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W-1 SLSF POST-TEST DATA ANALYSIS

PART 1. THERMAL HYDRAULIC ANALYSIS

D. D. Knight

October, 1980

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1.0 INTRODUCTION

The W-1 Sodium Loop Safety Facility (SLSF) experiment was conducted between May 27 and July 20, 1979. This program was under sponsorship of the Department of Energy directed by the Hanford Engineering Development Laboratory (HEDL). The experiments were performed in the Experimental Test Reactor (ETR) at the Idaho National Engineering Laboratory operated by EG&G. Pre-test and post-test analyses were performed by General Electric - Advanced Reactor Systems Department. (Ref. 5, 13).

The W-1 experiment was performed as a part of the National Fast Breeder Reactor Safety Program to provide data addressing second line-of-assurance (LOA-2) safety issues. The key issue was:

coolability of fuel pin bundles and structural stability with fresh fuel and with irradiated fuel after initiation of sodium boiling during a loss of piping integrity accident for CRBR conditions.

Specifically the tests were aimed at determining:

- 1) conditions for the onset of sodium boiling
- and 2) the time required for boiling to become established throughout the fuel bundle after boiling initiation at different power levels.

In addition, the W-1 tests addressed subsidiary issues.

- Sodium boiling initiation and void progression characteristics.
- Duration and conditions of boiling without dryout.
- Sodium boiling conditions for dryout and incipient fuel pin failure.

The combined results of the W-1 test sequences provide verification of code predictions of core response to loss of piping integrity accidents, and the rate of sodium voiding progression in fuel assemblies operating at a range of power and low flow conditions. These conditions are of interest in safety analyses which account for boiling incoherencies in a core with low flow conditions. The purpose of these analyses is to show that time phasing of boiling in LOPI's and low flow/low power reactor conditions prevents damage to the entire core, i.e. that no damage or limited damage results, consistent with the line of assurance (LOA-2) goals.

2.0 SUMMARY OF TEST CONDITIONS AND ANALYSES PERFORMED

Four types of tests were performed: (1) a decay heat transient test, (2) Loss-of-Piping-Integrity (LOPI) tests, (3) Boiling Window Tests (BWT), and (4) a fuel pin dryout and failure test. In addition, preliminary tests were run to check systems performance, instrumentation performance and test section heat balance. The objective of the decay heat test was to determine the decay heat transfer characteristics of fresh fuel pins with subcooled sodium. The objective of the LOPI experiments was to test the thermal behavior of fuel pins with four different fuel conditions subjected to the same transient. The transient was designed to simulate a rapid flow decrease as a result of pipe rupture followed by a reactor scram. The objective of the Boiling Window Tests was to study boiling initiation and progression of boiling within the fuel pin bundle. The Boiling Window Tests were conducted at three fuel pin power levels. The power was kept constant during the transient while the test section flow was reduced within 1/2 second, held at a reduced level for several seconds then returned with 1/2 second to nominal flow to terminate the test. The last test of the series was performed with the reduced flow conditions severe enough to result in dryout in the test section and failure of fuel pins. A summary of the test program is given in Table 1.

The decay heat test was performed with an initial power level of 174 kW corresponding to an average linear pin power of 3.05 kW/ft. The test was initiated by scrambling the ETR while maintaining the test section flow constant. Temperature data were taken with in-fuel thermocouples and sodium immersed thermocouples.

The LOPI 1 transient was initiated after only a few minutes at full power (668 kW or 11.72 kW/ft average) to provide a steady-state thermal condition in fresh fuel with minimal restructuring. The LOPI 2 test was run at approximately 4% overpower and a scram occurred earlier than planned. The LOPI 2A transient, a replacement for LOPI 2, was run after approximately 5 days of full power operation. Fuel restructuring was manifested through decreased fuel temperatures. The steady state fuel temperature measured with thermocouples 14 inches below the top of the fuel was 350°F lower in LOPI 2A than in LOPI 1, at the same full power condition.

TABLE 1
SUMMARY OF SLSF W-1 TESTS

Test Designation	Date Performed	Test Objective	Test Conditions	Remarks
Decay Heating	5/30/79	Determine decay heating rate	174 kW test section power	
LOPI 1	6/9/79	Transient response of fresh unrestructured fuel	Nominal power (670.8kW) and flow.	No boiling observed
LOPI 2	6/12/79	Transient response of restructured fuel	Burnup approx. 2 days at full power Approx. 4% over power at test initial condition	Scram occurred early. Test invalid
LOPI 2A	6/21/79	Repeat LOPI 2 test	Nominal Burnup approx. 4 days at full power	Successful test. No boiling
LOPI 3	7/7/79	Transient response of fully restructured fuel with moderate burnup and healed cracks	Burnup approx 15 days at full power Approx. 3% under power at test initial condition	Ran 3 days at full power without scram prior to test to assure healed fuel cracks. No boiling
LOPI 4	7/7/79	Transient response of fuel in LOPI 3 condition except cracked due to LOPI 3 transient	Approximately 7% over-power at test initial condition	Transient initiated as soon as full power steady-state conditions achieved to prevent crack healing. Boiling observed

TABLE 1
SUMMARY OF SLSF W-1 TESTS

Test Designation	Date Performed	Test Objective	Test Conditions	Remarks
BWT 2	7/11/79	Incipient boiling @ 345 kW (6.05 kW/ft average)	Approx. 3% over power. Reduced flow to 22% for 3 seconds	No boiling
BWT 2'	7/11/79	Incipient boiling @ 345 kW	Approx. 4% overpower. Reduced flow to 22.8% for 5 seconds	Repeat of BWT 2 with low flow for longer time. Boiling occurred. Indicated by wire wrap t/c for approx. .8 sec.
BWT 4	7/12/79	Incipient boiling @ 510 kW (8.95 kW/ft average)	Approx. 9% overpower. Reduced flow to 34.4% for 4 seconds	Boiling occurred for approximately 1.0 sec.
BWT 6	7/13/79	Incipient boiling @ 668 kW (11.72 kW/ft average)	Approx. 1% overpower. Reduced flow to 44% for 3.0 sec.	Approximately 0.2 seconds of boiling.
BWT 6'	7/19/79	Incipient boiling @ 668 kW	Approx. 2% overpower. Reduced flow to 44% for 3.5 sec.	Sodium saturation temperature reached.
BWT 6"	7/19/79	Incipient boiling @ 668 kW	Approx. 3% overpower. Reduced flow to 44% for 4.0 sec.	Boiling occurred for approx. 0.9 sec.
BWT 7a	7/20/79	Fuel Pin Dryout and failure	Approx. 3% overpower. Reduced flow to 40% for 3.0 sec.	Boiling occurred for 1.6 sec. No indication of fuel pin failure.
BWT 7b	7/20/79	Fuel pin dryout and failure	Approx. 4% overpower. Reduced flow to 38.7% for 3.0 sec.	Boiling occurred for approx. 2.0 sec before cladding dryout and fuel pin failure.

The LOPI 3 test was run after a total of about 11 days of burnup at full power. Prior to the test, there were 3 days of operation with no scram to assure that there were no unhealed cracks in the fuel. The LOPI 4 test was run immediately after LOPI 3 so that the fuel burnup was the same and the fuel was expected to be cracked as a result of the LOPI 3 transient. The LOPI 4 transient was run from a 7% overpower steady state condition and was the only LOPI test to produce boiling. The sodium saturation temperature was reached after about 1.2 seconds of the transient and boiling lasted for about 0.6 seconds. There was no indication of sodium superheat.

The Boiling Window Tests (BWT) were performed within the test conditions established by the pre-test analysis (Ref. 5). The test matrix included several alternate conditions including variations of lower flows or longer time periods at low flow in order to produce boiling, and for the final test to produce dryout and fuel pin failure. The development of the test procedures and selection of test conditions were influenced by the results of previous tests.

The first boiling window test, BWT 2 was performed at a fuel bundle power of 356 kW and bundle flow reduced to 22% of nominal flow for 3 seconds. Boiling did not occur so the next test, BWT 2' was run with reduced flow for 5 seconds. The wire wrap thermocouple data indicated sodium boiling for approximately 0.8 seconds at the top of the fuel. Boiling occurred as soon as the sodium reached the saturation temperature. There was no indication of sodium superheat prior to boiling in any of the tests.

At the intermediate power level, a single boiling window test, BWT 4 was run. During this test the flow was reduced to 34.4% of nominal for 4 seconds and boiling was observed for about one second.

At the highest power level, 668 kW, three tests were conducted to study boiling initiation and progression. The tests, BWT 6, BWT 6', BWT 6'' were performed at full power and 44% full flow for times of 3, 3.5 and 4 seconds. During BWT 6'', boiling was observed for about 1.5 seconds and was severe enough to affect the test section inlet flow. The inlet flow dropped to about 34% of nominal flow as a result of boiling before the flow was returned to nominal to terminate the test.

