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EXPERIMENTAL RESULTS OF SUBASSEMBLY HEAT-UP RATE TEST

by

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ABSTRACT

Heat transfer calculations are being relied upon to specify the maximum decay heat that an EBR-II subassembly may have and still safely and passively withstand a loss-of-forced cooling event in the Hot Fuels Examination Facility-South (HFEF-S) air cell while awaiting reprocessing. From preliminary analysis, a limit of 500 W has been proposed in order to assure adequate passive cooling. To provide a benchmark for more precise calculations, a pre-irradiated 91 element EBR-II core-type subassembly, with approximately 500 W of decay power, was instrumented and the cooling flow to it was stopped. During the loss of forced cooling the temperatures of the hex duct and center element were measured and recorded. The results of the test were a maximum measured fuel element temperature of 524°C (975°F) for the case where the subassembly was exposed to the cell air flow, and 548°C (1019°F) with the subassembly isolated from the cell air flow by a surrounding metal shroud.

I. INTRODUCTION

In the conversion of HFEF-S to a fuel processing facility, it has been proposed to store fuel subassemblies awaiting reprocessing in the air cell in forced-cooled storage racks. However a design criterion is that the subassemblies must be passively cooled if forced cooling is lost. Heat transfer calculations are being performed to determine the maximum center fuel element temperature as a function of subassembly decay heat and emissivity. To provide a benchmark for the calculations, a heat-up test was performed on an actual subassembly. Since an IFR irradiated 61-element subassembly was not available for use in the test, a standard 91 element EBR-II MK-IIA core-type subassembly was used.

The test was conducted in three phases. During Phase I, the subassembly was placed in the vertical assembler and dismantler (VAD) machine and cooling flow to it was stopped. During this phase some cooling of the subassembly was achieved by the cell air flow around it, since the cell ventilation exhaust blowers must remain on at all times. In the second phase (Phase II), a shroud was placed around the subassembly to isolate it from the cell air flow. The third phase (Phase III) test was performed to verify the data from Phase II. In the final portion of Phase III, a lid was placed on the top of the shroud to stop any upward air flow around the subassembly and to completely isolate it, thus approximating a cask or closed storage pit.

The remainder of this report describes the subassembly used in the test, the instrumentation used for the temperature measurements, how the test was conducted, the estimated subassembly decay heat levels, and the results.

II. TEST ASSEMBLY DESCRIPTION

The subassembly used for the test was C-2781E, a standard EBR-II MK-IIA core-type subassembly. This subassembly was selected because it had decay heat in the range needed for the test. Also, it was scheduled to go to the Idaho Chemical Processing Plant (ICPP) so if damaged during the test, no programmatic data would be lost. Data on the subassembly and fuel elements is given in Appendix A.

The subassembly was transferred from EBR-II to HFEF-S on January 15, 1988. Upon removal from the storage basket, it was given a normal blowdown to remove as much residual sodium as possible prior to transferring it into the Fuel Unloading Machine (FUM). The blowdown consists of blowing 343°C (650°F) argon through the subassembly for 8 minutes then decreasing the argon temperature to 232°C (450°F) for 7 minutes to cool it down. The blowdown occurs in the reactor fuel transfer port and is performed just prior to raising the subassembly into the FUM. The subassembly is then transferred from the FUM to the interbuilding cask (IBC). The cooling gas used in the FUM and IBC is argon until subassembly cleaning is started.

Upon receipt of the subassembly in HFEF-S, the sodium was removed using a standard driver subassembly "wash". The interbuilding cask is used as the sodium removal chamber. In the wash, the sodium is humidified with moisture saturated air at 1.9×10^{-4} m^3/s (0.4 cfm) for 5 minutes then at 3.3×10^{-3} m^3/s (7 cfm) for 25 minutes. After completion of the humidification process, the IBC is purged with argon for 5 minutes. Following the purge, the subassembly is rinsed with 0.095 m^3 (25 gal) of demineralized water then dried for 30 minutes with air at a flow rate of 0.014 m^3/s (30 cfm). After the sodium removal, the subassembly was transferred into the HFEF-S air cell for storage in the cooled pits.

The center fuel element in the subassembly was subsequently removed and replaced by an instrumented dummy element. The dummy element was made of a piece of reject MK-IIA cladding with a spacer wire and spade tip welded to it. The element was 0.533 m (21-in.) long by 4.42 mm (0.174-in.) OD by

3.81 mm (0.150-in.) ID with a 1.24 mm (0.049-in.) spacer wire on a 0.152 m (6-in.) pitch. The cladding and spacer wire were made of 20% CW 316 SS. Inside the element, five 1.59 mm (1/16 in.) mineral insulated type K (chromel/alumel) thermocouples (Aero Research number 100-M-24BK-9F) were spot welded to the cladding using a reverse polarity DC spot weld. To facilitate the welding and to allow air flow to reach the thermocouples, a section of the element's cladding was removed opposite to the weld location (see Figs. 1A and 2B). The axial location of the thermocouples is shown in Fig. 1A. The second and fourth thermocouples from the bottom were displaced slightly from the line which includes the top, middle and bottom thermocouples in order to clear the spacer wire. If the vertical plane of the top, middle and bottom thermocouples, and the centers of the removed sections of cladding, is considered the reference plane, then the second thermocouple from the bottom (TC-4) was rotated approximately 15 degrees, and the fourth thermocouple from the bottom (TC-2) was rotated approximately 20 degrees from the plane as shown in Fig. 1B. With the element on the grid, the thermocouples were facing away from the orientation notch on the subassembly as shown in Fig. 1C.

The length of the dummy element was slightly shorter than the standard MK-IIA element to allow the thermocouple lead wires to protrude straight out of the top of the element (see Fig. 2A), while clearing both the top of the fuel bundle and the top shield in the upper preassembly. The thermocouple lead wires were terminated in two Amphenol connectors since a single connector would have been too large to fit through any reasonably sized hole in the hex duct. The connectors were spaced approximately 0.15 m (6-in.) apart on the cabling to allow feeding them through the hole in the duct.

The outer surface of the fuel subassembly hex-duct was instrumented with thermocouples placed at the same vertical locations as were the dummy element thermocouples. The thermocouple strip used for measuring the temperature of the hex duct consisted of five type K thermocouples attached to a 25.4 mm (1-in.) wide by 0.356 m (14-in.) long by 3.18 mm (1/8-in.) thick strip of phenolic material. A 3.18 mm (1/8-in.) thick steel strip of equal length and width was attached to the phenolic to give the assembly rigidity. Each thermocouple was fed through the steel backing and phenolic then crimped in place. The thermocouple wires were positioned along the back of the strip and held

