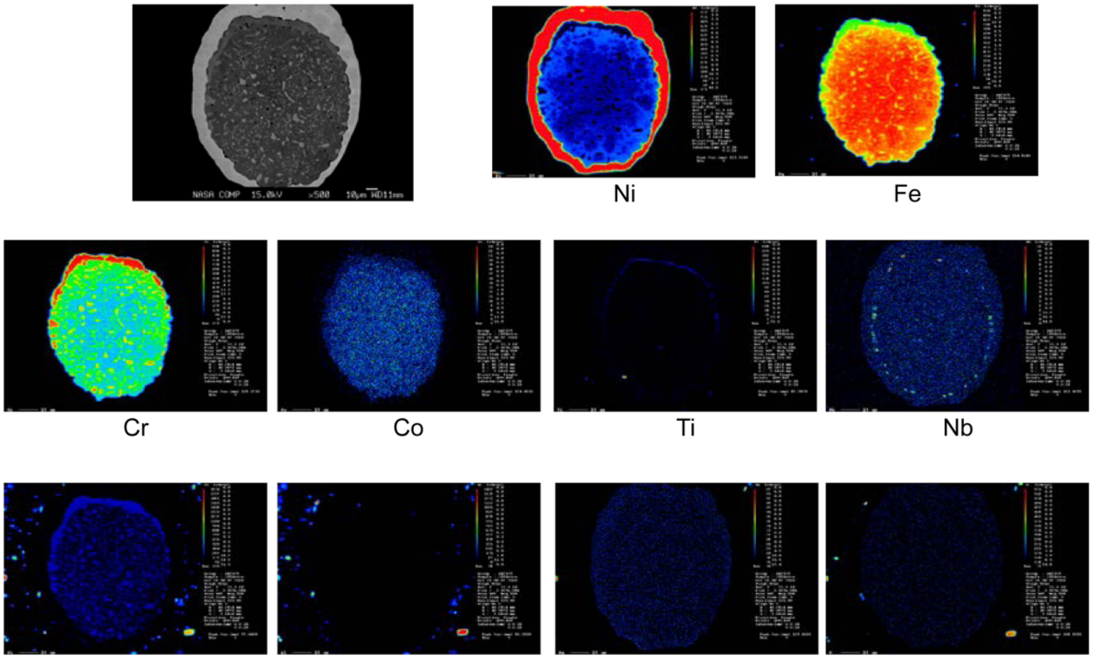


Ni Fe

Cr Co Ti Nb

Si Al Na O

Figure 23.—Microprobe wavelength dispersive spectroscopy (WDS) maps of sodium (inner) side of Sample 1A.

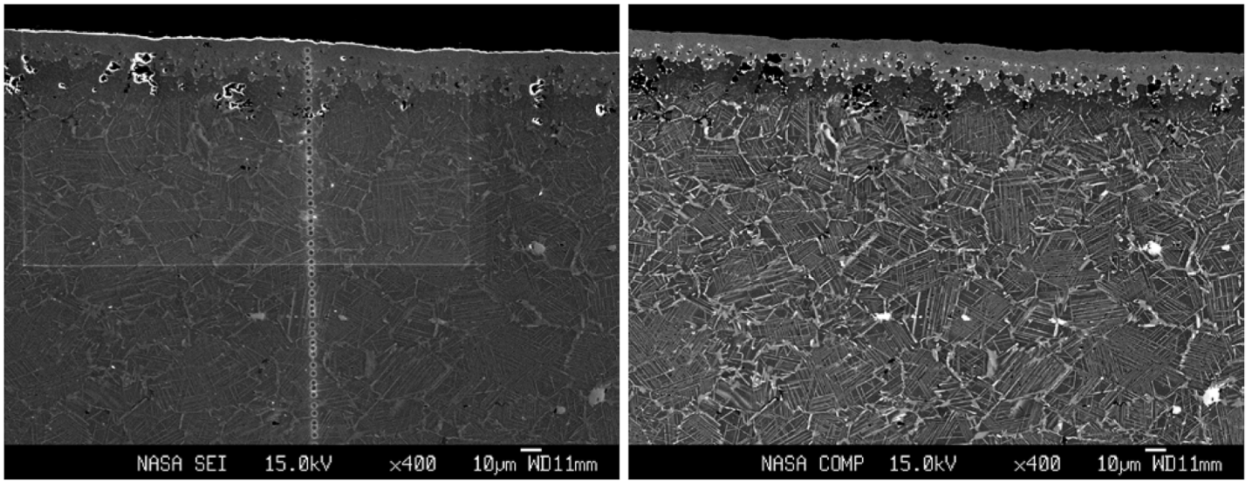


Ni Fe

Cr Co Ti Nb

Si Al Na O

Figure 24.—Microprobe wavelength dispersive spectroscopy (WDS) maps of stainless steel wire sample from 1A.