The dryout and fuel pin failure test was conducted at 668 kW with a programmed reactor scram at the time of return to full flow, i.e. 3.5 seconds after initiation of the transient. The first test, BWT 7a', was run with the flow reduced to 39.5% of nominal for 3 seconds. Boiling occurred for approximately 1.6 seconds and was severe enough to cause reduction of the test section inlet flow. There was no indication of fuel pin dryout or failure. For BWT 7b', the flow was reduced to 37.2% of full flow for 3 seconds. The test produced dryout, flow reversal and fuel pin failure and can be considered to be a success.

During BWT 7b', boiling was observed for a full 2 seconds before dryout occurred. Thermocouple data showed a radial progression of boiling from the center of the bundle to the edge which took about 0.2 seconds. Axial progression of boiling was also shown by the thermocouples. Boiling at the top of the fuel started after about 1.75 seconds of transient and reached the bundle axial mid-plane after about 3.1 seconds of transient. The test section inlet flow was reversed by boiling at about 2.8 seconds in the transient and flow oscillations were measured by the inlet flowmeter. Dryout was indicated by rapid increase of thermocouple temperatures after about two seconds of boiling at the top of the fuel. Peak wire wrap thermocouple temperatures of about 20.5°F were reached before cooling as a result of the scram and return to full flow.

The post-test data analysis was performed with several computer codes as shown in the schematic in Figure 1. Each code is best suited for a specific analysis of one or more features of the experiment. The primary results from the analysis are sodium temperature transient calculated with the COBRA-3M code (Ref. 14) and the fuel pin thermal response calculated with THT-D (Ref. 15).

Computer codes used for generating input information for the thermal analyses included RAFFLE which was used to calculate test section power distributions (Ref. 18), THYME-C (Ref. 16) which was used to evaluate the SLSF conditions and LIFE-4 (Ref. 17) which was used to determine the fuel condition.

TEST
DATA

EG&G
ANALYSIS

GE POST TEST
ANALYSIS

3.0 CONCLUSIONS

The post-test data analysis and evaluation of the thermal-hydraulic conditions and response of the W1 SLSF experiment may be summarized with several conclusions:

- 1) COBRA-3M predicted boiling to occur in the LOPI tests although there was no boiling (except in LOPI 4 which was run with an overpower condition). The effect of fuel restructuring was to delay boiling initiation, probably as a result of lower fuel temperatures and consequently lower energy content.
- 2) COBRA-3M predicted sodium temperature increases which are more rapid than those measured.
- 3) During the transients, radial heat losses or heat sinking due to the hex can resulted in a radial temperature gradient. The sodium in the outer subchannel was consistently predicted and observed in the test to reach boiling temperature later in time than the center subchannels.
- 4) During the boiling window tests COBRA-3M consistently predicted boiling initiation earlier than measured. COBRA-3M also consistently predicted boiling initiation to occur first near the center of the bundle and the data show this trend also. A summary of boiling initiation predictions and measurements is given below.

BWT	BOILING INIATION TIME CENTER OF BUNDLE (sec)	BOILING TIME DELAY FOR OUTER BUNDLE (sec)
2'	3.3 (4.58)	.23 (NB in outer)
4	2.4 (2.53)	.23 (.99)
6"	1.8 (2.41)	.04 (.4)
7b'	1.2 (1.2)	.17 (.2)

Predicted (Measured)*

*Measured times given are from wire-wrap thermocouples corrected for thermocouple time log.

NB = no boiling

- 5) The response of the in-fuel thermocouple during the first ten seconds of the decay heat test confirmed the thermal analysis. At long times (50 sec to 100 sec) after the scram, the calculated temperature is low. This could be due to uncertainty in the value of decay heat or uncertainty in the value of gap conductance. No resolution was reached.
- 6) Steady state in-fuel temperatures indicate that restructuring occur during the first 50 to 60 hours of operation at full power and that the fuel/cladding gap is closed after about 250 hours. The gap was closed at the initial conditions for the LOPI 3, LOPI 4, BWT 6 series and BWT 7 series tests. The steady state conditions for BWT 2 indicate that the gap was open.
- 7) The calculated in-fuel thermocouple response agreed very well with the data at both locations (2" and 14" below the top of the fuel) with operable thermocouples. The measured thermocouple response in LOPI 3 shows an initial temperature decrease rate which is very rapid and becomes slower after about two seconds. This data suggests a delay in opening of the gap during the transient.

The performance of the W-1 SLSF test bundle was very similar to the expected performance based on pre-test predictions of steady state and transient response.

Post-test calculations of steady state conditions and the test data show that the W-1 SLSF design for the 19 fuel pin bundle provided a good simulation of a core assembly. Throughout the test program, the radial heat transfer at steady state was into the fuel pin bundle. The insulator was 200°F to 300°F hotter than the coolant as a result of gamma heating. Measured insulator temperatures were used to specify a radial boundary condition for the analyses.

Post-test calculations of fuel pin heating rates resulted in a pin-to-pin variation of +3.2% to -2.1%, from the average. Heating in the outer ring of fuel pins was generally a little above average while the center pin was very close to average.

The axial heating rate profile showed a peak to average as high as ~1.32 in some cases. Combining this value with the +3.2% results in a peak heating rate of 15.96 kW/ft at the nominal 668 kW bundle power or 11.72 kW/ft average. This compares to the pre-test intention to test at 14.14 kW/ft peak based on 15% overpower for CRBRP conditions.

Test conditions, particularly steady state and transient flow, were highly repeatable. There were some anomalies including the LOPI 4 test which was run at a total power of 715 kW instead of 668 kW due to the use of a faulty thermocouple in a heat balance calculation.

Steady state sodium temperature data measured with wire wrap thermocouples agree very well with prediction. This provides a degree of confirmation of the test section heat balance and the axial power distribution. In practice, the axial sodium temperature distribution is not sensitive enough to check the axial power distribution. In addition, sodium temperatures can be used to check the power to flow ratio but cannot be used to provide an absolute magnitude for power or flow. The calculated steady state sodium temperatures at the top of the fuel shows a gradient across the fuel bundle. The temperature of the outer subchannel is approximately 25°F higher than the temperature of the center subchannel at full power and steady state. The data indicates that radial gradients are less.

Four in-fuel thermocouples functioned throughout the test and provide a unique data base for analysis of fuel conditioning and thermal response. Steady state in-fuel thermocouple data show the effects of fuel restructuring near the fuel pin mid-plane. During the first 50 to 60 hours of operation at full power (~10.5 kW/ft average or greater), the fuel center temperature decreases with time due to restructuring and the corresponding increase in-fuel thermal conductivity. After this time, the fuel center temperature continued to decrease due to closure of the fuel/cladding gap. After about 140-150 hours at full power, the fuel center temperature stabilized and remained constant, indicating that the gap was closed. Calculations with the LIFE-4 code do not duplicate the in-fuel temperature history. The LIFE-4 calculated temperatures are lower in the beginning of the irradiation. Later, the LIFE-4 calculations do not result in a closed gap probably due to the low temperatures resulting in less fuel swelling. Later in the transient, LIFE-4 predicted that the gap width decreased but the release of fission gas just compensated so the predicted gap heat transfer properties remained almost constant.

In order to match the calculated in-fuel thermocouple results from the THT-D code with the data at steady state, it was necessary to adjust the gap conductance values. For LOPI 3 and subsequent tests at full power, gap

conductance values in excess of 3000 BTU/hr ft² °F were required indicating a closed gap.

Thermal response calculations for the fuel pins and the sodium coolant are qualitatively accurate. The THT-D calculations of in-fuel thermocouple response show a slower rate of cooling during the LOPI transients than measured with the in-fuel thermocouples. A comparison of THT-D calculations of fuel temperature with calculated in-fuel thermocouple response show that the deviation is not due to inaccurate modeling of the thermocouples. The slower predicted cooling rate could be a result of over predicting the heating rate in the fuel pin or underpredicting the rate of heat transfer to the sodium.

Comparisons of calculated wire wrap thermocouple response with measured data show that the calculations predict sodium temperatures to increase too quickly. COBRA-3M predicts boiling for the LOPI tests when none occurred. For the boiling tests, COBRA predicts boiling initiation to occur earlier than observed from the data.

4.0 TEST CONDITIONS

The W-1 SLSF experiment began on 27 May 1979 and was concluded on 20 July 1979. This test period included approximately fifteen days of operation at full power for the purpose of fuel pin conditioning. Four LOPI tests were performed with different fuel conditions. The fuel conditions tested were:

- 1) Fresh unrestructured fuel,
- 2) Partially restructured fuel,
- 3) Fully restructured fuel with moderate burn-up and healed cracks,
- 4) Same as condition 3 except with unhealed cracks.