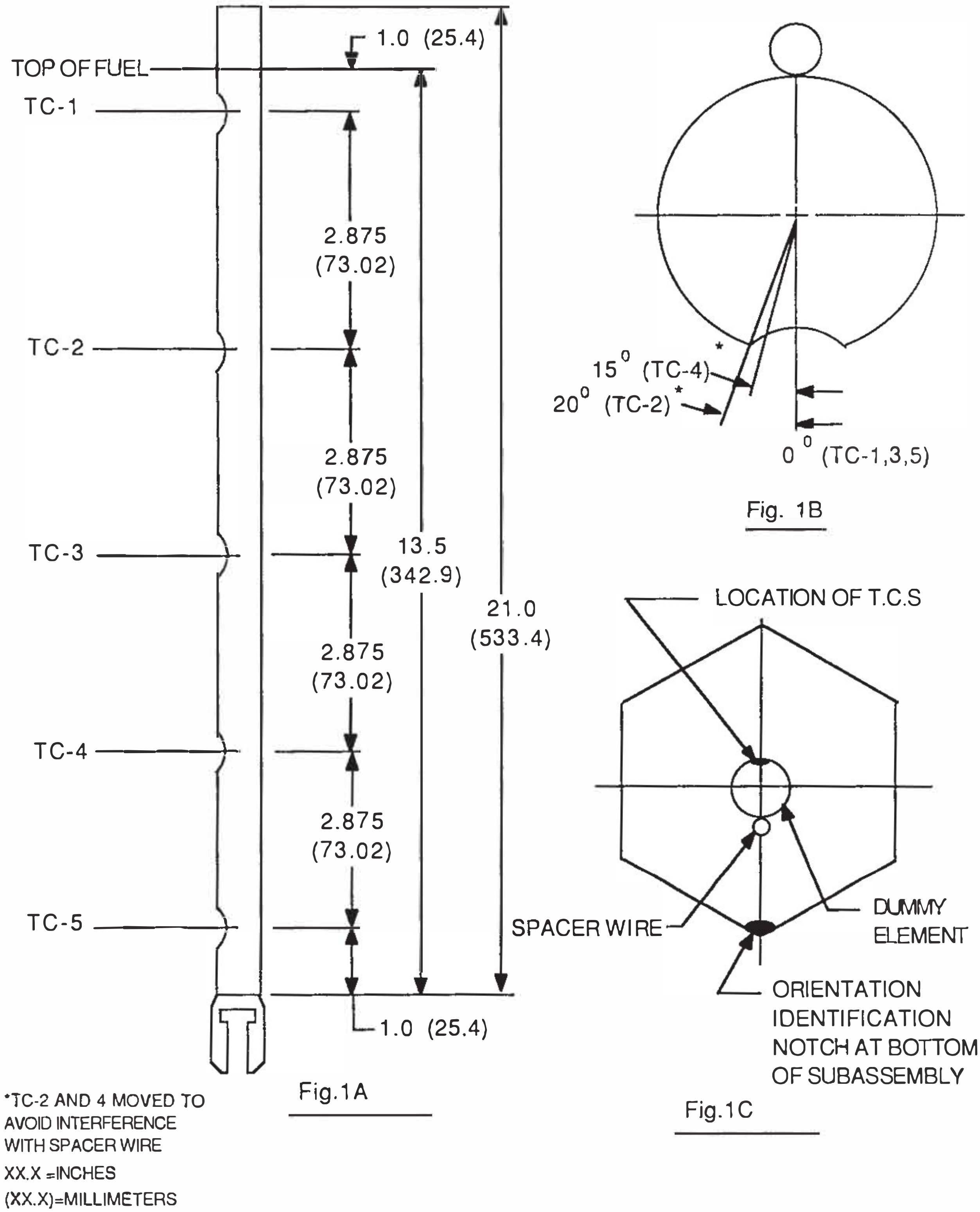

Fig. 1. Thermocouple Locations

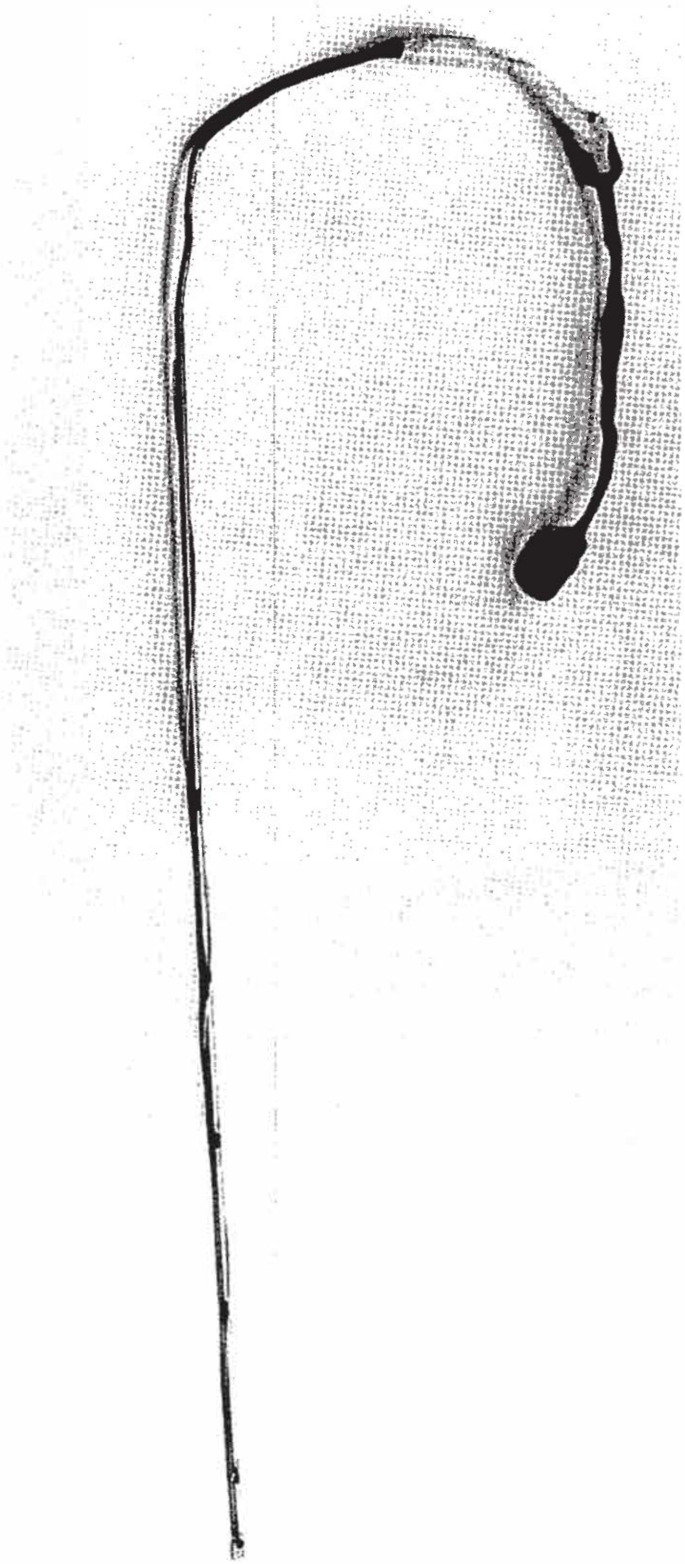

Fig. 2A. Dummy Element
(ANL/W Neg. No. R12262)

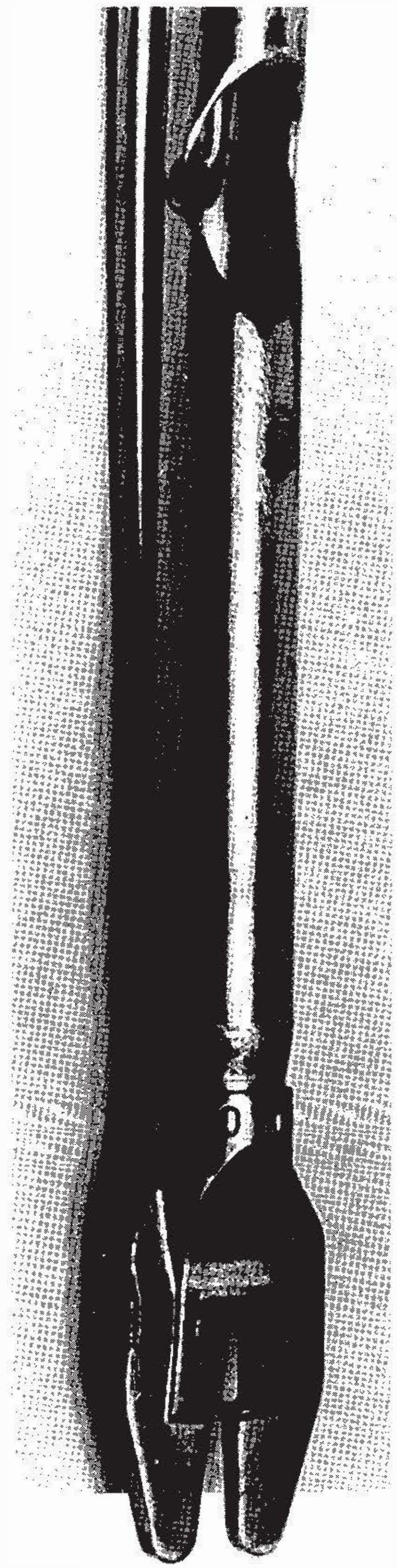

Fig. 2B. Dummy Element (Expanded View of Thermocouple Slot and Attachment) (ANL/W Neg. No. R12257) in place by aluminum blocks attached to the steel backing. One of the thermocouples, TC-4, on the strip was not attached to the back of the strip but was left loose so that it could be used for measuring the cell ambient temperature during Phase I of the test and the shroud temperature during Phases II and III. The entire thermocouple strip was attached to the hex duct by hose clamps at the top and bottom. An electrical diagram showing the thermocouple connections is given in Fig. 3.

The Phase II test was intended to simulate a subasseembly in a cask or storage pit. To isolate the subassembly from the cell air flow, an aluminum shroud was constructed to fit around the subassembly in the vertical assembler and dismantler (VAD). The shroud was made of a 1.82 m (72.5-in.) long piece of 0.102 m (4-in.) schedule 5 aluminum pipe. The pipe was split along its axis and hinges were installed at the top, middle and bottom to allow installation around the subassembly. The shroud was held closed by dial-latch clamps riveted to the pipe at the bottom and near the top. To bring the cables from the dummy element and hex duct thermocouples out of the shroud, a slot was cut in one of the halves on the joint containing the dial-latch clamps. A removable electro-mechanical manipulator "T" handle at the top was used to handle the shroud in cell. All surfaces of the shroud were painted with a flat black paint to give it an emissivity of near 1.0.

The Phase III test was conducted to verify the data from the Phase II test. At the end of the test, after equilibrium temperatures had been reached, a plate was placed on the top of the shroud to stop any upward air flow from the area between the subassembly and inside of the shroud.

All air-flow measurements near the fuel subassembly were taken with a mass flowmeter using the heated thermopile principle, with noble metal thermocouples being the sensing elements in a low voltage a-c bridge circuit.