Secondary electron image Back-scattered electron image

Figure 25.—Electron microprobe images of the sodium (inner) side of Sample 5A.

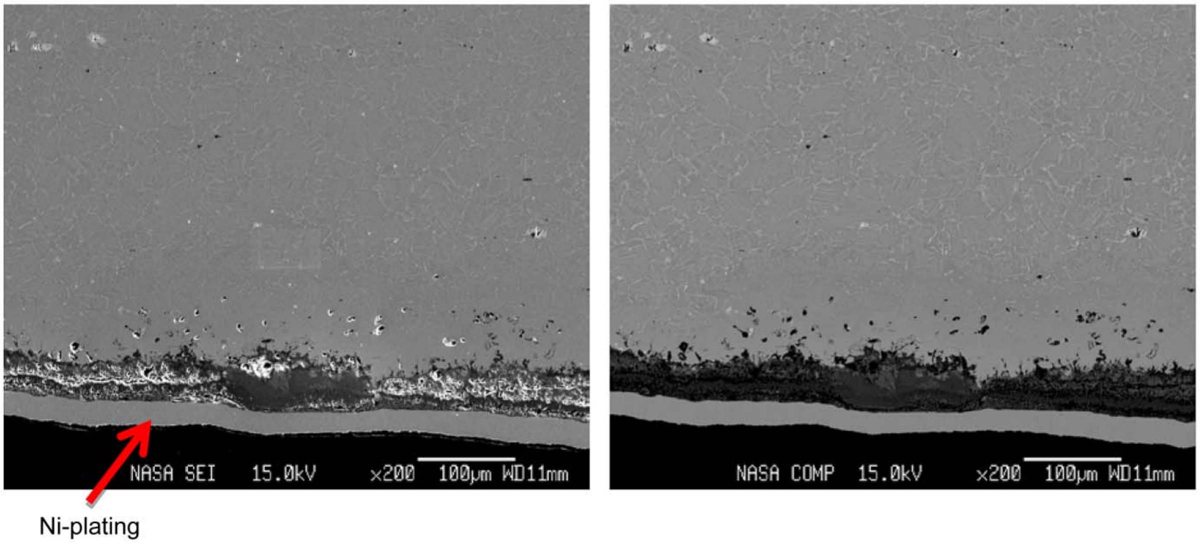


Figure 26.—Electron microprobe images of the SiC side of Sample 5A.