Data taken during steady state irradiation consist of test section flow rate, sodium temperatures measured with wire wrap thermocouples and fuel temperatures measured with in-fuel thermocouples. Appendix C contains schematics which show the test instrumentation. Test section heat balances calculated with this data were used to determine power conditions during irradiation.

The condition of the fuel throughout the steady state irradiation was analyzed using the LIFE-4 code. The results from the LIFE-4 code include calculated values of fuel microstructural radii, fuel porosity, O/M ratio, fission gas composition and in addition calculated values of the fuel/cladding gap conductance. This information was used to specify the fuel condition and properties at the start of each transient test.

4.1 Test Section Power History

Figure 2 (Reference 1) shows the total fuel bundle power history throughout the five 10-day ETR operating cycles. These values of bundle power were obtained with a test section heat balance as follows (Reference 2);

$$\text{Power units} = \dot{m}(H_{\text{OUT}} - H_{\text{IN}}) \times 1.05479$$

where: $\dot{m}$ = test section flow = 0.3436 x total flow (lbm/sec)
 H_{OUT} = sodium enthalpy at the top of the fuel region (Btu/lbm)
 H_{IN} = sodium enthalpy at the test section inlet (Btu/lbm)
Power = kw

BUNDLE POWER (KW) VS OPERATING DATE

FIGURE 2: POWER HISTORY - 1st 10-DAY CYCLE

BUNDLE POWER (KW) VS OPERATING DATE

FIGURE 2 (Continued) POWER HISTORY - 2nd 10-DAY CYCLE

BUNDLE POWER (KW) VS OPERATING DATE

FIGURE 2 (Continued) POWER HISTORY - 3rd 10-DAY CYCLE

BUNDLE POWER (KW) VS OPERATING DATE

FIGURE 2 (Continued) POWER HISTORY - 4th 10-DAY CYCLE

BUNDLE POWER (KW) VS OPERATING DATE

FIGURE 2 (Concluded) POWER HISTORY - 5th 10-DAY CYCLE

For the test section flow, data from the total flow meter, FE 3-1, was used since this meter appeared to be the most consistent and reliable throughout the testing. The factor, .3436, relating test section flow and total flow was obtained from ALIP performance testing in the W-1 SLSF (Reference 3). The power values in Figure 1 were evaluated with the enthalpy at the inlet, H_{IN} , calculated from an average of the temperature data obtained with TE 1-1, 1-2, and 1-3. The enthalpy at the top of the fuel region was calculated from an average of the temperature data obtained with the wire wrap thermocouples, TE 3-7 and TE 4-6 (see Appendix C for an identification of instrumentation).

The test section power history actually used in the LIFE-4 analysis is given in Table 2. Selected points were chosen to represent the power history. The data in the table were obtained from a digital listing of test section data at ten-minute intervals throughout the steady state irradiation. The heat balance used to calculate the test section power values listed in Table 2 is slightly different from that given in the previous paragraph. The powers in Table 2 were calculated with a heat balance based on data from thermocouples TE 3-4 and TE 4-6 corrected for position. The sodium enthalpy at the top of the fuel was calculated with a sodium temperature defined as:

$$T_{top} = 1/2 [(TE\ 3-4) + (TE\ 4-6)] - .015 * POWER$$

The last term is a correction to account for sodium heating between the top of the fuel and the position of the thermocouples 1.7" above the top of the fuel. This correction was derived from the results of steady state sodium temperature distributions calculated with the COBRA-3M code.

Steady state initial conditions for each of the transient tests are included in Table 2. This data was taken from the tapes containing the transient data. Data for several seconds before initiation of the transient was averaged to obtain accurate steady state flow rates and temperatures.

TABLE 2 W-1 SLSF IRRADIATION HISTORY
STEADY STATE POWER AND FUEL TEMPERATURE

DAS(3) TIME	TEST SECTION POWER(1) kW	In-Fuel Thermocouple Data °F					LIFE - 4 Calculation ⁽²⁾		
		at 2"	at 14"				TIME hrs.	Fuel Temperature °F	
		TC 22-5	TC 22-3	TC 22-6	TC 22-7	Average at 14"		At 2"	At 14"
149:7:8:13	83.8	1176	1358	1379	1379	1372	0	1023	1270
149:9:49:13	84.1	1111	1340	1360	1353	1351	2.68	1022	1266
149:10:19:33	161.1	1364	1777	1878	1820	1808	3.18	1283	1741
149:13:50:56	157.7	1334	1737	1784	1776	1766	6.69	1271	1719
149:14:10:56	186.0	1429	1904	1966	1961	1944	7.03	1368	1896
150:11:28:38	165.8	1343	1781	1846	1846	1824	28.33	1299	1772
Reduced Power to NL									
150:13:59:40	164.3	1381	1794	1868	1868	1843	28.33	-	-
150:15:18 -	174.1	1373	1841	1910	1911	1887	29.80	1327	1824
SCRAM FOR DECAY HEAT TEST END OF 1st TEN DAY CYCLE									
158:21:0:17	66.5	1063	1246	1254	1250	1250	29.80	-	1145
159:1:2:10	67.3	1054	1229	1238	1229	1232	33.84	963	1153
159:2:2:40	174.5	1409	1849	1901	1892	1881	34.84	1329	1822
160:2:13:25	175.3	1364	1815	1880	1867	1854	59.02	1331	1827
Reduced Power to NL									
160:5:29:3	0	-	-	-	-	-	-	-	-
160:5:21:28	561.6	2750	3785	4013	3889	3926	59.02	2619	3851
160:5:38:7	0	-	-	-	-	-	-	-	-
SCRAM									

- NOTES: 1. Revised test section power values for DAS times to 190:22:1:1. Based on TE 3-4 and TE 4-6.
HEDL calculated test section power values after DAS time 190:22:1:1. (TE 3-4 became unreliable)
See page
2. Results for inner diameter of annular fuel pin # 7.
3. Data Acquisitions System (DAS) Time: Day: Hour: Minute: Second

TABLE 2 Continued

[illegible]

TABLE 2 Continued

[illegible]

LIFE - 4 Calculation⁽²⁾

DAS TIME	TEST SECTION POWER(1) kW	In-Fuel Thermocouple Data °F					Average at 14"	TIME hrs.	LIFE - 4 Calculation °F	
		at 2"	at 14"			At 2"			At 14"	
		TC 22-5	TC 22-3	TC 22-6	TC 22-7					
192:15:39:42	334.1	1943	2755	2656	2815	2742	456.25	2140	2969	
192:18:10:42	363.3	2054	2929	2918	2938	2928	459.10			
192:18:20:42	246.3	1663	2251	-	2307	2279	459.27			
SHUT DOWN										
192:19:11:2	344.8	2006	2874	2839	2904	2872	459.27	2140	2969	
192:23:38:-	359.3	2068	2938	2900	2948	2929	463.72			
BWT 2'										
193:0:4:9	369.7	2091	2939	2698	2918	2852	464.15	2140	2969	
SCRAM										
193:0:34:19	362.9	2044	2887	2722	2898	2836	464.15	2140	2969	
193:3:25:19	365.4	2066	2920	2691	2915	2842	467.00			
SCRAM										
193:7:17:44	660	--	--	--	--	--	467.00	2140	3829	
193:15:46:-	557.1	2665	3668	3626	3524	3606	475.47			
BWT 4										
194:1:12:32	660.9	3047	3904	3582	3758	3748	484.91	2140	2969	
194:1:38 -	676.7	3046	4025	3751	3907	3894	485.34			
BWT 6										
SHUTDOWN of 4th TEN DAY CYCLE										

TABLE 2 Continued

DAS TIME	TEST SECTION POWER(1) kW	In-Fuel Thermocouple Data °F					LIFE - 4 Calculation ⁽²⁾			
		at 2"	at 14"				Average at 14"	TIME hrs.	Fuel Temperature °F	
		TC 22-5	TC 22-3	TC 22-6	TC 22-7	At 2"			At 14"	
199:7:28:55	234.8	1689	2210	2220	2238	2223	485.34			
199:8:49:25	236.4	1675	2149	2060	2182	2130				
199:15:36:59	212.0	1604	2053	1894	2112	2082*				
199:16:47:29	214.9	1580	2033	1744	2073	2053				
199:16:57:29	346.3	2051	2728	2873	2763	2745				
199:17:37:49	463.2	2457	3192	3436	3197	3194				
199:22:33:28	494.7	2619	3447	3560	3345	3396				
199:23:21:28	670.6	3195	3778	3688	2995	3886	510.8			
200:8:57 -	682.3	2997	3863	3443	3780	3881				
BWT 6'										
200:14:33:39	654.7	2991	3796	3385	3705	3750	523.43			
200:21:12:22	677.1	3068	3903	3476	3859	3881				
200:21:34:-	689.5	3065	3914	3487	3870	3892				
BWT 6"										
200:21:42:32	704.0	3113	3878	3424	3798	3838	526.31			
200:23:17:4	702.0	3111	3892	3336	3833	3862				
201:0:21:14	688.3	3013	3805	3399	3687	3746				
201:0:27 -	697.8	2991	3802	3427	3657	3729				
BWT 7a'										
SCRAM										
201:1:11:34	377.1	2101	2971	2863	2997	2984	526.31			
201:2:1:54	385.0	2106	3007	2919	3028	3017				
201:2:32:4	692.8	3138	3921	3585	3967	3944	532.72			
201:7:31:44	682.0	3102	3930	3423	3915	3922				
201:7:36 -	694.3	3095	3964	3472	3949	3956				
BWT 7b'										
COMPLETION OF TESTS										

* Data from TC 22-6 appears erratic and was not used in the average for DAS TIME 199:15:36:39 and later.