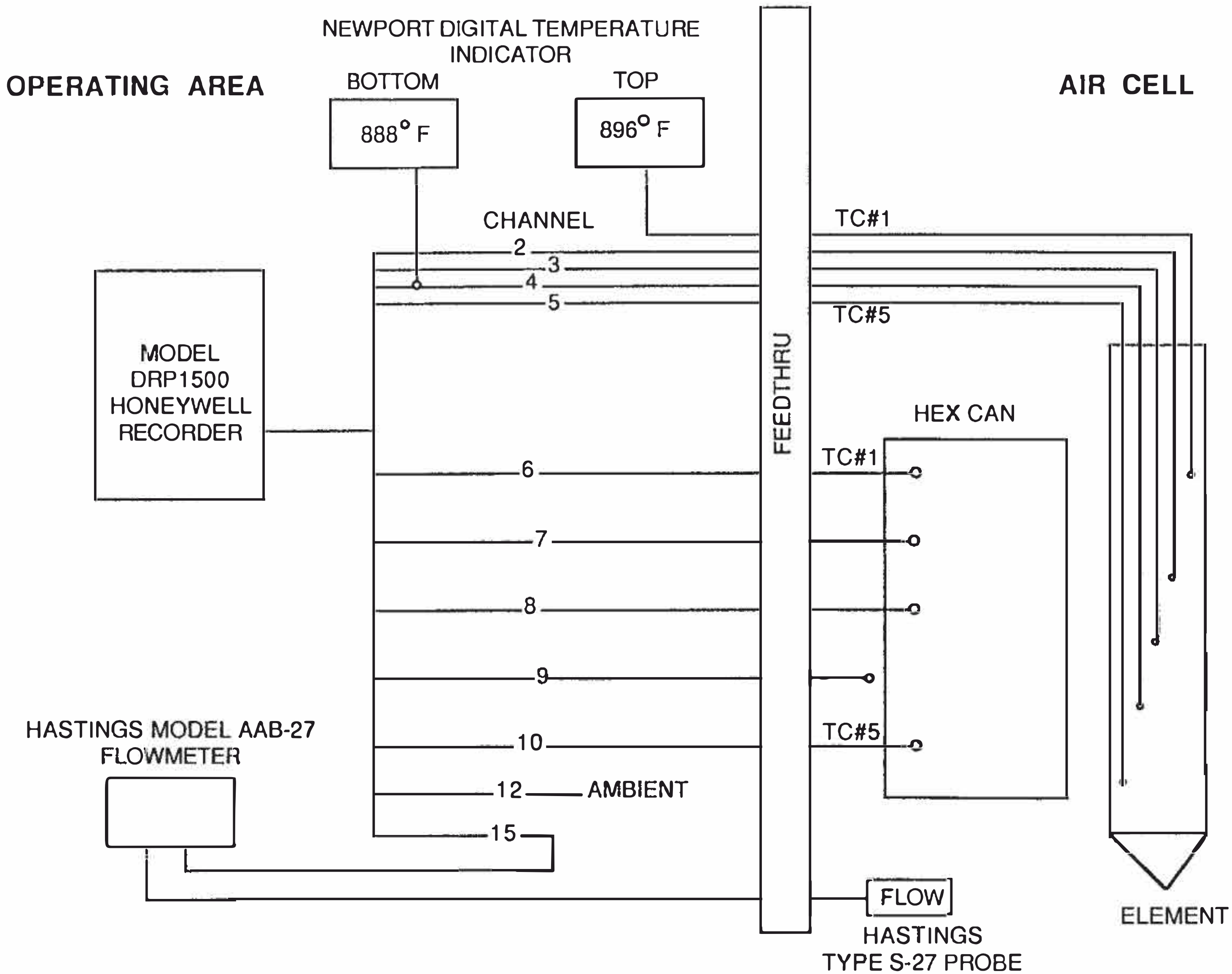

Fig. 3. Measurement Apparatus Connection Diagram

III. INSTRUMENTATION CHECKOUT

The proper operation of the data recorders was checked prior to the tests. A thermocouple simulator was input into the recorder through the cabling and feedthroughs, and the recorder output was noted. Appendix B gives the results for the chart recorder and the Newport Indicator used for the top thermocouple. The Newport Indicator was used to record (by hand because of a last-minute change in procedure) the output of top thermocouple on the dummy element, and the chart recorder was used to record the data from the remaining thermocouples.

Factory calibration was used for the flowmeter except that the meter was rezeroed at zero flow with the actual cable length as recommended by the manufacturer. During the tests, the flow sensor was located approximately 0.15 m (6 in.) from the subassembly and was held in place by a master-slave manipulator. During the Phase I and II tests, the flow sensor was moved to various locations around the subassembly and shroud to observe variations in the air flow across the subassembly. These measurements indicated very little variation in flow across the subassembly or shroud.

IV. PHASE-BY-PHASE DESCRIPTION OF TESTS

A. Phase I Test

Phase I of the test was performed on January 28, 1988. During the installation of the hex duct over the fuel bundle, the center thermocouple in the dummy element, TC-3, was damaged. Because of this, the temperatures measured by this thermocouple are not reported.

Prior to starting the test the subassembly was removed from the storage pits, placed in the VAD and prepared for the test by performing the following operations:

- The hex duct was removed from around the fuel bundle and marked with a felt-tipped pen at the top and bottom of the fuel bundle.
- Fuel elements 46 through 91 were removed from the bundle.
- Element 46 (the center element of the fuel bundle) was replaced by the instrumented dummy element.
- Fuel elements 47 through 91 were placed back in the bundle.
- A 0.051 m (2-in.) long by 0.038 m (1.5-in.) wide section of the hex duct was removed from flat 3 just below the upper shield block in the upper preassembly.
- The duct was reinstalled over the fuel bundle.
- The thermocouple leads of the dummy element were routed through the hole in the duct and a patch was installed over the hole.
- The hex duct thermocouple strip was installed on the duct. The strip was placed on flat 4 and was in juxtaposition with the fuel region in the elements.

Phase I of the test was started after the subassembly was reassembled. The cooling flow to the subassembly was stopped and the temperatures monitored. When the temperature reached equilibrium, cooling flow to the subassembly was re-established. The thermocouple outputs were recorded on the strip chart recorder. As stated earlier, TC-4 on the hex duct thermocouple strip was used to measure the cell ambient temperature during Phase I of the test, and the shroud temperature during Phases II and III of the test.

The raw data from Phase I is reproduced in Appendix B, and the dummy element temperature data is plotted and overlayed in Fig. 4. All temperature instrumentation readouts were in English units and therefore are presented in these units. The data from the hex-duct thermocouples is shown in Fig. 5.

B. Phase II Test

Phase II of the test was also conducted on January 28, 1988. After the completion of Phase I, the subassembly was cooled for approximately 2 hours and 24 minutes to allow the temperatures to reach equilibrium, then Phase II of the test was started. To prepare for Phase II, the shroud was installed around the subassembly and the fifth thermocouple on the hex-duct thermocouple strip was attached to it using a hose clamp. The exact location of the shroud thermocouple with respect to the fuel is not known; however, at the time of installation it was estimated to be in line with the top of the fuel.

When the preparations were complete, the cooling flow to the subassembly was stopped and it was allowed to heat-up until it reached equilibrium temperature. Upon reaching equilibrium temperature, the cooling flow was again started and the subassembly cooled down.

The raw data from the Phase II heatup test is reproduced in Appendix C and the data from the dummy fuel element are plotted and overlayed in Fig. 6. The plotted and overlayed data from the hex duct thermocouples are shown in Fig. 7.