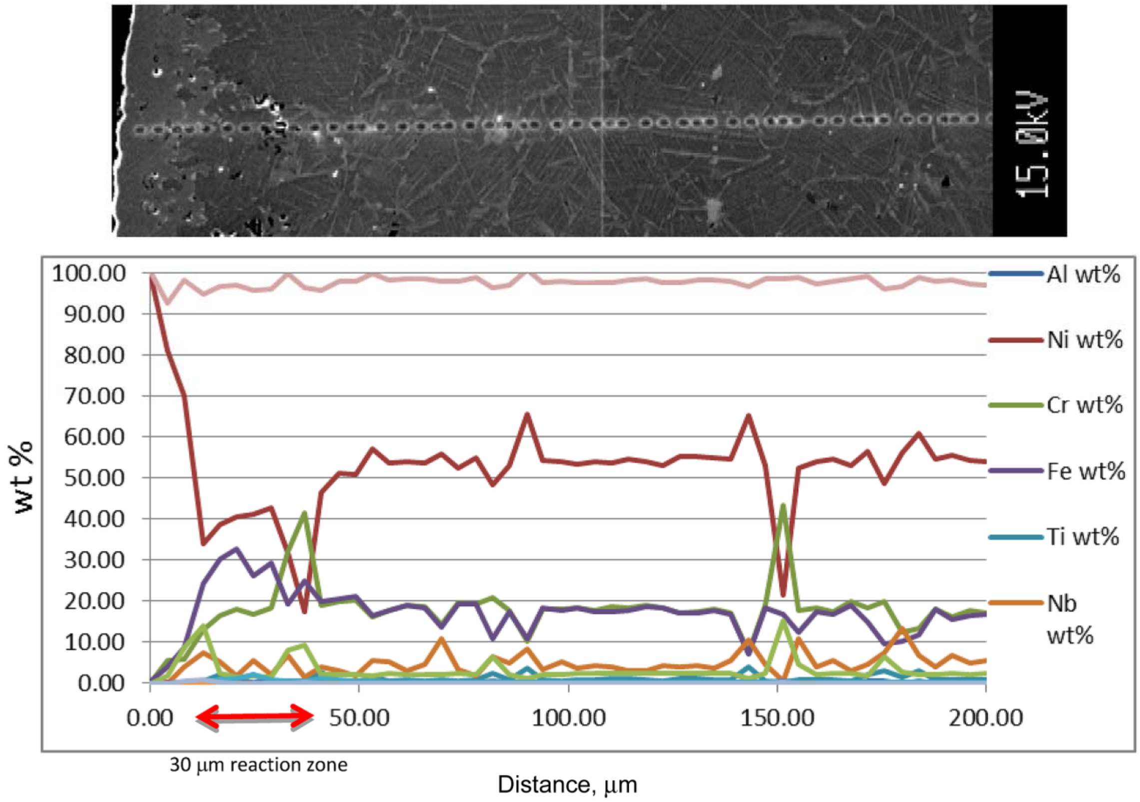


Figure 27.—Electron microprobe image and wavelength dispersive spectroscopy (WDS) quantitative line scan of major elements for test Sample 5A near the sodium (inner) surface.

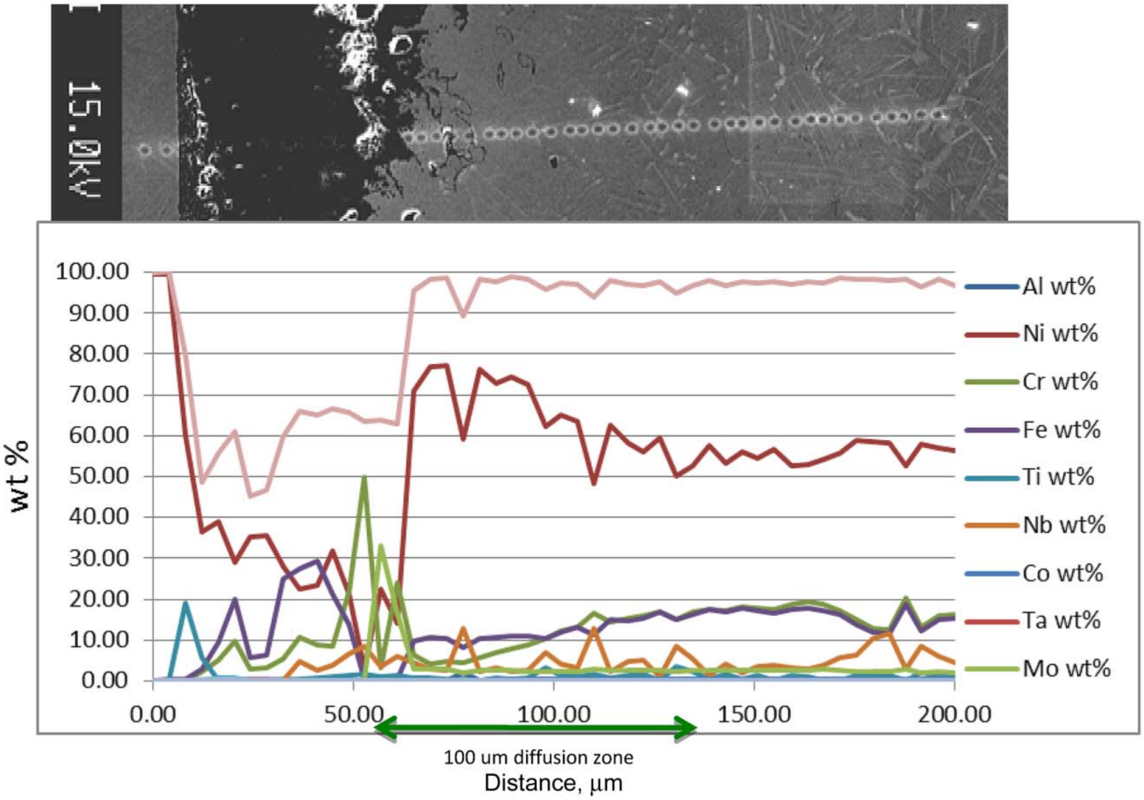


Figure 28.—Electron Microprobe Image and Wavelength Dispersive Spectroscopy (WDS) Quantitative Line Scan of Major Elements for Test Sample 5A Near the SiC (Outer) Surface.