4.2 SLSF Steady State Temperature Distributions

A complete set of steady state initial temperature data for thermocouple throughout the test section was obtained for each transient by averaging the data from the transient tapes for a few seconds prior to initiation of the transient. Selected steady state data sets are given in Table 3. The table also contains temperatures calculated with the THYME-C code.

Analyses were performed with the THYME-C Code with the specific initial conditions of each of the tests. The model used for THYME during the pretest analysis was used with minor modifications to account for as built dimensions and to include changes of input required to define heat conductances referred to in Figure 3.

The heat conductance, UASH5, between the insulator and the insulator duct was originally calculated to be .013 BTU/Sec °F with an assumed gap. THYME calculations with this value resulted in insulator temperatures much higher than measured in test. Most of the heat generated in the insulator is conducted outward to the insulator duct so UASH5 was chosen for adjustment to reduce the insulator temperature. The value of UASH5 was adjusted until the calculated insulator temperature agreed with data. This was done at full power, 668kw.

The temperatures calculated with THYME are given in Table 4 with the corresponding measured thermocouple data. The information of most interest from this table are the hex can and insulator temperatures since they define the radial boundary condition for the fuel pin bundle. Hex can inner and outer surfaces were instrumented with TE 6- and TE 20- series thermocouples respectively. The TE 21- series thermocouples were inside the insulator.

A summary of the radial temperature distribution at two axial locations near the top of the fuel is given in Table 4. The temperature of the insulator is higher than the hex can and sodium temperatures. The heat transfer to the fuel pin bundle is radially inward from the insulator. The heat conductance from the fuel pin bundle to the insulator was adjusted to match THYME results with data at the full power conditions - LOPI 1, 4, BWT 6" and 7b'. The agreement between calculated insulator temperatures and data at other power levels supports the approach.

TABLE 3

STEADY-STATE TEMPERATURE CONDITIONS (°F)

TEST SECTION AND LOOP - COMPARISON OF THYME RESULTS TO THERMOCOUPLE DATA

DECAY HEAT TEST INITIAL CONDITIONS

TEST SECTION FLOW = 4.401 lb/sec

TEST SECTION POWER = 174.1 kW

THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA
TE 1-1,-2,-3,-4	730	734	TE 8-1	770	772	TE 6-1	848	821
TE 2-1,-2,-3	844	859	8-2	768	-	6-2	828	847
TE 3-1	854	-	8-3	768	762	6-3	794	787
3-2	837	853	8-4	768	766	6-4	758	763
3-3	796	800	TE 7-1	731	636	6-5	811	807
3-4	854	860	7-2	740	720	6-6	856	761
3-5	730	733	7-3	737	-	6-7	854	855
3-6	849	859	7-4	738	730	TE 20-2	848	807
3-7	854	852	7-5	733	-	20-3	830	783
4-1	843	-	7-6	732	730	20-4	794	774
4-2	837	857	7-7	739	-	20-9	811	796
4-3	852	868	7-8	738	726	20-11	851	851
4-4	747	745	7-9	741	734	20-12	858	1011
4-5	853	859				TE 21-2	955	943
4-6	854	863				21-3	910	-
4-7	817	817				21-5	917	1056
4-8	772	773				TE 22-1,2	1233	-
4-9	817	822				22-3,6,7	1356	1876
4-10	849	-				22-5	1099	1373
4-11	851	861						
4-12	854	862						

TABLE 3 Continued

STEADY-STATE TEMPERATURE CONDITIONS (°F)

TEST SECTION AND LOOP - COMPARISON OF THYME RESULTS TO THERMOCOUPLE DATA

LOPI 1 INITIAL CONDITIONS

TEST SECTION FLOW = 4.34 lb/sec

TEST SECTION POWER = 670.8 kW

THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA
TE 1-1,-2,-3,-4	730	733	TE 8-1	885	889	TE 6-1	1209	1092
TE 2-1,-2,-3	1182	1208	8-2	875	-	6-2	1120	1189
TE 3-1	1223	-	8-3	875	869	6-3	985	971
3-2	1155	1185	8-4	875	866	6-4	841	867
3-3	981	986	TE 7-1	732	623	6-5	1052	1118
3-4	1220	1221	7-2	768	750	6-6	1230	993
3-5	730	735	7-3	754	-	6-7	1224	1213
3-6	1200	1203	7-4	757	737	TE 20-2	1209	1151
3-7	1223	1199	7-5	741	-	20-3	1126	1797
4-1	1185	-	7-6	737	721	20-4	985	931
4-2	1155	1197	7-7	764	-	20-9	1052	1075
4-3	1214	1222	7-8	757	728	20-11	1216	1197
4-4	799	773	7-9	768	755	20-12	1230	1494
4-5	1217	1220				TE 21-2	1600	1383
4-6	1220	1234				21-3	1421	-
4-7	1077	1062				21-5	1457	1430
4-8	884	-				TE 22-1,2	2754	-
4-9	1077	1053				22-3,6,7	3195	4411
4-10	1200	-				22-5	2272	2976
4-11	1210	1220						
4-12	1223	-						

TABLE 3 Continued

STEADY-STATE TEMPERATURE CONDITIONS (°F)

TEST SECTION AND LOOP - COMPARISON OF THYME RESULTS TO THERMOCOUPLE DATA

BWT 2' INITIAL CONDITIONS

TEST SECTION FLOW = 4.185 lb/sec

TEST SECTION POWER = 359.3 kW

THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA
TE 1-1,-2,-3,-4	730	733	TE 8-1	813	811	TE 6-1	975	929
TE 2-1,-2,-3	972	988	8-2	808	-	6-2	938	980
TE 3-1	994	-	8-3	808	802	6-3	866	819
3-2	958	972	8-4	808	800	6-4	789	800
3-3	870	863	TE 7-1	731	614	6-5	902	788
3-4	992	797	7-2	750	738	6-6	997	836
3-5	730	733	7-3	743	-	6-7	993	986
3-6	983	992	7-4	745	731	TE 20-2	975	940
3-7	994	994	7-5	736	-	20-3	943	887
4-1	971	-	7-6	734	727	20-4	866	814
4-2	958	-	7-7	748	-	20-9	902	900
4-3	999	986	7-8	745	728	20-11	982	976
4-4	767	764	7-9	751	741	20-12	997	993
4-5	998	-				TE 21-2	1196	1025
4-6	996	997				21-3	1098	-
4-7	916	-				21-5	1116	1100
4-8	813	814				TE 22-1,2	1815	-
4-9	916	888				22-3,6,7	2076	2938
4-10	983	-				22-5	1554	2068
4-11	776	-						
4-12	994	-						

TABLE 3 Continued

STEADY-STATE TEMPERATURE CONDITIONS (°F)

TEST SECTION AND LOOP - COMPARISON OF THYME RESULTS TO THERMOCOUPLE DATA

BWT 4 INITIAL CONDITIONS

TEST SECTION FLOW = 4.37 lb/sec

TEST SECTION POWER = 557.1 kW

THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA
TE 1-1,-2,-3,-4	730	732	TE 8-1	857	854	TE 6-1	1110	1069
TE 2-1,-2,-3	1099	1106	8-2	850	-	6-2	1048	1091
TE 3-1	1132	-	8-3	850	837	6-3	938	872
3-2	1077	1080	8-4	850	832	6-4	821	906
3-3	934	924	TE 7-1	732	618	6-5	991	811
3-4	1135	897	7-2	760	744	6-6	1136	912
3-5	730	732	7-3	750	-	6-7	1105	1100
3-6	1114	1117	7-4	753	731	TE 20-2	1110	1039
3-7	1132	1124	7-5	739	-	20-3	1054	1138
4-1	1097	-	7-6	736	723	20-4	938	882
4-2	1077	-	7-7	758	-	20-9	993	962
4-3	1141	1104	7-8	753	728	20-11	1119	1086
4-4	787	775	7-9	761	750	20-12	1136	1020
4-5	1130	-				TE 21-2	1452	1124
4-6	1135	1139				21-3	1303	-
4-7	1013	-				21-5	1327	1272
4-8	870	855				TE 22-1,2	2420	-
4-9	1013	972				22-3,6,7	2817	3606
4-10	1114	-				22-5	1986	2665
4-11	1126	-						
4-12	1132	-						