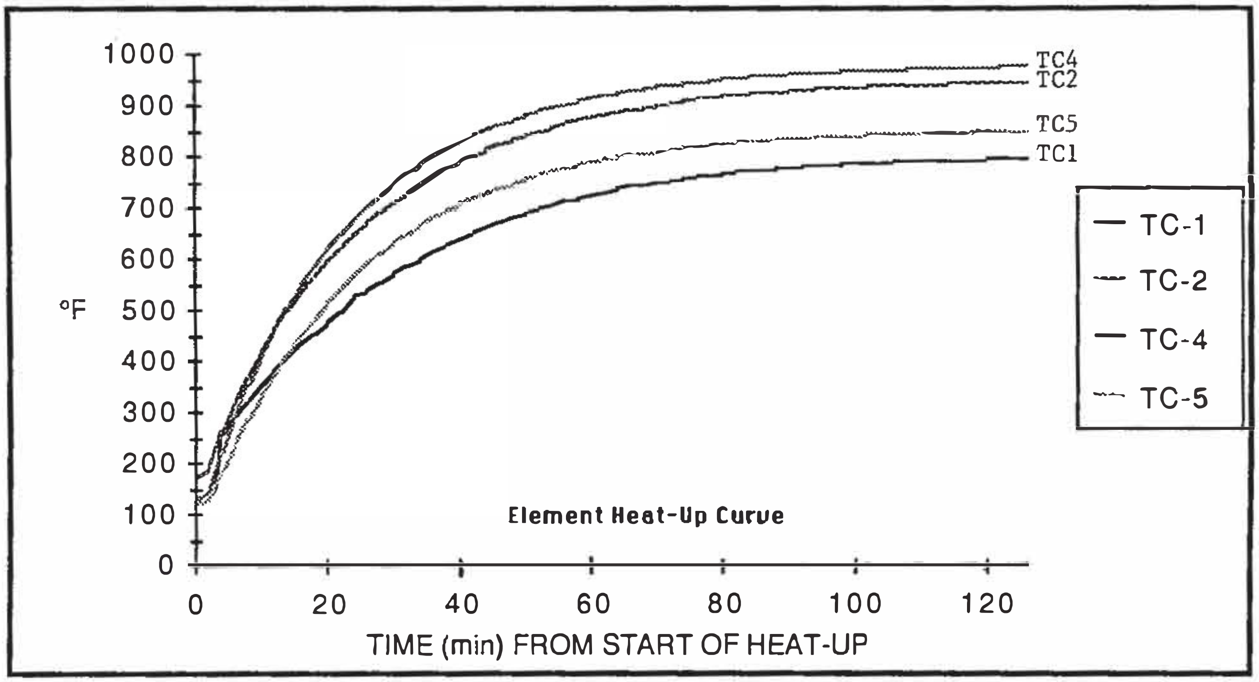

Fig. 4. Heatup Temperature Curves for Dummy Element - Phase I

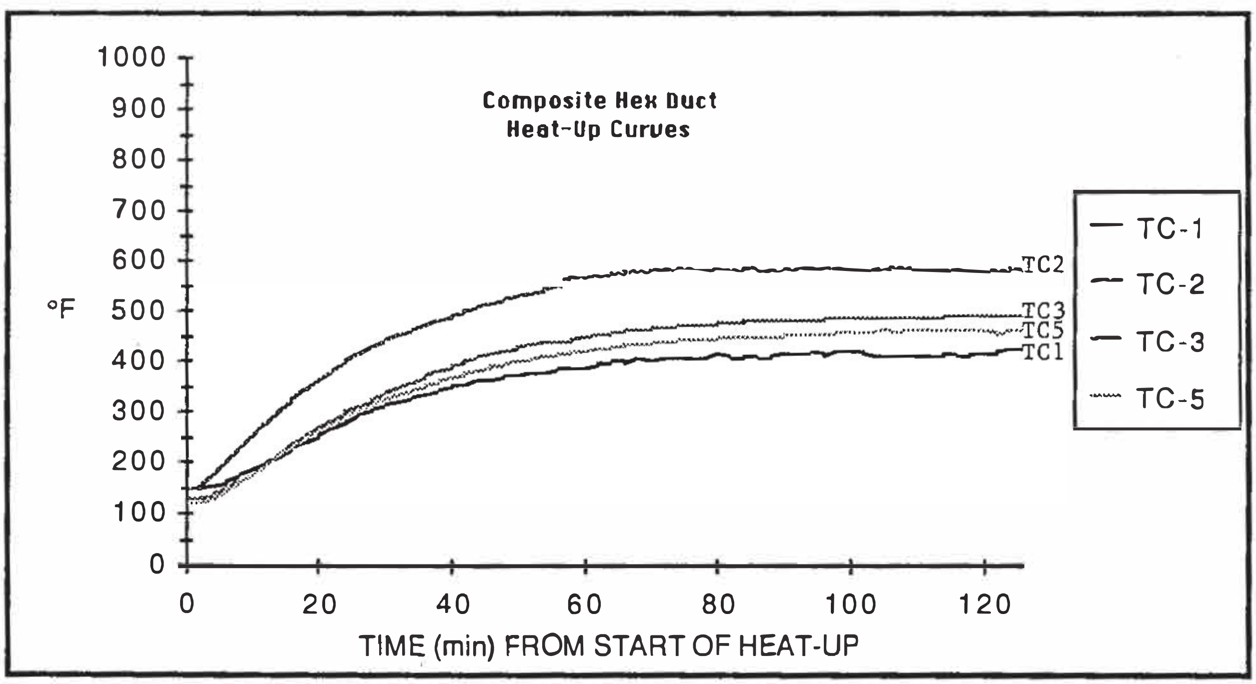

Fig. 5. Heatup Temperature Curves for Hex Duct - Phase I

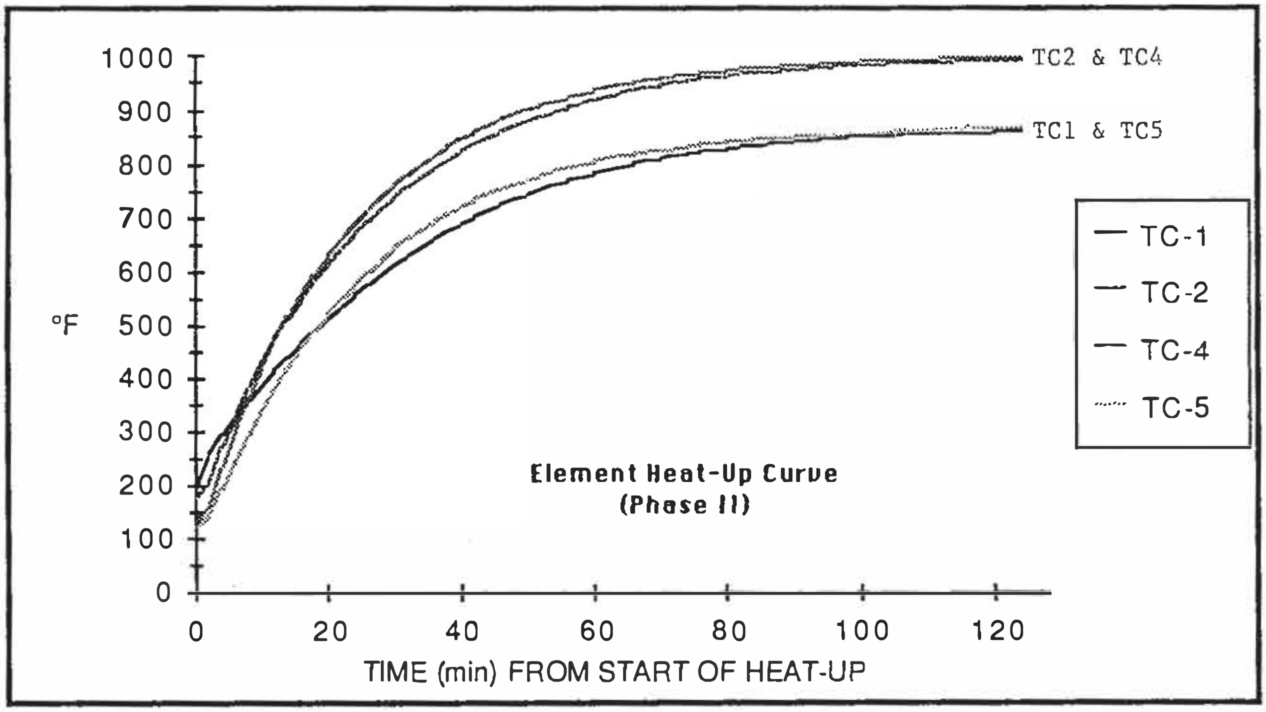

Fig. 6. Heatup Temperature Curves for Dummy Element - Phase II

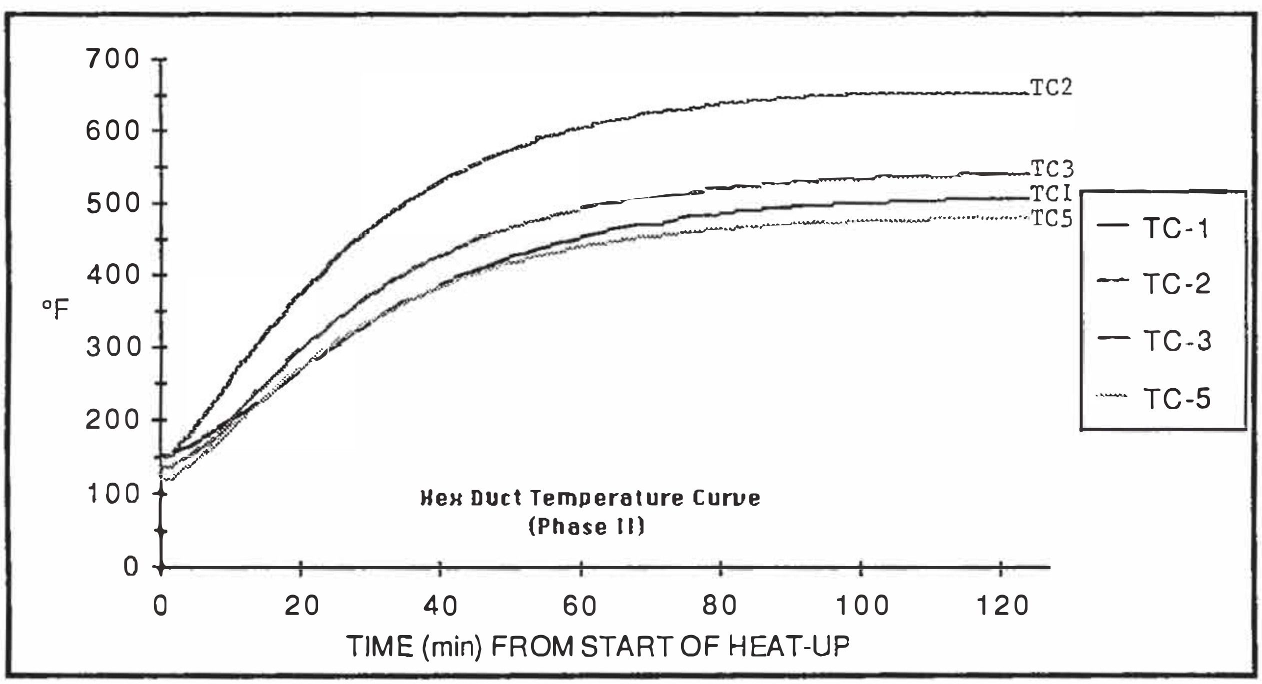

Fig. 7. Heatup Temperature Curves for Hex Duct - Phase II

C. Phase III Test

After Phase II of the test the subassembly was cooled for approximately 16 hours to allow both the subassembly and shroud to reach equilibrium temperatures. Following the 16 hour cooldown, Phase III of the test was started by stopping cooling flow to the subassembly and allowing it to heat up to its equilibrium temperature. When equilibrium was reached, a heavy steel lid was placed on the top of shroud and the temperatures were again allowed to reach equilibrium. The purpose of the lid was to inhibit any thermally driven air currents that might have exited the top of the shroud due to air in-leakage from the seams.

When the final equilibrium temperature was reached, the lid was removed from the shroud and cooling flow to the subassembly was started. This completed the test. The raw data from the Phase III heatup test is reproduced in Appendix D and the data from the dummy fuel element is plotted and overlayed in Fig. 8. The point near equilibrium at which the lid was placed over the shroud can be identified by the discontinuity in the slope of the curves.

The plotted and overlayed data from the hex-duct surface heatup during the Phase III test is shown in Fig. 9.

D. Typical Cooldown

Although not considered a primary objective of these tests, data was taken during the transient period after forced cooling was re-established, following each heatup test. Typical cooldown curves (Phase II test) are shown in Figs. 10, 11, and 12 for the dummy element, hex-duct, and shroud respectively.