6.4 Heat Pipe Adiabatic Region Envelope

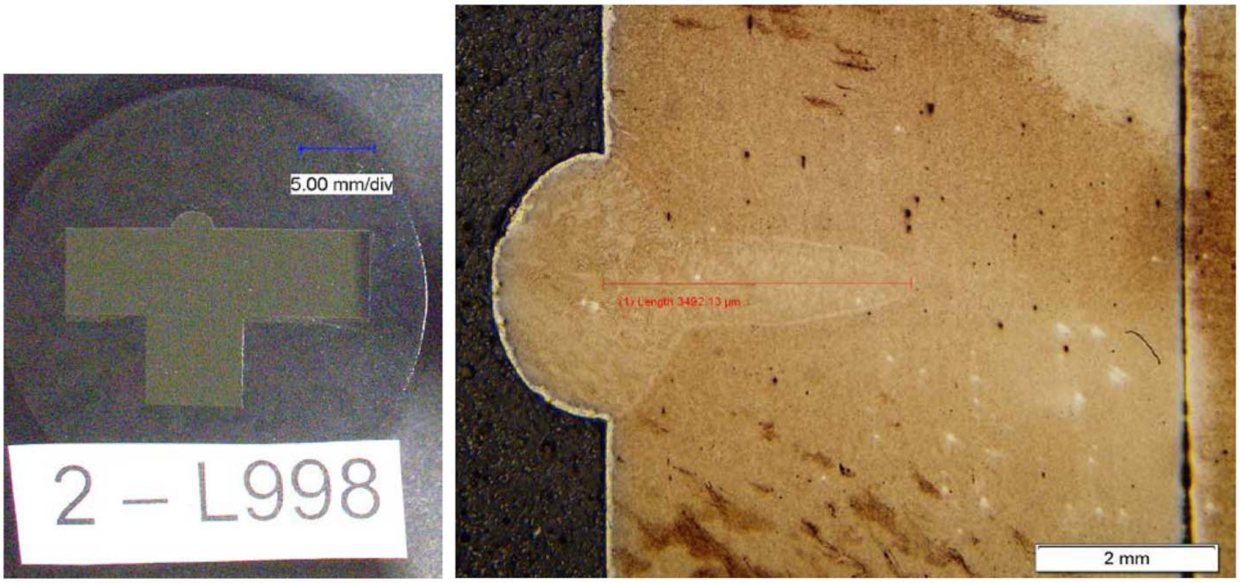
Microprobe analysis was performed on samples taken from the adiabatic region of the heat pipe, e.g., Samples 1B and 5B. Analysis of test samples showed similar metallurgy changes to those found in the evaporator region; a 30-µm-thick region near the inner envelope surface was depleted of nickel, and other alloying elements had migrated in a similar manner.

6.5 Heat Pipe Condenser Region Envelope

Microprobe analysis was also performed on a sample taken from the condenser region of the heat pipe, i.e., Sample 6. Analysis of test sample showed element migration and other changes similar to those found in the evaporator and adiabatic regions; a 30-µm-thick region near the inner envelope surface was depleted of nickel, and other alloying elements had migrated in a similar manner.