TABLE 3 Continued

STEADY-STATE TEMPERATURE CONDITIONS (°F)

TEST SECTION AND LOOP - COMPARISON OF THYME RESULTS TO THERMOCOUPLE DATA

BWT 6" INITIAL CONDITIONS

TEST SECTION FLOW = 4.340 lb/sec

TEST SECTION POWER = 689.5 kW

THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA
TE 1-1,-2,-3,-4	730	734	TE 8-1	882	890	TE 6-1	1189	1076
TE 2-1,-2,-3	1175	1211	8-2	873	-	6-2	1113	-
TE 3-1	1215	-	8-3	873	871	6-3	981	945
3-2	1148	951	8-4	873	861	6-4	840	847
3-3	977	982	TE 7-1	732	-	6-5	1046	824
3-4	1212	960	7-2	766	755	6-6	1220	993
3-5	730	737	7-3	754	-	6-7	1214	1222
3-6	1193	1213	7-4	757	736	TE 20-2	1189	1108
3-7	1215	1224	7-5	741	-	20-3	1120	1032
4-1	1172	-	7-6	737	723	20-4	981	904
4-2	1148	-	7-7	763	-	20-9	1046	1077
4-3	1205	-	7-8	757	732	20-11	1200	1201
4-4	798	1200	7-9	768	756	20-12	1220	1017
4-5	1209	-				TE 21-2	1594	1137
4-6	1212	1240				21-3	1417	-
4-7	1071	-				21-5	1445	1428
4-8	882	905				TE 22-1,2	2739	-
4-9	1071	1050				22-3,6,7	3180	3892
4-10	1193	-					2258	3065
4-11	1202	-						
4-12	1215	-						

TABLE 3 Concluded

STEADY-STATE TEMPERATURE CONDITIONS (°F)

TEST SECTION AND LOOP - COMPARISON OF THYME RESULTS TO THERMOCOUPLE DATA

BWT 7b' INITIAL CONDITIONS

TEST SECTION FLOW = 4.333 lb/sec

TEST SECTION POWER = 694.3 kW

THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA	THERMOCOUPLE	THYME	DATA
TE 1-1,-2,-3,-4	730	733	TE 8-1	887	886	TE 6-1	1204	1154
TE 2-1,-2,-3	1189	1197	8-2	878	-	6-2	1126	-
TE 3-1	1231	-	8-3	878	871	6-3	989	931
3-2	1162	1121	8-4	878	861	6-4	844	856
3-3	985	976	TE 7-1	732	-	6-5	1057	-
3-4	1228	953	7-2	768	755	6-6	1237	963
3-5	730	736	7-3	754	-	6-7	1230	1212
3-6	1208	1226	7-4	757	735	TE 20-2	1204	1093
3-7	1231	1221	7-5	741	-	20-3	1133	1225
4-1	1186	-	7-6	737	750	20-4	989	905
4-2	1162	-	7-7	764	-	20-	1057	1231
4-3	1221	-	7-8	757	730	20-	1215	1164
4-4	801	1156	7-9	769	756	20-12	1237	1019
4-5	1225	-				TE 21-2	1621	1091
4-6	1228	1239				21-3	1437	-
4-7	1082	-				21-5	1467	1424
4-8	887	905				TE 22-1,2	2795	-
4-9	1082	1041				22-3,6,7	3240	3956
4-10	1208	-				TE 22-5	2311	3095
4-11	1217	-						
4-12	1231	-

$$UASH2 = .0014 \text{ BTU/Sec } ^\circ\text{F}$$

$$UASH3 = .144$$

$$UASH4 = .144$$

$$UASH5 = .0260$$

Figure 3 Thyme Model
Heat Conductances

Radial heat transfer in the test section has two aspect for the post test data analysis. The test hardware was designed to minimize radial heat loss so that the conditions in the nineteen pin bundle would approximate the conditions in a full size core. In particular, the radial sodium temperature gradients due to edge effects were to be minimized. The data in Table 6 indicates proper functioning of the test hardware throughout the test program as shown by the consistent data for the insulator temperature. The comparison of THYME calculated temperature with the data also confirms the use of THYME result to specify the boundary conditions for fuel bundle analysis with COBRA-3M.

4.3 Fuel Condition

Calculations were made with the LIFE -4 code to determine the condition of the fuel throughout the steady state irradiation. The power history given in Table 2 was used as input information for this purpose. A check or confirmation of the LIFE -4 calculation may be obtained by a comparison of the LIFE -4 calculated temperature at the fuel inner diameter with the in-fuel thermocouple data. The LIFE -4 temperatures at 2" and 14" from the top of the fuel are given in Table 2 along with the in-fuel thermocouple data. Figure 4 is a comparison plot for the full power conditions, i.e., with test section power greater than 600 KW, during the LOPI phase of testing.

The agreement of the LIFE -4 temperature results with the in-fuel thermocouple data is very good at 2" below the top of the fuel. At 14" below the top of the fuel, the LIFE -4 results deviate from the data by -260°F to + 500°F (-5.8% to + 12.8%). The most notable deviation is in the trend with respect to time. The data show a consistant decrease in temperature with time at 14" below the top of the fuel. The LIFE -4 results do not follow this trend. The temperatures at 2" from the top of the fuel do not show a decrease with time, so this effect seems to be related to the higher temperature level at the center of the fuel.

The high thermocouple temperatures near 80 hours in Figure 3 are believed to correspond to an open fuel-cladding gap with higher thermal resistance than predicted with the LIFE -4 code. Between 80 and 220 hours, the thermocouple readings decrease, probably as a result of gap closure. After 200 hours, the thermocouple readings are relatively constant, indicating a closed gap.

TABLE 4
TEST SECTION RADIAL TEMPERATURE GRADIENT⁽¹⁾
STEADY STATE INITIAL CONDITIONS

TEST	SODIUM		HEX CAN		INSULATOR
	Subchannel 1	Subchannel 2	Inner	Outer	
	TE 3-2	TE 4-9	TE 6-2	TE 20-3	TE 21-5
Decay Heat	837 (853)	817 (822)	828 (847)	830 (783)	917 (1056)
LOPI 1	1155 (1185)	1077 (1053)	1120 (1189)	1126 (1797)	1457 (1430)
BWT 2'	958 (972)	916 (888)	938 (980)	943 (887)	1116 (1100)
BWT 4	1077 (1080)	1013 (972)	1048 (1091)	1054 (1138)	1327 (1272)
BWT 6"	1148 (951)	1071 (1050)	1113 (-)	1120 (1032)	1445 (1428)
BWT 7b	1162 (1121)	1082 (1041)	1126 (-)	1133 (1275)	1467 (1424)

TEST	SODIUM			HEX CAN	
	Subchannel 1		Subchannel 2	Inner	Outer
	TE 3-6	TE 3-4	TE 4-6	TE 6-1	TE 20-2
Decay Heat	849(859)	854(860)	854 (863)	848 (821)	848 (807)
LOPI 1	1200(1203)	1220(1221)	1220 (1234)	1209 (1092)	1209 (1151)
BWT 2'	983(992)	992(797)	996 (997)	975 (929)	915 (940)
BWT 4	1114(1117)	1135(897)	1135 (1139)	1110 (1069)	1110 (1039)
BWT 6"	1193(1213)	1212(960)	1212 (1240)	1189 (1076)	1189 (1108)
BWT 7b	1208(1226)	1228(953)	1228 (1239)	1204 (1154)	1204 (1093)

(1) Values given are temperatures in °F. The first is the THYME-C result followed by Data in parenthesis.

Figure 4 Fuel Temperature Steady State History Data and Life-4 Analysis

4.3.1 Fuel and Fuel/Cladding Gap Properties

Results from the LIFE -4 calculation were used to define the fuel and fuel/cladding gap thermal parameters for use in transient thermal analyses. The parameters which define fuel condition are summarized in Table 5 for the initial conditions of each of the LOPI tests.