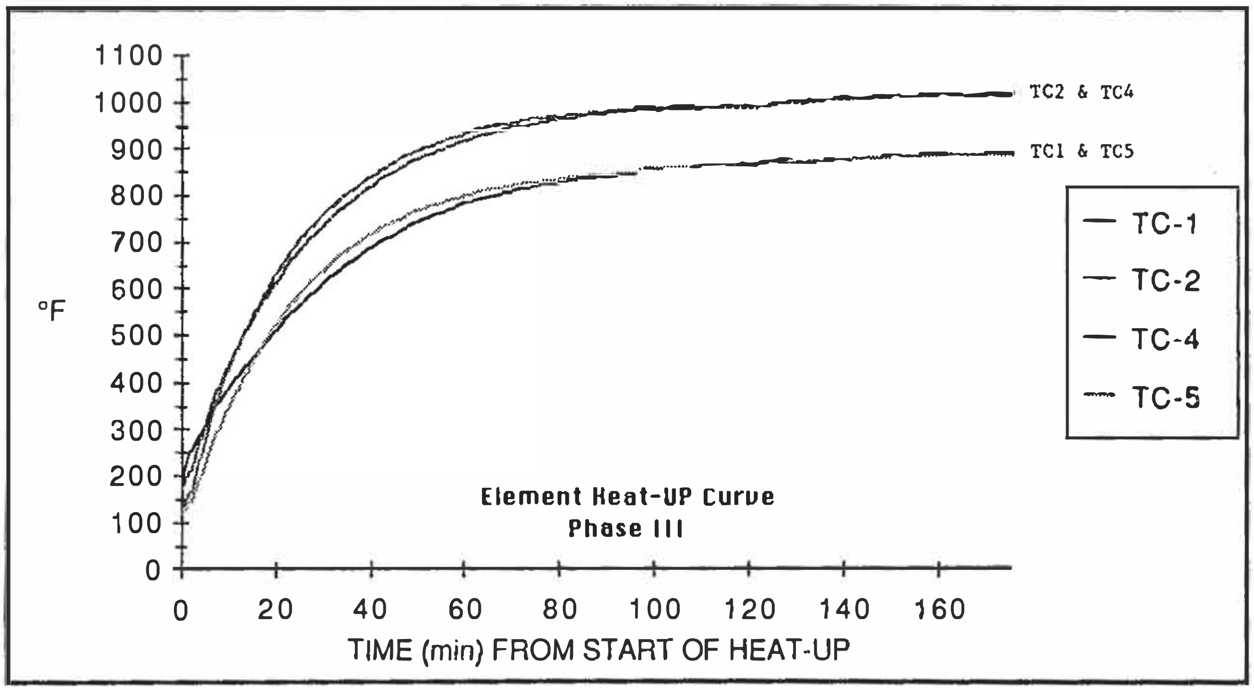

Fig. 8. Heatup Temperature Cruves for Dummy Element - Phase III

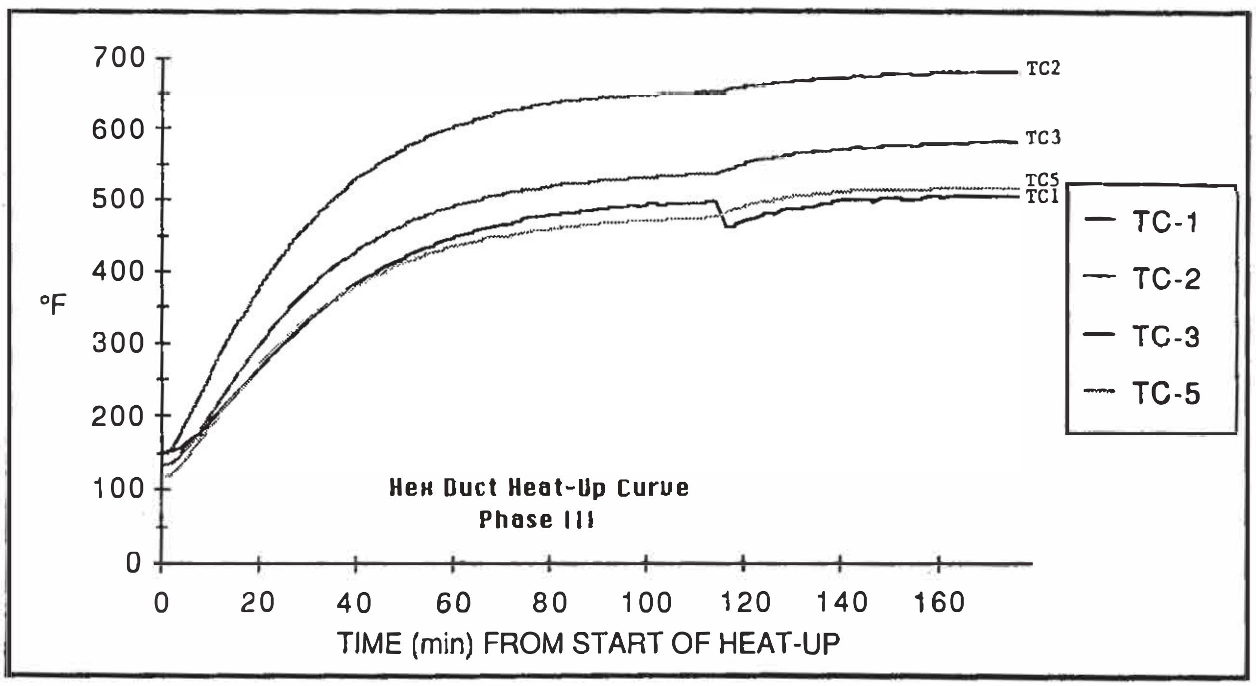

Fig. 9. Heatup Temperature Curves for Hex Duct - Phase III

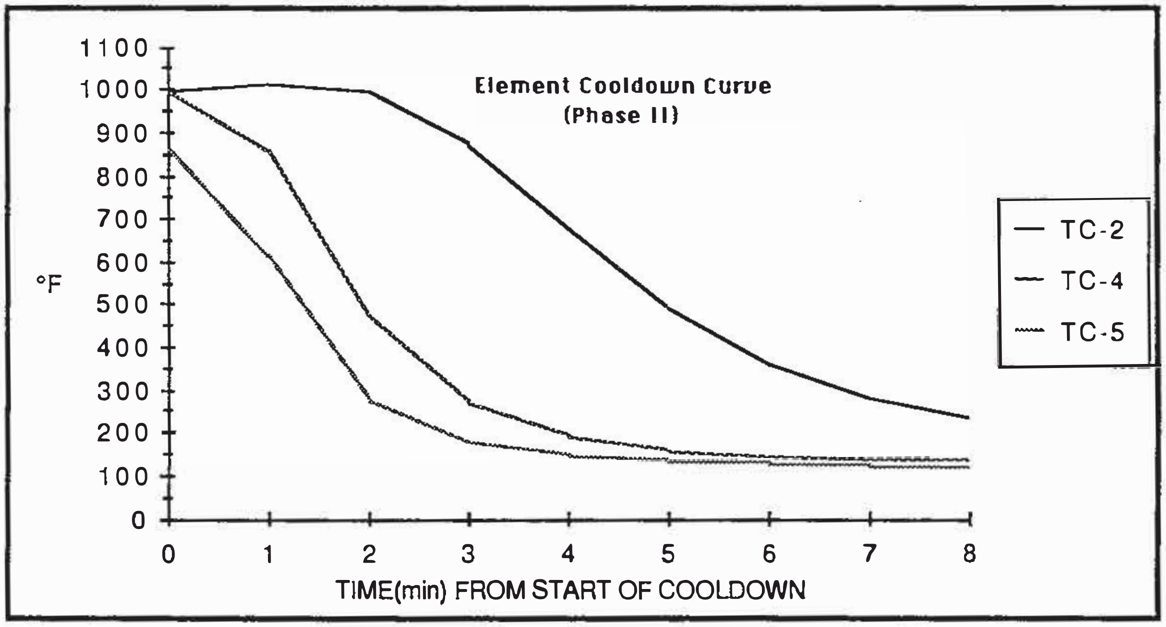

Fig. 10. Typical Dummy Element Cooldown After Re-establishing Flow Through Subassembly - Phase II

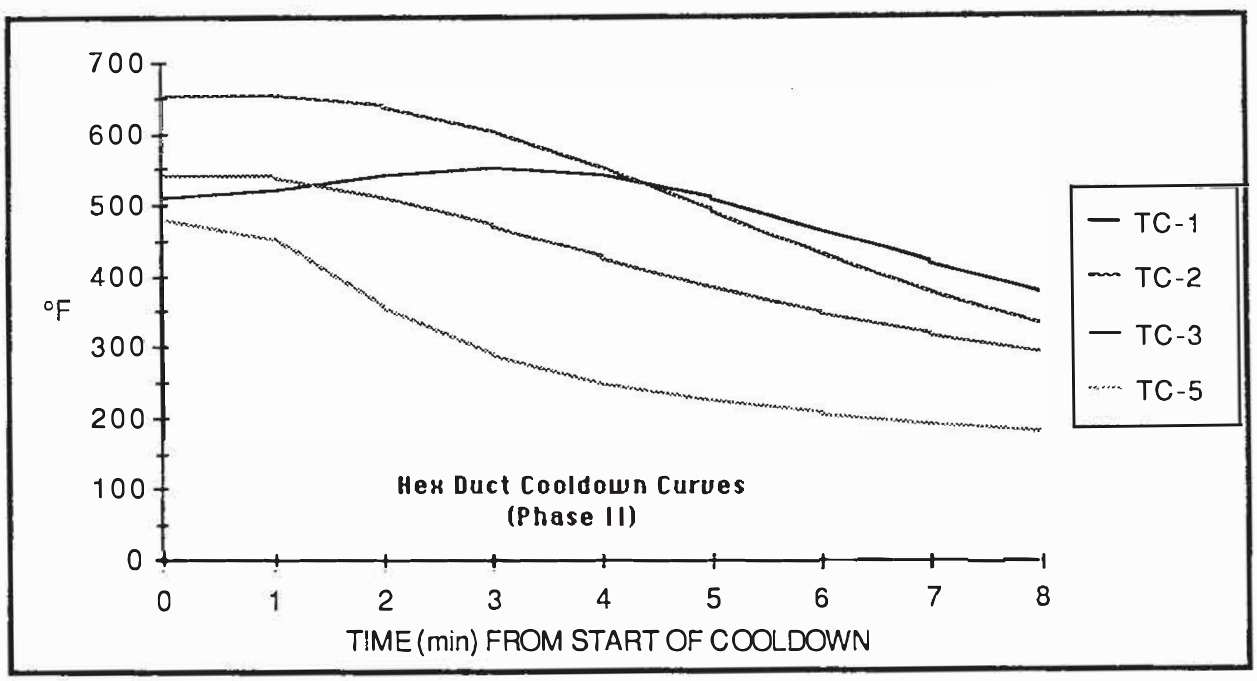

Fig. 11. Typical Hex Duct Cooldown After Re-establishing Flow Through Subassembly - Phase II