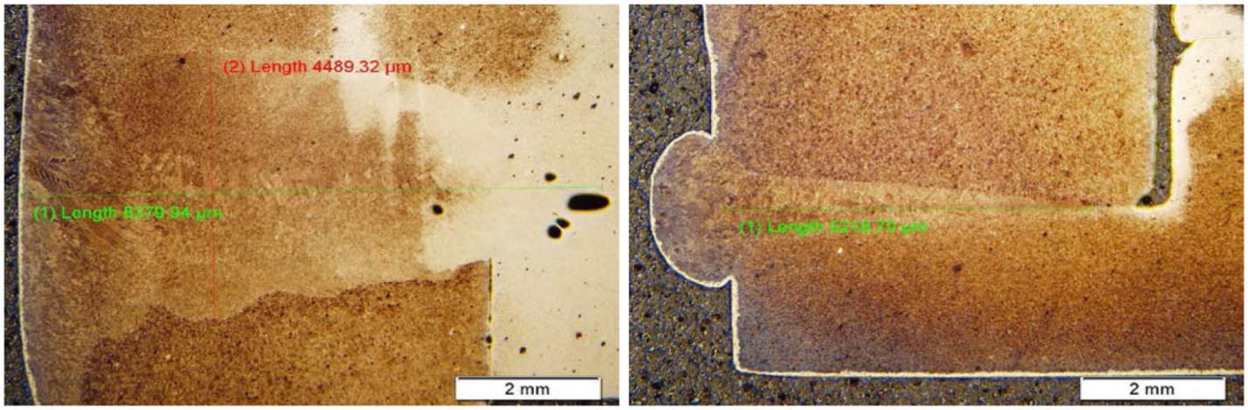
6.6 Heat Pipe Wick Structure Analysis

The screen wick material was analyzed to determine the effects of long term exposure to the sodium working fluid. Observations of the electron beam welds indicated no evidence of corrosion in the weld metal or heat affected zone. Figures 29 to 32 are images of the electron beam welds observed. Electron beam weld penetrations were measured to be between 3.5 and 5.4 mm. Electron microprobe images of the screen wick material are shown in Figures 33 to 36. Microprobe analysis indicated deposition of sodium, oxygen, and carbon on the surface of the screen wires (Figs. 34 and 36). These elements were most likely residues of sodium hydroxide and sodium methoxide that remained from the sodium removal and disposal process. Some evidence was seen of species migration in the screen wires; this effect did not seem to affect the integrity of the wires. Physical observation showed that the wires retained ductility and did not separate from the envelope inner surfaces near the tack-weld locations.



Electron beam weld penetration of 3.5 mm

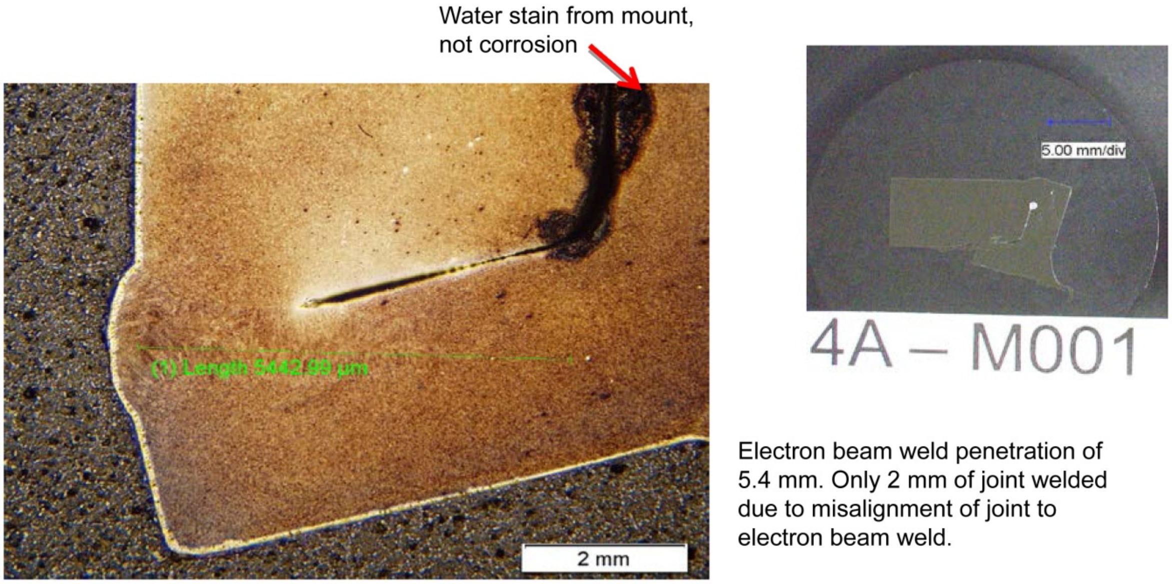
Figure 29.—Electron beam weld on Sample 2.