The intention during the LOPI test phase was to test fuel pins with fuel in four different conditions. The LOPI 1 test was performed with fresh fuel. The LOPI 2A test was planned to test the thermal response of restructured fuel with minimal burn up. The results of the LIFE -4 calculation show that the fuel was fully restructured in the midspan of the fuel pin at the time of the LOPI 2A test. Fuel conditioning between the LOPI 2A and LOPI 3 transients increased the burn up from .193 to .474 atom % at the midplane of the pin. The LOPI 4 test was run immediately after the LOPI 3 transient. The fuel is assumed to have been cracked as a result of the LOPI 3 scram. The LIFE -4 calculations do not reflect the cracked condition of the fuel and therefore did not predict differences between LOPI 3 and LOPI 4.

4.3.2 Gap Conductance

The heat conductance from the fuel to the cladding across the fuel/cladding gap is an important quantity for THT-D and COBRA-3M analyses. The values of gap conductance calculated with the LIFE -4 code were used as input to both THT-D and COBRA-3M after modification to match data at steady state.

The results from the LIFE -4 analyses can be presented in terms of $1/h_{gap}$ vs gap width as shown in Figure 5 for the LOPI initial conditions. Presentation in this form illustrates a linear dependence of gap conductance on gap width (an inverse relationship) and permits consideration of other factors which affect gap conductance. It may be seen that gap conductance at constant gap width decreases as the test sequence progressed from LOPI 1 to 2A to 3. This is attributed to an increase in the fission gas fraction (decrease helium fraction) within the fuel pin with burn up. The LOPI 4 gap conductance points fall on the LOPI 3 line since there was no increase in burn up between LOPI 3 and 4.

TABLE 5 FUEL AND GAP PARAMETERS
LIFE -4 CODE RESULTS
STEADY STATE INITIAL CONDITIONS

		Section 3 ⁽²⁾ at 18"				Section 5 ⁽²⁾ at 3.6"			
		LOPI 1	2A	3	4	LOPI 1	2A	3	4
Fuel Dimensions (inches)	ID	.03441	.0376	.0371	.0373	.03484	.0347	.0347	.0347
	Columnar	.03541	.0817	.0855	.0857	.03584	.0357	.0357	.0357
	Equiaxed	.03741	.0837	.0875	.0877	.03784	.0377	.0377	.0377
	O D	.09976	.0999	.1004	.1006	.09915	.0993	.0998	.0998
Porosity ⁽¹⁾	Restructured	-	.03116	.03309	.0351	-	-	-	-
	Unrestructured	.06633	.0777	.0981	.0942	.0694	.0747	.0856	.0858
O/M Ratio ⁽¹⁾	Restructured	-	1.934	1.934	1.934	-	-	-	-
	Unrestructured	1.940	1.966	1.967	1.967	1.940	1.9401	1.9402	1.9402
Burn up (Atom %)		.022	.193	.474	.474	.010	.090	.221	.221
Helium Mole Fraction		.937	.883	.704	.704	.937	.883	.704	.704
Gap	Width (mils)	1.15	0.96	0.46	0.335	1.95	1.74	1.30	1.30
	Conductance (BTU/hr ft ² °F)	1087	1046	1060	1190	797	753	646	663

NOTES: (1) Parameters are average values averaged across the fuel pin cross section.

(2) Axial location measured from the top of the fuel.

The gap properties given in Table 5 show that the analysis with LIFE -4 predicts gap closure with time during the irradiation. The decreased gap width is balanced by decreased gas thermal conductivity and the gap conductance decreases slightly with time. The LIFE -4 calculations predict that the gap remains open during the testing.

A similar correlation is presented in Figure 6 for the boiling window tests (BWT). The LIFE -4 calculations for the BWT initial conditions were made assuming no change in fuel condition after LOPI 4, i.e. with no additional burn up accounted for after LOPI 4. The gap conductance values for the BWT conditions are the same as those for LOPI 4 (for equal gap widths).

It may be noted from the figures that all of the lines correlating the LIFE -4 results intersect the abscissa at the same value. This point gives the gap conductance for a closed gap as $h_{gap} = 2080 \text{ BTU/hr ft.}^2 \text{ } ^\circ\text{F}$ at gap width = 0. A single value for this parameter is believed to be reasonable since no substantial fuel-cladding contact pressure was predicted during steady state or transient operation.

As noted previously, the measured data from the in-fuel thermocouples is different than the LIFE -4 calculated fuel temperatures. Use of LIFE -4 values of gap conductance to calculate fuel steady state temperatures with the THT-D code would not agree with the data. The gap conductance values for input to THT-D were adjusted to provide a match between calculated and measured steady state pretransient temperatures. Table 6 summarizes the original and adjusted gap conductances for the initial conditions of the tests.

The need to adjust gap conductances to values in excess of $2000 \text{ BTU/hr ft.}^2 \text{ } ^\circ\text{F}$ to match the in-fuel thermocouple data indicates that the gaps were closed in the test. Failure of the LIFE -4 code to predict a closed gap is believed to be caused by the fact that the fuel temperatures predicted by LIFE -4 are too low to produce fuel swelling.

It is tentatively concluded that the LIFE -4 results fail to decrease properly with time at 14" below the top of the fuel column because predicted fuel temperatures near 80 hours are too low to produce gap closure and/or fuel restructuring of the required amount. This hypothesis is being investigated further in an attempt to determine the cause of the discrepancy at 80 hours.

Figure 5 LIFE-4 GAP Conductance at LOPI Initial Steady State Conditions

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Figure 6 LIFE-4 Gap Conductance at BWT Initial Conditions

TABLE 6 GAP CONDUCTANCE [BTU/hr ft.² °F]
 STEADY STATE INITIAL CONDITIONS
 FUEL PIN MIDPLANE

TEST	LIFE-4	ADJUSTED*
Decay Heat		428
LOPI 1	1087	661
2A	1046	-
3	1060	3200
4	1190	~3200
BWT 2'	710	785
4	939	1683
6"	1103	~4000
7b'	-	~4000

*Values required as input to THT-D in order to produce calculated steady state temperatures which match the in-fuel thermocouple data.

4.3.3 Fuel and Gas Conductivity

The thermal conductivity of the fuel and the helium/fission gas mixture inside the fuel pin were calculated using the parameters given in Table 5. The results are shown in Figure 7. There is little difference in fuel thermal conductivity as a result of the additional burn up between LOPI 2A and LOPI 3. There was a significant change in gas conductivity due to the release of fission gas during burn up. This change in gas conductivity is implicitly accounted for with the gas conductance values already discussed. The gas conductivity has a direct effect on the thermal response of the in-fuel thermocouples during the transients by its effect on heat transfer between the thermocouple and the inner surface of the fuel. The THT-D model also contains a gap within the in-fuel thermocouple. Originally, the in-fuel thermocouples were encapsulated in an argon environment. There is a good possibility that during the tests, the thermocouple sheaths did not remain intact. The post-test analyses with THT-D examined the effect of replacing the argon inside the thermocouple gap with a helium/fission gas mixture.

4.4 Sodium Temperature Distributions

At the steady state initial test conditions, COBRA-3M calculations of the axial distribution of sodium temperature may be compared to data from the wire wrap thermocouples. These comparisons provide a confirmation of the test section heat balance at the initial conditions.

Calculations were made with the COBRA-3M code with gap conductance and fuel properties taken from the results of the LIFE-4 calculations. A change in the modeling used for the pre-test analysis concerns the treatment of the boundary condition on the fuel bundle. The COBRA-3M code provides for radial heat transfer from the hex can to a boundary of uniform temperature (Figure 8). The input includes a value for the heat conductance to the boundary and the temperature history of the boundary. For this analysis, the boundary is the insulator. The heat conductance from the hex to the insulator was specified $5.0 \text{ BTU/hr ft.}^2 \text{ } ^\circ\text{F}$ the value used in THYME. The insulator temperature values used, were taken as an axial average of the calculated THYME insulator temperatures and were constant throughout the transients.

Figure 7 Fuel and Fuel Pin Gas Thermal Properties

COBRA-3M Boundary Condition Temperatures

LOPI 1	1430°F	BWT 2'	1115°F
2A	1430°F	4	1320°F
3	1430°F	6"	1430°F
4	1430°F	7b'	1430°F

Figure 8 COBRA-3M Thermal Hydraulic Model

Figures 9 to 11* show the steady state sodium temperatures calculated with COBRA-3M and show as data points the wire wrap thermocouple data. The agreement is very good. At full power conditions, calculations with COBRA-3M predict a 25°F gradient across the fuel bundle at the top of the fuel. The temperatures of the sodium at the outside is higher than the temperature at the inside of the bundle due to radial heat transfer from the insulator. The data also indicate that the radial gradient is small.