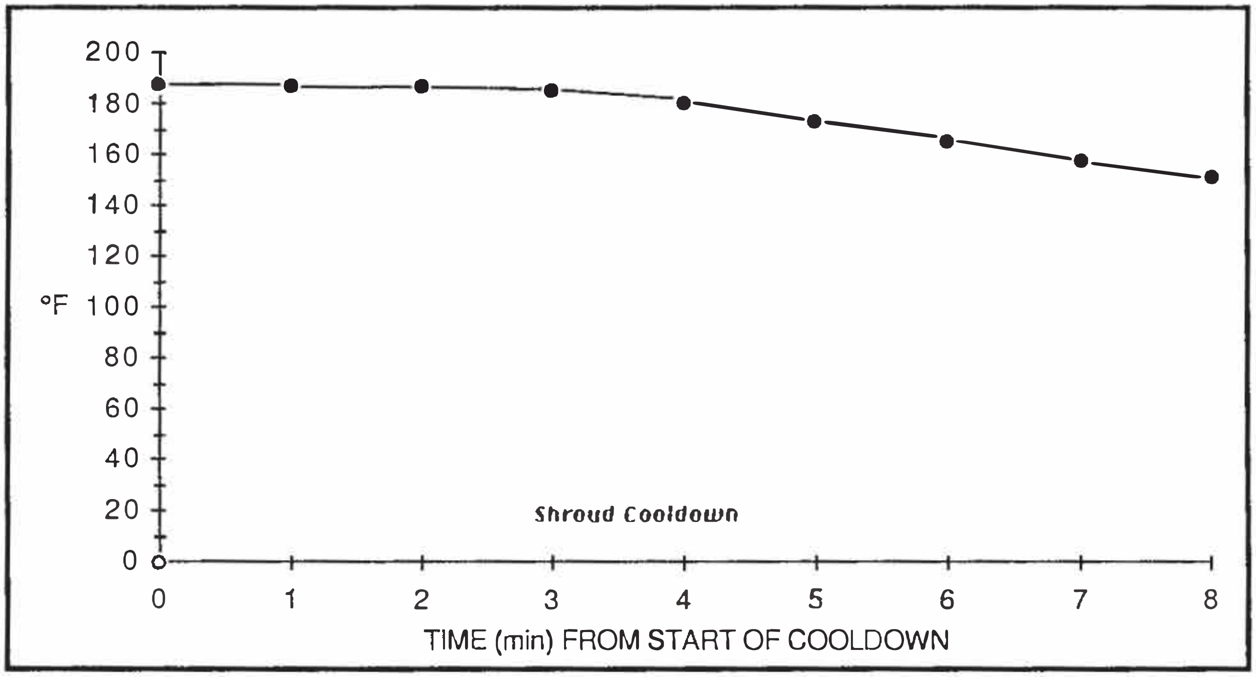

Fig. 12. Cooldown Curve for Shroud Following Re-establishment of Flow Through Subassembly - Phase II Test

V. RESULTS AT NEAR-EQUILIBRIUM TEMPERATURES

Tables I, II, and III below summarize the maximum temperatures obtained for both dummy element and hex duct during Phase I, II, and III tests, respectively.

The maximum temperature reached during any phase of the test was 548°C (1019°F). This temperature was well below the 713°C (1315°F) fuel-clad eutectic temperature for the elements.

TABLE I

Maximum Element and Hex Duct Temperatures in Phase I of Test

Element Temperatures

Thermocouple	Temperature °C	Temperature °F
TC-1	424	796
TC-2	507	945
TC-4	524	975
TC-5	453	848

Hex Duct Temperatures

Thermocouple	Temperature °C	Temperature °F
TC-1	218	425
TC-2	313	595
TC-3	254	490
TC-5	240	464

TABLE II

Maximum Element and Hex Duct Temperatures in Phase II of Test

Element Temperatures

Thermocouple	Temperature °C	Temperature °F
TC-1	461	862
TC-2	534	994
TC-4	537	999
TC-5	463	866

Hex Duct Temperatures

Thermocouple	Temperature °C	Temperature °F
TC-1	265	509
TC-2	345	653
TC-3	283	541
TC-4	86	187
(Shroud Temperature)		
TC-5	249	481

TABLE III

Maximum Element and Hex Duct Temperatures in Phase III of Test

Element Temperatures

Thermocouple	Temperature °C	Temperature °F
TC-1	478	893
TC-2	548	1018
TC-4	548	1019
TC-5	477	891

Hex Duct Temperatures

Thermocouple	Temperature °C	Temperature °F
TC-1	264	508
TC-2	361	681
TC-3	306	582
TC-4	104	219
(Shroud Temperature)		
TC-5	269	517

VI. IRRADIATION HISTORY AND ESTIMATED DECAY HEAT LEVELS

The 91-element MK-IIA subassembly C2781E was irradiated in core position 2F1 to a burnup of 7.4 at.% and had produced an integrated power of 20354 MWd of reactor. The last reactor run (145A) ended on November 2, 1987. For the test performed on January 28, 1988, the subassembly had cooled 87 days. During the irradiation, the subassembly power changed between runs, and the power for the last run was 833 kW. A detailed irradiation history of the subassembly is given in Table IV. The radial power gradient across the subassembly is relatively flat and varied by only 1.2%. The axial power gradient is essentially a chopped cosine with a maximum-to-average of 1.124.

The beta-gamma decay-heat levels were calculated using the Burris-Dillon correlation,[1] the ANSI/ANS 5.1-1979 standard,[2] and the ORIGEN/S program.[3] Most of the power is produced by fissioning of the U-235. The U-238 produces about 4% of the total and plutonium about 0.5% at end-of-irradiation conditions.

For the Burris-Dillon method, the decay-heat level is calculated for each subrun and then summed to obtain the total decay power level. Therefore, the power variations noted in Table IV are accounted for. The program does not account for burnout of the fission products during irradiation. Fission product yields from fast fission are used and decay heat levels are calculated for U-235 and Pu-239. The decay-heat for U-238 was assumed to be the same as for U-235.

A decay-heat correlation is available from the ANSI/ANS 5.1 standard for light-water reactors and was used for comparison, even though the isotope-fission product yields may be slightly different. No corrections were made for isotope burnout. The decay-heat levels were calculated for U-235 and U-238. Since the contribution from Pu-239 was so low, this isotope was not considered. The subassembly power-levels for the various subruns was accounted for. Burnout of the fission products was neglected.

The ORIGEN-SCALE (ORIGEN/S) program calculates the decay-heat levels by considering the current fast-fission product yields* and the decay chain of each isotope. As such, it is probably more accurate than the previous two correlations. Burnout of the fission products in the fast neutron spectrum is also accounted for. The various subassembly power levels during the subruns are accounted for in the calculation of decay-power levels.

The results of calculations by the three methods are shown in Table V. The decay-heat levels during the three methods are in reasonable agreement. The values vary by 6.4% from lowest to highest. In addition to the calculated decay heats shown, about 5 W of gamma power originates from the stainless steel in the cladding, wire wrap, and hex duct.

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* Fission product yields for the Liquid Metal Fast Breeder Reactor (LMFBR) in the ORIGEN/S code consisted of those from fission-spectrum-energy neutrons for ^{235}U, ^{238}U, and ^{239}Pu, with Pu-239 yield substituted for ^{241}Pu and ^{240}Pu.

TABLE IV

Irradiation History MK-II Subassembly
C-2781E Core Position 2F1

Reactor Run Number	Run Ending Date	Subassembly Power kW	Run Length Days	Time Cooled End of Run to 1/28/88 Days
145A	11/2/87	833	64.7	87
144A	8/24/87	840	93.8	156
143A	4/9/87	833	51.9	293
142B	2/9/87	673	3.0	354
142A	2/5/87	840	49.2	358
141C	12/10/86	524	7.3	414
1418	12/1/86	729	8.9	423
141A	11/17/86	786	55.9	437

TABLE V

Predicted Fission Products Decay-Heat
Generation for the C2781E* Subassembly

Cooling Time, days	87	88
Calculation Method:		
Burris-Dillon	513W	508W
ANSI/ANS-5.1-1979	488W	484W
ORIGEN	482W	478W

*Values are for 91 elements. The heatup-test was conducted using 90 elements and one dummy element. Therefore, heatup test decay heat is 90/91 of above values.