Electron beam weld penetration of > 8 mm with multiple passes

Electron beam weld penetration 5.2 mm

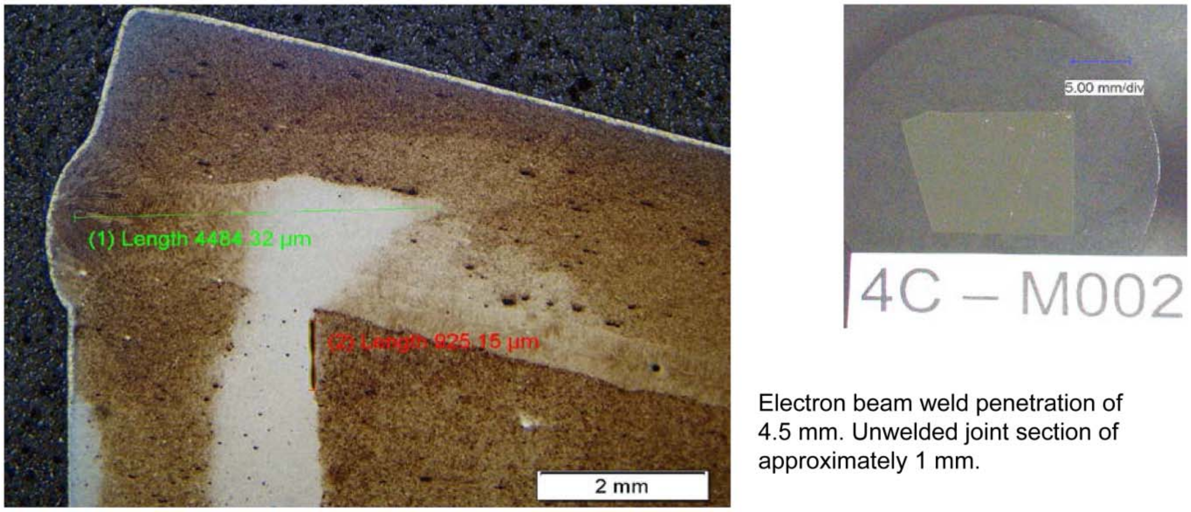
Figure 30.—Electron beam weld on Sample 3.



Water stain from mount, not corrosion

Electron beam weld penetration of 5.4 mm. Only 2 mm of joint welded due to misalignment of joint to electron beam weld.

Figure 31.—Electron beam weld on Sample 4A.



Electron beam weld penetration of 4.5 mm. Unwelded joint section of approximately 1 mm.

Figure 32.—Electron beam weld on Sample 4C.

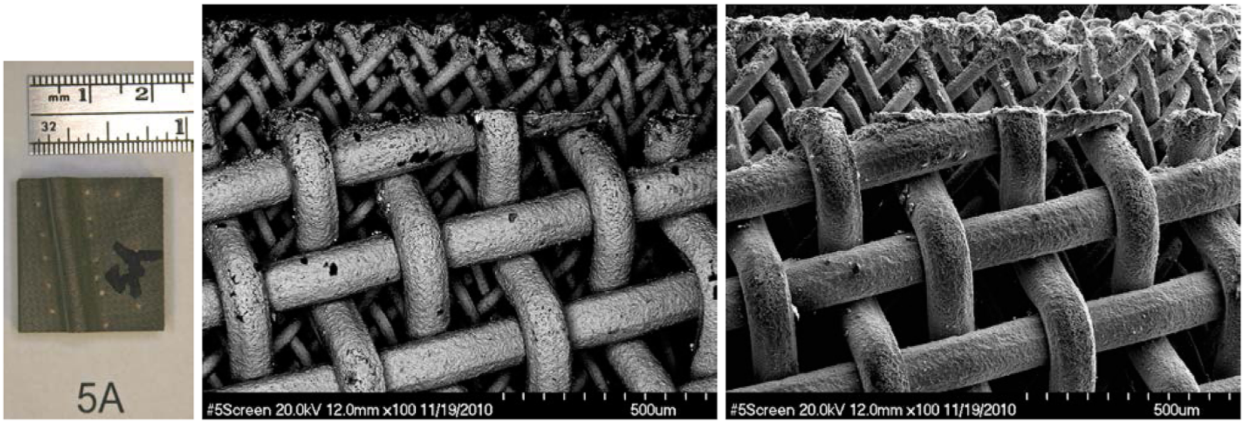


Figure 33.—Electron microprobe images of fine and course stainless steel screens from Sample 5A.