*Figure 11 was deleted.

Figure 9 Steady State Sodium Temperature Axial Distribution
LOPI 1 Initial Condition

Figure 10 Steady State Sodium Axial Temperature Distribution
Boiling Window Test Initial Conditions

5.0 TEST TRANSIENTS

Transient analyses were done with several computer codes for different purposes. LIFE-4 results provide fuel pin conditions required in the following calculations with other codes. Calculations were made with COBRA-3M for the fuel pin bundle to study the sodium temperature response and distribution and the time for initiation of boiling. Calculations were made with the THT-D code for a single fuel pin to study the fuel pin thermal response.

5.1 Fuel Pin Gap Conditions

Calculations were made with LIFE-4 with the transient flow and power conditions specified in order to determine the behavior of the gap during the transients. Gap conductance as a function of time is an input required for the fuel pin thermal analysis with THT-D. The COBRA-3M code used for transient analysis was modified so that it also uses gap conductance as an input. The gap conductance versus time input generated for THT-D analyses was used for COBRA 3-M.

The gap conductance results calculated with the LIFE-4 code for the LOPI 1 transient are shown in Figure 12. This figure shows gap conductance correlated with gap width as discussed previously. The line at $t = 0$ corresponds to Figure 5. Results for other times have also been included and can also be represented by straight lines all going through the point $h_{gap} = 2080$ @ gap width = 0. The dependence on time as indicated by the different straight lines is a result of gap temperatures changing with time. Since the primary effect of temperature, change in gap width, is removed by the presentation in Figure 12, the effect indicated by the different lines is attributed to changes in properties (i.e., thermal conductivity) of gas in the fuel cladding gap. During the first 1 1/2 to 2 seconds of the LOPI transient, the cladding temperature increases. During the remainder of the transient, the cladding cools and after about 4.0 seconds is colder than at $t = 0$. Increased h_{gap} early in the transient is due to increased conductivity of the gas as a result of the higher temperature. It was convenient for data manipulation to represent the time variation as shown in Figure 13 which was derived from the lines in Figure 12.

Figure 12 Gap Conductance Correlation at Various Times in LOPI 1 Transient

Figure 13 Gap Conductance vs Time - LOPI 1 Transient

It was necessary to adjust the gap conductance at $t = 0$ in order to match the calculated fuel temperature to temperature data measured with in-fuel thermocouples. Adjustments to the gap conductance were made throughout the transient. In order to make these adjustments, the gap widths calculated with the LIFE-4 code were assumed to be correct. The slope of the straight line correlating $1/h_{gap}$ versus gap width was adjusted to obtain the desired value at axial Section 3 at $t = 0$. The procedure is illustrated in Figure 14.

The gap conductance at any axial section at any time was obtained with the corresponding gap width as calculated with LIFE-4. The gap width was used in Figure 14 to determine the $1/h_{gap}$ value from the adjusted line at $t = 0$. The h_{gap} value from the $T = 0$ line was then corrected for time using the relationship shown in Figure 13.

This technique was used to derive gap conductance values for input to THT-D and COBRA-3M analyses. The gap conductance history is shown in Figure 15 for the LOPI 1 transient. A check on this approach is that the gap conductance obtained at the top of the fuel (2 inches below the top of the fuel) is close to the value indicated by the in fuel thermocouple at the top of the fuel.

A similar approach was taken to obtain the gap conductance history during the LOPI 3 transient. At the fuel midplane, the adjusted gap conductance value $3200 \text{ Btu/hr ft}^2\text{°F}$ indicates a closed gap. At the upper thermocouple location (2 inches below the top of the fuel) the temperature data correspond to a gap conductance value in good agreement with the LIFE-4 results. The LIFE-4 results were used directly near the top and bottom of the fuel pin. In the midsection of the pin (center 9 inches of pin), the gap was assumed closed at the beginning of the transient. At intermediate points, the initial gap was assumed to be smaller in fuel width than predicted by LIFE-4. In the midsection of the pin, the LIFE-4 calculated values of gap width change (i.e., gap width increase with respect to gap width of the beginning of the transient) were used with the correlation shown in Figure 5.

The gap width starts to increase after about .4 seconds. At this time the gap conductance is assumed to be $2080 \text{ Btu/hrft}^2\text{°F}$ at the center corresponding

Figure 14 Adjustment of GAP Conductance for LOPI 1

Figure 15 Gap Conductance for LOPI 1 Transient Analysis

Figure 16 Gap Conductance for LOPI 3 Transient Analysis

Figure 17 Axial Distribution of Gap Conductance, BWT Initial Conditions

FIG 18 GAP CONDUCTANCE DURING BWT TRANSIENTS

FIGURE 1 GAP CONDUCTANCE DISTRIBUTION - BWT 6"

to the zero gap width. At later times as the gap width increases, the gap conductance decreased along the line in Figure 5. The values in the THT-D and COBRA-3M analyses are shown in Figure 16. COBRA-3M analyses for the LOPI-4 transient were performed with gap conductance values the same as those used for LOPI-3.

The boiling window tests were analyzed with the COBRA-3M code using simplified gap conductance values. The normalized axial distribution shown in Figure 17 was used throughout the transients for BWT 2 and BWT 4 with the normalized time variation shown in Figure 18. The initial conditions for the midspan of the fuel pin for BWT 6" indicate a closed gap. During the transient, calculations with LIFE-4 indicate the gap width increased by .22 mils at the midspan so it probably remains closed. The assumed axial variation of gap conductance at $t = 0$ is shown in Figure 19. For time variation shown in Figure 18 was applied to the entire pin. Gap conductance values for analyzing the BWT 7a and BWT 7b tests were assumed to be the same as the BWT 6" values.

5.2 Fuel Pin Transient Temperature Response

Calculations were performed with the THT-D computer code. The model is a two-dimensional (r,z) model of a single fuel pin in the flowing sodium environment. Pin 7 was selected because it contained a thermocouple which gave reliable data throughout the test. The model is very detailed, accounting for the in-fuel thermocouple, fuel pin heating distributions, fuel dimensions and properties including restructuring and fuel/cladding gap conductance.

The THT-D calculations were performed to calculate fuel temperature and to calculate the response of the in-fuel thermocouples. The calculated values were compared to temperatures measured with the in-fuel thermocouples. This comparison give direct information in fuel pin thermal response, a primary objective of the W-1 SLSF test. This is unique information since this is the first test of this nature with fuel pins instrumented with thermocouples.

THT-D calculations were made for three tests: Decay heat, LOPI 1 and LOPI 3. The decay heat test was analyzed to determine if the data could be used to infer the transient decay heat following a scram. The LOPI 1 and LOPI 3 tests were analyzed in detail as representative tests at near nominal conditions with different fuel conditions.

Figures 20 and 21 present a comparison of the results of the THT-D decay heat test calculation for node 18, the thermocouple tip at 14" below the top of the fuel to data from TE 22-6 and TE 22-7. A comparison at 2" below the top of the fuel is shown in Figure 22. The calculation was performed with the theoretical decay heat transient derived in Appendix E for the W-1 SLSF fuel bundle. The analysis and data are in good agreement during the first 10 seconds of the transient. Later in time, the fuel pin approaches steady state conditions at a temperature level much higher than that calculated with THT-D. The difference is probably due to the gap conductance values used for the THT-D analysis. The value at ten seconds was applied throughout the remainder of the transient. In general, the gap conductance decreases at low temperature levels due to increase of the gap width. Use of lower gap conductance at later times in the THT-D analysis would raise the THT-D calculated results and provide better agreement to the data.

The calculated responses of the thermocouples in the LOPI 1 test are shown in Figure 23 and 24 compared to the data. The agreement at 2" below the top of the fuel is excellent. At 14" below the top of the fuel, the calculated thermocouple response logs the data. A possible reason for the calculation to log is inaccuracies in the modeling of the fuel to thermocouple heat transfer and the thermal properties of the thermocouple. To check this hypothesis, the inner surface of the fuel adjacent to the thermocouple tip was re-examined. The THT-D results for the fuel, node 318, are shown in Figure 25. The fuel also logs the data indicating that the disagreement is due to the fuel pin modeling and is not due to the thermocouple model. There is a significant time constant for the thermocouple Figure 25 shows the time constant to be about 400 msec. This effect is included explicitly in the analysis because the thermocouple is included in the thermal model.

Similar comparisons are shown in Figures 26 and 27 for the LOPI 3 transient. The transient behavior calculated with THT-D approximates the general response measured with the in-fuel thermocouples. The differences between the in-fuel thermocouple data are larger than the difference between data and analysis. The peak in the data at about 1 1/2 seconds may be due to changes in the gap i.e., gap opening as the cladding temperature increases.