VII. SUMMARY

The heat test provides confidence that EBR-II MK-IIA subassemblies with 500 W radioactive decay power can be safely stored in the HFEF-S air cell uncooled, when provided with low-temperature boundary conditions. The maximum temperature reached during any phase of the test was 548°C (1019°F), which is well below the U-Fe eutectic temperature of 715°C (1319°F) for MK-II fuel. An analysis for these tests can be found in Ref. 4.

VIII. REFERENCES

1. L. Burris and I. G. Dillon, "Estimation of Fission Product Spectra in Discharged Fuel from Fast Reactors," ANL-5742 (July 1957).

2. American National Standard for Decay Power in Light Water Reactor, ANSI/ANL-5.1-1979.

3. O. W. Herman and R. M. Westfall, "ORIGEN-S, Scale System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms," NUREG/CR-0200, Volume 2, Section F7 (November 1980, Revised December 1984).

4. J. F. Koenig and R. M. Lell, "Prediction of Temperatures in an EBR-II Subassembly Heated by Fission Product Decay without Forced Cooling," ANL-IFR Report (to be published).

APPENDIX A

SUBASSEMBLY AND FUEL ELEMENT DATA

Subassembly Type:	MK-IIA
Hex Duct Material:	12% CW 316 SS
Upper Shield Block Material:	304 SS
Upper Adapter Material:	304 SS
Lower Preassembly Material:	304 SS
Subassembly Drawing Numbers:	EB-1-54064-B/M
Element Type:	MK-IIA
Element Length:	25.050-in.
Element Diameters:	0.174-in. OD by 0.150-in. ID
Spacer Wire Diameter and Pitch:	0.049-in. with a 6-in. Pitch
Fuel Bond:	Sodium
Cladding Material:	20% CW 316 SS
Spacer Wire Material:	20% CW 316 SS
Fuel Column Length:	13.5-in.
Element Drawing Numbers:	EB-1-53916-B/M

The fuel column on the MK-IIA elements starts 0.750-in. from the bottom tip of the spade on the element. The fuel in the column is U-5 wt % Fs. The constituents of the fissium (Fs), in weight, % are as follows:

Molybdenum	2.44
Ruthenium	1.94
Rhodium	0.28
Palladium	0.19
Zirconium	0.085
Niobium	0.015
Silicon	0.05

APPENDIX B

CALIBRATION CHECKS FOR THERMOCOUPLE OUTPUT RECORDERS

TEMPERATURE		
Simulated Input Temperature °F	Top Newport Indicator	Recorder
0	0	-0-
100	98	100.3
200	199	200.1
300	300	300.3
400	398	400.4
500	498	500.3
600	598	600.6
700	697	700.5
800	798	800.3
900	899	900.4
1000	1000	1000.8
1100	1101	1100.3
1200	1203	1200.4
1300	1303	1300.4
1400	1402	1400.5
1500	1500	1500.7

APPENDIX C

PHASE I - SUBASSEMBLY HEATUP TEST WITHOUT SHROUD

TIME	TEST TIME	TEMP. (F) OF DUMMY ELEMENT TC #1	TC #2	TC #4	TC #5	TC1	TEMP. (F) OF HEX DUCT TC2	TC3	TC4	TC5	TEMP. (F) AMBIENT	FLOW (ft/min)
9:16	0	- -	172	129	121	146	150	129	102	118	73	3
9:18	2	- -	199	145	131	146	153	129	102	119	73	5
9:20	4	256	261	223	186	153	177	138	102	131	73	4
9:22	6	293	319	291	237	162	202	149	101	146	73	3
9:24	8	326	372	354	287	175	227	164	102	162	73	4
9:26	10	355	419	410	332	188	252	179	102	179	73	3
9:28	12	382	461	460	374	199	276	195	102	195	73	5
9:30	14	408	500	506	413	212	301	214	109	214	73	4
9:32	16	432	534	547	449	227	324	233	111	231	73	5
9:34	18	455	566	584	482	240	345	251	107	247	73	3
9:36	20	477	596	618	513	251	365	268	105	263	73	5
9:38	22	498	622	648	541	267	382	282	103	276	73	5
9:40	24	528	647	677	567	279	399	298	103	290	73	5
9:42	26	537	670	702	591	295	413	312	103	302	73	5
9:44	28	554	691	725	612	303	428	325	103	313	73	5
9:46	30	570	712	746	632	313	442	337	104	325	73	3
9:48	32	586	729	766	650	322	454	348	103	335	73	4
9:50	34	600	746	784	667	329	464	360	103	344	73	4
9:52	36	615	761	800	682	334	473	371	106	353	73	4
9:54	38	627	776	815	695	342	483	382	110	361	73	5
9:56	40	639	789	829	708	351	492	391	109	369	73	4
9:58	42	651	802	841	720	351	501	400	105	375	73	4
10:00	44	662	813	853	731	361	509	408	104	383	73	4
10:02	46	672	824	863	741	363	517	415	103	389	73	5
10:04	48	682	833	872	749	371	523	421	103	394	73	3
10:06	50	690	842	881	758	371	530	427	103	399	73	4
10:08	52	698	850	889	765	377	536	432	103	404	73	4
10:10	54	705	858	896	772	377	541	437	103	409	73	3
10:12	56	716	865	902	778	384	546	440	104	413	73	3
10:14	58	719	871	909	784	388	551	444	103	418	73	5
10:16	60	725	878	914	790	386	554	450	108	421	73	4
10:18	62	730	883	920	794	396	560	455	110	426	74	4
10:20	64	736	888	924	799	398	563	458	107	429	73	4
10:22	66	741	893	929	804	395	566	461	105	432	74	4
10:24	68	745	897	932	807	406	568	464	104	435	73	3
10:26	70	750	902	936	811	399	570	467	103	438	73	5
10:28	72	754	906	940	814	406	572	469	104	440	73	4
10:30	74	757	909	943	818	406	575	472	103	442	7[illegible]	4
10:32	76	761	912	946	820	407	576	473	104	444	73	3
10:34	78	764	915	949	823	406	576	474	103	444	74	5
10:36	80	766	918	951	825	415	578	476	103	446	73	4
10:38	82	770	920	953	827	407	578	478	103	448	74	4
10:40	84	772	923	955	829	409	580	480	103	450	74	5
10:42	86	774	924	957	831	407	579	480	103	449	73	4
10:44	88	776	926	958	832	410	579	482	104	450	73	4
10:46	90	778	928	960	834	417	581	484	109	452	74	4
10:48	92	780	930	961	835	415	585	484	108	453	74	5
10:50	94	781	931	962	837	418	585	483	105	455	74	3
10:52	96	783	933	964	838	411	585	484	104	455	74	5
10:54	98	785	934	965	839	422	586	485	104	456	74	4
10:56	100	786	935	966	840	420	586	486	103	458	74	4
10:58	102	787	936	967	641	417	587	486	103	458	74	4
11:00	104	788	938	968	841	411	588	486	369	460	74	4
11:02	106	789	938	969	842	409	590	488	358	459	74	5
11:04	108	790	940	970	843	412	590	488	381	461	74	4
11:06	110	791	940	971	844	410	589	488	389	462	74	4
11:08	112	792	941	971	844	409	590	488	301	462	74	4
11:10	114	792	942	972	845	414	591	489	167	462	74	3
11:12	116	793	942	973	846	410	591	489	110	463	74	3
11:14	118	793	943	973	846	413	593	491	106	465	74	5
11:16	120	794	944	974	847	416	592	490	109	462	74	5
11:18	122	795	944	974	848	419	591	490	112	453	74	5
11:20	124	795	945	975	846	426	593	490	113	464	74	5
11:22	126	796	945	975	848	425	595	490	112	464	74	5