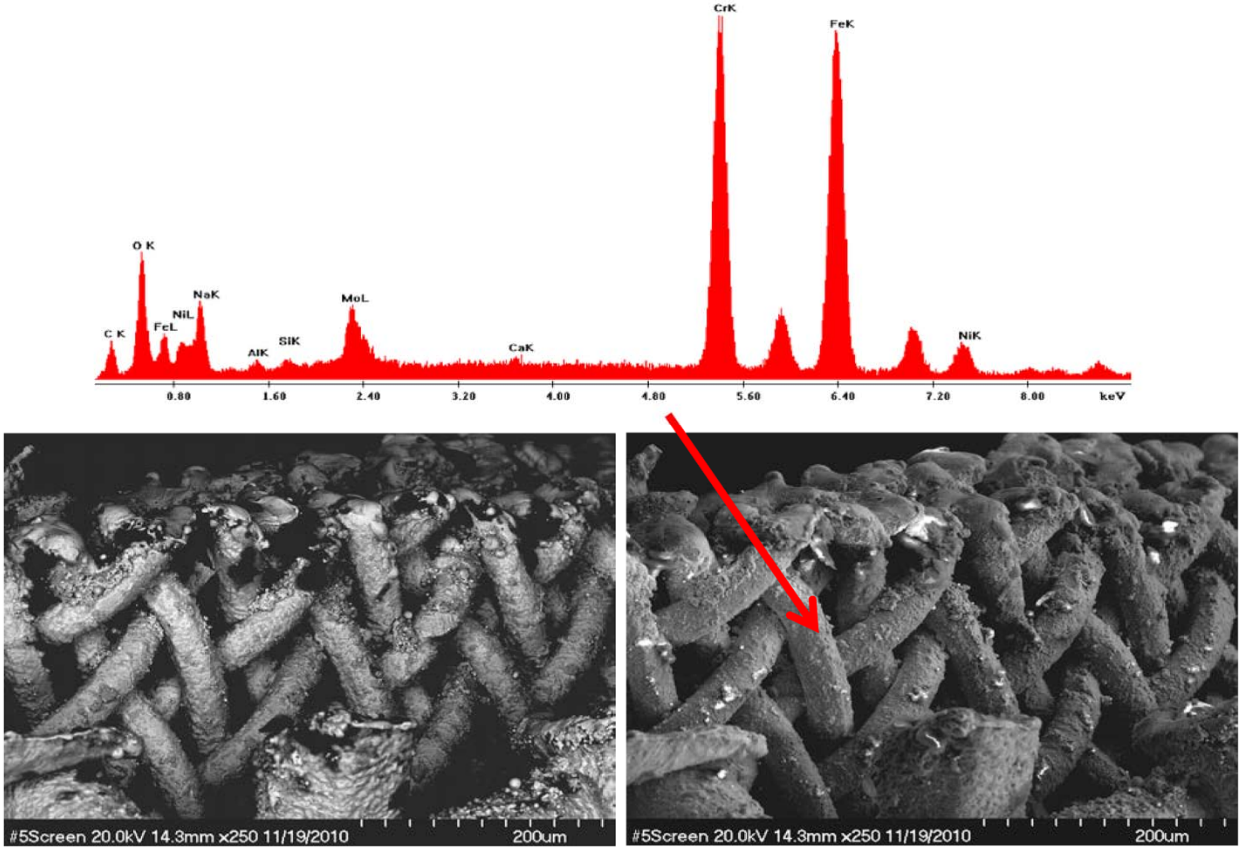


Figure 34.—Concentration chart of major elements and electron microprobe images of the fine stainless steel screen from Sample 5A.

Figure 35.—Higher magnification electron microprobe images of the fine stainless steel screen from Sample 5A.