APPENDIX D

PHASE II - SUBASSEMBLY HEATUP WITH SHROUD

TIME	TEST TIME	TEMP. (F) OF DUMMY ELEMENT				TEMP. (F) OF HEX DUCT					TEMP. (F)	FLOW
		TC #1	TC #2	TC #4	TC #5	TC 1	TC 2	TC 3	TC 4	TC 5	AMBIENT	(ft./min.)
13:54	0	194	174	129	123	155	152	137	126	121	75	5
13:56	2	256	204	159	142	157	157	139	126	124	75	5
13:58	4	294	273	234	195	165	179	150	122	139	75	5
14:00	6	327	331	302	245	177	204	165	120	154	75	5
14:02	8	358	383	363	292	189	230	182	119	170	75	5
14:04	10	386	431	419	340	200	256	200	119	188	75	5
14:06	12	414	474	470	382	211	281	220	120	205	75	5
14:08	14	440	514	516	422	225	307	240	121	223	76	5
14:10	16	465	550	557	458	239	331	260	123	239	75	5
14:12	18	489	583	595	491	254	354	279	125	256	76	5
14:14	20	513	614	629	520	270	375	297	127	271	76	5
14:16	22	535	642	660	550	283	395	314	129	286	75	5
14:18	24	556	569	689	576	298	414	330	132	300	75	5
14:20	26	575	693	715	600	311	432	345	134	313	75	5
14:22	28	594	716	739	622	324	450	360	137	325	75	5
14:24	30	612	738	761	641	336	466	373	140	337	76	5
14:26	32	629	758	782	660	349	481	386	142	348	76	5
14:28	34	645	776	800	677	361	494	398	144	358	76	5
14:30	36	660	793	817	693	368	508	409	147	368	76	5
14:32	38	677	809	832	708	378	520	419	150	376	75	5
14:34	40	688	823	847	720	387	531	428	152	384	75	5
14:36	42	701	837	860	732	396	541	437	154	392	76	5
14:38	44	712	849	871	744	404	550	446	156	400	75	5
14:40	46	723	861	883	754	411	559	453	158	406	75	5
14:42	48	734	872	892	763	419	567	460	160	412	75	5
14:44	50	743	682	901	772	426	575	466	161	418	75	5
14:46	52	752	891	910	780	430	582	473	163	423	75	5
14:48	54	761	899	918	787	438	589	478	165	427	75	5
14:50	56	769	907	925	794	444	595	483	167	432	75	5
14:52	58	777	915	931	800	448	600	488	168	436	75	5
14:54	60	783	921	937	806	453	605	492	169	440	75	5
14:55	62	789	927	943	811	457	610	496	170	443	75	5
14:53	64	795	933	948	816	463	614	500	171	447	75	5
15:00	66	801	938	952	820	466	618	503	173	450	75	5
15:02	68	806	943	956	824	471	622	507	174	453	75	5
15:04	70	810	947	960	827	471	626	510	174	455	75	5
15:06	72	815	952	964	332	475	629	513	176	458	75	5
15:03	74	619	956	967	834	479	632	515	177	459	75	5
15:10	76	823	959	970	837	484	634	517	178	461	75	5
15:12	78	826	962	972	840	484	637	519	179	463	75	5
15:14	80	829	965	975	842	487	639	522	181	465	75	5
15:16	82	832	968	977	844	489	642	524	182	467	75	5
15:18	84	835	970	979	846	491	643	525	181	468	75	5
15:20	86	838	973	981	848	492	645	527	181	469	75	5
15:22	88	840	975	983	850	495	647	528	182	471	75	5
15:24	90	843	977	985	851	498	648	530	183	472	75	5
15:26	92	845	979	986	853	498	650	531	184	473	75	5
15:28	94	846	980	987	854	498	651	532	184	474	75	5
15:30	96	848	982	989	856	499	652	533	184	475	75	5
15:32	98	850	984	990	857	500	652	534	184	475	75	5
15:34	100	851	985	991	858	502	653	535	185	477	75	5
15:36	102	853	986	992	859	501	653	536	185	477	75	5
15:38	104	854	987	993	860	503	653	536	185	477	75	5
15:40	106	855	988	994	861	503	653	537	185	478	75	5
15:42	108	856	989	995	861	504	653	537	186	478	76	5
15:44	110	857	990	995	862	504	653	538	185	479	75	5
15:46	112	853	991	996	863	505	653	538	185	479	75	5
15:48	114	859	992	997	863	507	653	539	186	479	75	5
15:50	116	859	992	997	864	506	653	540	186	480	76	5
15:52	118	859	993	998	864	507	653	540	186	480		
15:54	120	861	993	998	865	507	653	541	186	480		
15:56	122	862	994	998	865	508	653	541	187	481		
15:58	124	862	994	999	866	509	653	541	188	481		

APPENDIX E
PHASE III - SUBASSEMBLY HEATUP TEST

TIME	TESTTIME	TEMP (F) OF DUMMY ELEMENT TC 1	TC2	TC 4	TC5	TEMP. (F) OF HEX DUCT TC1	TC2	TC3	TC4	TC 5	TEMP. (F) AMBIENT	FLOW (ft./min.)
10:42	0	196	173	128	120	153	150	132	111	117	73	5
10:44	2	255	213	167	147	151	156	136	111	121	73	5
10:46	4	293	279	241	198	159	178	149	111	134	73	5
10:48	6	326	336	307	250	169	203	164	112	151	74	5
10:50	8	356	387	368	298	180	229	182	113	168	74	4
10:52	10	385	433	422	343	192	255	201	115	185	73	5
10:54	12	412	476	472	383	207	282	221	117	203	74	5
10:56	14	438	514	517	422	221	308	240	119	220	74	4
10:58	16	463	549	557	458	236	333	260	121	237	74	4
11:00	18	487	582	594	490	250	356	280	124	253	74	4
11:02	20	510	612	630	521	265	377	297	126	269	74	4
11:04	22	532	640	657	549	279	397	315	128	283	74	4
11:06	24	553	666	686	574	292	417	331	131	298	74	4
11:08	26	573	691	711	596	306	434	347	134	310	74	5
11:10	28	591	713	735	618	318	451	361	136	323	74	5
11:12	30	609	734	756	637	331	467	375	140	334	74	5
11:14	32	626	754	776	656	343	481	388	142	345	74	4
11:16	34	642	772	794	673	354	494	399	144	355	74	5
11:18	36	657	788	811	688	364	507	410	147	364	74	5
11:20	38	672	804	826	702	374	519	420	149	373	74	5
11:22	40	685	819	840	716	383	530	429	151	381	74	5
11:24	42	698	832	853	728	392	540	438	153	389	74	5
11:26	44	709	844	864	739	399	549	446	156	396	74	5
11:28	46	720	856	875	747	408	558	454	157	402	74	4
11:30	48	731	866	885	757	415	566	460	159	408	74	4
11:32	50	740	876	894	766	421	573	467	161	413	74	5
11:34	52	749	886	902	774	427	581	473	162	419	74	5
11:36	54	758	894	910	780	434	586	478	164	424	74	5
11:38	56	766	902	917	787	438	593	483	166	428	74	4
11:40	58	773	909	924	794	444	598	487	167	432	74	4
11:42	60	782	916	929	799	448	603	492	169	436	74	4
11:44	62	786	922	934	803	452	608	496	170	439	75	4
11:46	64	792	927	939	808	456	612	499	171	442	74	4
11:48	66	798	933	944	813	459	616	502	172	445	74	3
11:50	68	803	938	948	817	462	619	505	173	448	74	5
11:52	70	807	942	952	820	466	623	508	175	450	74	5
11:54	72	812	946	955	824	468	626	511	175	452	74	4
11:56	74	816	950	959	827	472	629	513	177	454	74	5
11:58	76	820	953	962	830	475	631	515	177	456	74	5
12:00	78	823	957	964	832	476	634	517	178	458	75	4
12:02	80	826	960	967	835	479	635	519	178	460	74	5
12:04	82	830	962	969	837	480	638	521	179	462	74	5
12:06	84	832	965	971	839	482	639	522	179	463	74	4
12:08	86	835	967	973	841	484	641	524	179	464	75	4
12:10	88	837	970	975	842	484	642	525	161	465	74	5
12:12	90	839	972	977	844	488	644	526	181	467	75	5
12:14	92	841	973	378	846	489	645	528	182	467	74	5
12:16	94	843	975	979	846	490	646	529	182	469	75	5
12:18	96	845	976	981	848	491	647	530	181	469	75	5
12:20	98	846	978	982	849	491	648	531	183	470	75	4
12:22	100	848	979	983	850	494	649	532	184	471	75	4
12:24	102	849	980	983	851	493	649	533	185	472	75	5
12:26	104	850	982	985	852	494	650	533	185	472	75	5
12:28	106	851	983	986	853	495	651	534	185	473	75	5
12:30	108	852	984	987	854	496	651	535	185	474	75	5
12:32	110	854	985	987	855	496	652	535	186	474	75	5
12:34	112	854	985	988	855	498	652	535	184	475	75	5
12:36	114	855	986	989	856	498	652	536	185	475	75	4
12:38	116	855	986	989	857	463	655	542	190	482	75	5
12:40	118	856	987	990	858	465	658	547	195	487	75	5
12:42	120	857	988	991	860	471	660	551	200	492	75	5
12:44	122	859	989	993	862	474	662	555	201	496	75	5
12:46	124	862	991	995	865	481	664	558	202	499	75	4
12:48	126	864	993	997	867	478	665	560	206	501	75	5
12:50	128	866	995	998	868	487	667	563	207	504	75	4
12:52	130	868	997	1,000	870	488	669	565	208	506	75	3
12:54	132	870	998	1,002	872	491	670	566	210	507	75	5
12:56	134	872	1,000	1,003	874	490	671	568	212	509	75	4
12:58	136	874	1,001	1,005	875	496	672	570	213	510	75	5
13:00	138	876	1,003	1,006	876	497	673	571	213	511	75	4
13:02	140	877	1,004	1,007	878	501	673	572	212	512	75	3
13:04	142	879	1,006	1,009	879	500	674	574	214	513	75	4
13:06	144	880	1,007	1,009	880	501	675	575	214	514	75	3
13:08	146	882	1,008	1,010	881	498	675	575	215	514	75	5
13:10	148	883	1,009	1,011	882	504	676	576	215	515	75	4
13:12	150	884	1,010	1,012	883	503	677	577	216	515	75	5
13:14	152	885	1,011	1,013	884	502	678	578	216	514	75	4
13:16	154	886	1,012	1,014	884	501	678	578	215	514	75	3
13:18	156	887	1,012	1,014	885	503	679	578	217	515	75	4
13:20	158	888	1,013	1,015	886	506	679	579	217	516	75	4
13:22	160	889	1,014	1,015	887	504	679	580	216	516	75	5
13:24	162	889	1,014	1,016	887	507	680	580	216	516	75	4
13:26	164	890	1,015	1,017	888	507	680	581	217	516	75	5
13:28	166	891	1,016	1,017	888	507	680	581	217	517	75	5
13:30	168	891	1,016	1,018	889	506	681	581	217	517	75	5
13:32	170	892	1,017	1,018	889	505	661	582	219	517	75	5
13:34	172	892	1,017	1,018	889	507	681	582	220	517	75	5
13:36	174	893	1,017	1,019	890	507	681	582	218	517	75	5
13:38	176	893	1,018	1,019	891	508	681	583	219	517	75	5