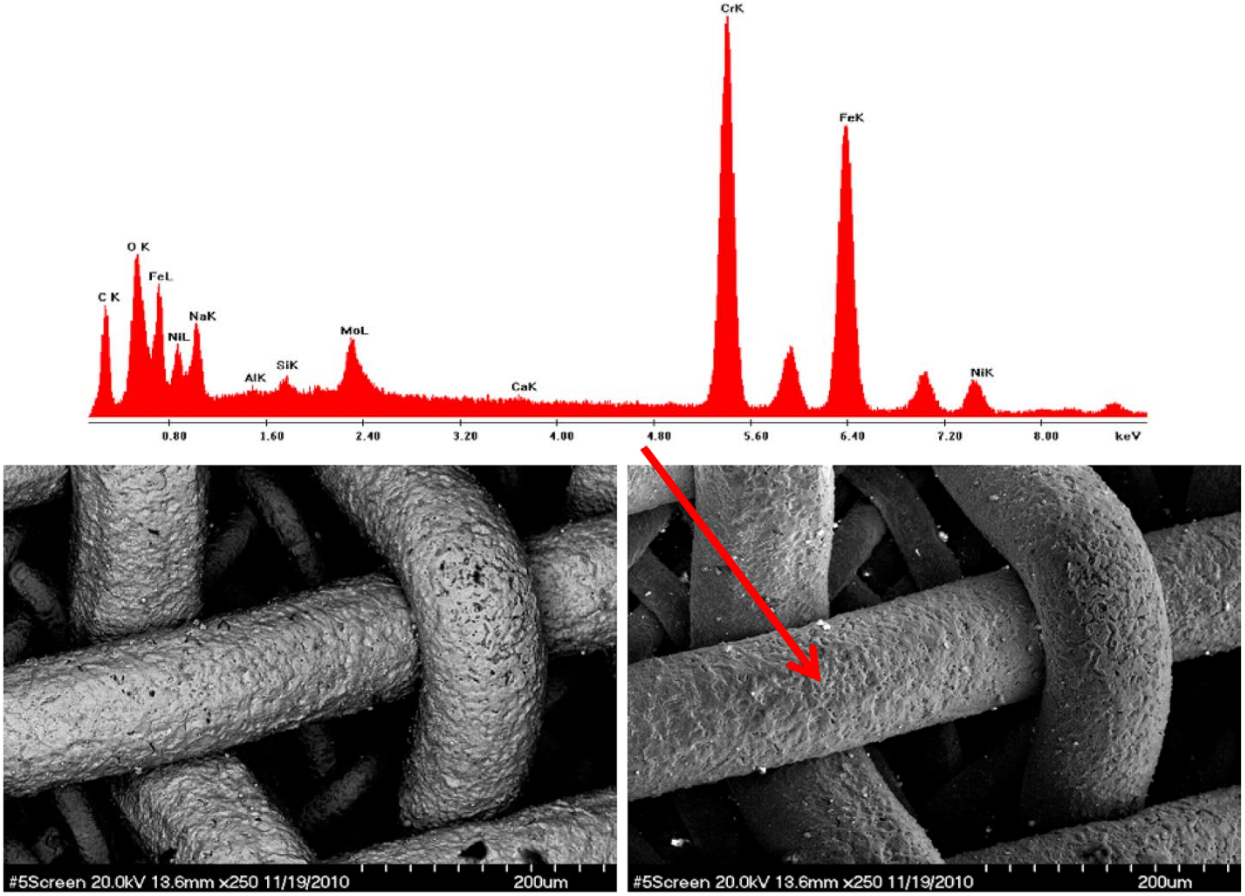


Figure 36.—Concentration chart of major elements and electron microprobe images of the course stainless steel screen from Sample 5A.

7.0 Conclusions and Recommendations

A sodium heat pipe demonstrated favorable materials compatibility and heat transport characteristics at 700 °C while operating in air for over 10 yr. A representative one-tenth segment Stirling Space Power Converter heat pipe with an Inconel 718 envelope and a stainless steel screen wick has operated for over 87,000 hr at nearly 700 °C. Post-test analysis revealed no significant degradation of the envelope or screen wick material as a result of the life test. The life test provides strong evidence for long-term chemical compatibility of sodium heat pipes at high operating temperatures.

Chemical composition was determined for the source sodium and for the fluid charge removed from the tenth segment unit after 87,000 hr of operation. The analysis of the sodium working fluid from the tenth segment unit showed small quantities of more than a dozen other elements, some of which were originally present in the source sodium.

Migration of some alloying elements was observed, though the end effect on the integrity of the envelope was minimal. A 30 µm region of the inner surface was significantly depleted of nickel; it appeared to migrate outward through the envelope, since no region of the envelope inner surface or wick contained re-deposited nickel.

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14. ABSTRACT

High-temperature heat pipes are being evaluated for use in energy conversion applications such as fuel cells, gas turbine re-combustors, Stirling cycle heat sources; and with the resurgence of space nuclear power both as reactor heat removal elements and as radiator elements. Long operating life and reliable performance are critical requirements for these applications. Accordingly, long-term materials compatibility is being evaluated through the use of high-temperature life test heat pipes. Thermacore, Inc., has carried out a sodium heat pipe 10-year life test to establish long-term operating reliability. Sodium heat pipes have demonstrated favorable materials compatibility and heat transport characteristics at high operating temperatures in air over long time periods. A representative one-tenth segment Stirling Space Power Converter heat pipe with an Inconel 718 envelope and a stainless steel screen wick has operated for over 87,000 hr (10 yr) at nearly 700 °C. These life test results have demonstrated the potential for high-temperature heat pipes to serve as reliable energy conversion system components for power applications that require long operating lifetime with high reliability. Detailed design specifications, operating history, and post-test analysis of the heat pipe and sodium working fluid are described.

15. SUBJECT TERMS
Heat pipes; Sodium; Stirling cycle

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