DECAY HEAT NODE 18 VS. CHANNELS 185,188,189

FIGURE 20 Comparison of THT-D Calculation to In-Fuel Thermocouple Data

Decay Heat Transient 14" Below Top of the Fuel

Figure 21 Decay Heat Transient Temperatures 14" Below top of the Fuel

Figure 22 DECAY HEAT NCDE 10 VS. CHANNELS 197
Comparison of THT-D Calculation to In-Fuel
Thermocouple Data

Decay Heat Transient 2" Below Top of Fuel

LOPI-1 THTD NODE 18 VS CHANNELS 185,188,189

FIGURE 23 Comparison of THT-D Calculation to In-Fuel Thermocouple Data

LOPI 1 Transient 14" Below Top of the Fuel

LOPI-1 THTD NODE 10 VS. CHANNEL 187

FIGURE 24 Comparison of THT-D Calculation to In-Fuel Thermocouple Data

LOPI 1 Transient 2" Below Top of the Fuel

LOPI-1 THTD NODE 18 VS. CHANNEL 189

FIGURE 25 Comparison of THT-D Results for Thermocouple Tip and Fuel Inner Diameter

LOPI 1 Transient 14" Below Top of the Fuel

TE 22-7 shows a temperature decrease rate from about 1 1/2 to 2 1/2 seconds of the transient which is faster than the calculation and faster than that measured at later times. This behavior could be due to the closed gap and a delayed opening of the gap.

LOPI-3 THTD NODE 318 VS CHANNELS 185,186,189

Figure 26 Comparison of THT-D Calculation to In-Fuel Thermocouple Data

LOPI 3 Transient 14" Below top of the Fuel

LOPI-3 IHTD NODE 10 VS CHANNEL 187

Figure 27 Comparison of THT-D Calculation to In-Fuel Thermocouple Data

LOPI 3 Transient 2" Below top of the Fuel

5.3 Sodium Temperature Response

The COBRA-3M model was modified to provide the gap conductance values as an input at steady state and throughout the transient. Pre-test COBRA-3M calculations were made with the gap conductances calculated by the code from input parameters and a simple relationship. COBRA-3M reevaluates the fuel/cladding gap width as the temperatures change and calculates gap conductance as a linear function of gap width. The resulting gap conductances did not agree (Reference 4) with those calculated by LIFE-4. For this analysis, gap conductances were obtained from LIFE-4, modified to match fuel temperature to thermocouple data at steady state, and input to COBRA-3M.

The results of the COBRA-3M calculation provide sodium temperature response throughout the test section. These results must be used to evaluate predicted wire wrap thermocouple response in order to compare with the data. In a transient environment such as the test section sodium which increases with time, the thermocouple temperature will lag the sodium temperature due to thermal inertia of the thermocouple. The technique used to evaluate predicted wire wrap thermocouple response from the predicted sodium temperatures is discussed in Appendix B.

Figures 28 to 30 present comparisons of wire wrap thermocouple temperatures to measured temperatures at different locations for the LOPI 1 transient. In addition, the COBRA-3M results for sodium temperature are shown to illustrate the magnitude of the difference in temperature between the sodium and the thermocouple. The figures show that COBRA-3M predicts boiling initiation at 0.90 seconds and a boiling duration of 1.1 seconds for subchannel 1. In contrast, the tests was performed with no boiling.

The COBRA-3M predictions at all axial locations are conservative in the sense that the sodium temperature increases more rapidly than the data indicates and peak sodium temperatures are too high. There is also a significant departure of the calculated results from the data during the cooling phase after the scram. The data indicate that the sodium cools more quickly than the analysis predicts.

Figures 31 to 33 show calculated and measured sodium temperature responses for the LOPI 3 transient. The results are very similar to those for LOPI 1. Differences as a result of the different fuel condition and fuel cladding gap

LOPI-1 COBRA NA VS. CHANNEL 3

Figure 28 LOPI 1 TE 3-3 17.7"

LOPI-1 COBRA NA VS. CHANNEL 13

Figure 29 LOPI 1 TE 3-7 35.7"

LOPI-1 COBRA NA VS. CHANNEL 19

Figure 30 LOPI 1 TE 4-6 37.7"

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SLSF T-5(W1) LOPI 3 (7-9-79 20:43:46)
Figure 31 Wire Wrap Thermocouple Comparison Calculation/Data LOPI 3
TE 3-7 35.7" above bottom of fuel

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FUEL PIN TEMP PIN 13
TEMPERATURE (F)

SLSF T-5(W1) LOPI 1 (6-9-79 08:06:43)
Figure 32 LOPI 1 TE 4-6 37.7"

-8/-

Figure 33 SLSF T-5(W1) LOPI 3 (7-9-79@20:43:46)
Wire Wrap Thermocouple Comparison Calculation/Data LOPI 3
TE 4-6 37.7" above bottom of fuel

condition show up as a delay in boiling for LOPI 3. This delay, coupled with the thermocouple time lag results in predicted thermocouple response for TE3-7 and TE 4-12 which do not reach saturation temperature. These thermocouples are predicted to not indicate boiling although the sodium is predicted to boil.

The sodium temperature response calculated with the COBRA-3M code shows the effect of the radial boundary condition. Heat losses and heat sinking by the hex can during the transient result in delayed boiling initiation in subchannel 4 when compared to subchannel 1 as in Figure 34. TE 4-12 is the only thermocouple in subchannel 4 and it was defective. Hex can temperatures were examined in order to evaluate the COBRA-3M predictions of sodium radial gradient. The temperature transient of the inside of the hex can is shown in Figure 35 from the data and from the COBRA calculations. The agreement is very good indicating the validity of the COBRA results. A different way of presenting this comparison is in the form of a radial temperature distribution at a particular time. This comparison, Figure 36, also shows validity of the conclusion that the temperature of the sodium in the outer subchannel remains below the sodium temperature at the center of the fuel bundle.

5.4 Boiling Window Tests

Calculated and measured wire wrap thermocouple temperature response in BWT 2', BWT 4, BWT 6" and BWT 7b' are shown in Figures 37 to 44. The figures also show the corresponding sodium temperature transient predicted with the COBRA-3M code. The results are similar to those presented for the LOPI transients, i.e., sodium temperatures higher in the center of the bundle than at the outer edge, calculated thermocouple response lagging the calculated sodium temperatures and the thermocouple data showing boiling initiation later than predicted.

A summary of boiling initiation times is given in Table 7. Three times are given for each test at each location; a COBRA-3M calculated time for the sodium to reach saturation, a calculated time for the thermocouple to indicate saturation temperature based on the COBRA-3M sodium transient and a time from the thermocouple data.

Figure 34 Comparison of Sodium Response in Subchannels 1 and 4

Fig 35 Hex Can Temperature Response Calculated/Measured LOP#1
SLSF T-5(W1) LOP1 1 (6-9-79 08:06:43)

Figure 36 Radial Temperature Distributions LOPI

COBRA-3M consistently predicts boiling initiation which starts in the inner subchannels and is later in the outer subchannels. The data verify this trend. COBRA-3M also consistently predicts boiling initiation to occur earlier than shown by the data.

TABLE 7 SUMMARY OF BOILING INITIATION TIMES

		Subchannel 1		Subchannel 2	Subchannel 3	Subchannel 4
		TE 3-6	TE 3-4	TE 3-7	TE 4-6	Te 4-12
		X = 33.7	X = 37.7	X = 35.7	X = 37.7	X = 35.7
LOPI 1	COBRA Na " T/C DATA	.83 1.50 NB	.9 1.58 NB	.9 1.58 NB	1.10 1.33 NB	1.33 1.53 NB
LOPI 3	COBRA Na " T/C DATA	1.13 1.35 NB	1.13 1.58 NB	1.28 NB NB	1.45 1.53 NB	1.69 NB NB
BWT 2'	COBRA Na " T/C DATA	3.60 3.75 4.8	3.30 3.60 4.8	3.45 3.67 4.8	3.53 3.65 NB	3.77 3.89
BWT 4	COBRA Na " T/C DATA	2.77 3.07 5.0	2.40 2.77 2.9	2.62 2.92 2.8	2.63 2.71 3.6	2.83 2.94
BWT 6"	COBRA Na " T/C DATA	2.25 2.55 2.9	1.80 2.18 -	2.10 2.25 3.2	1.84 2.04 3.6	2.20 2.32
BWT 7b'	COBRA Na " T/C DATA	1.20 1.73 1.8	1.20 1.80 -	1.20 1.80 1.8	1.37 1.57 2.0	1.53 1.73

NB = No Boiling

X = Distance from bottom of fuel inches

Times are seconds after start of transient

BW2(1) COBRA NA VS. CHANNEL 13

Figure 37 Wire Wrap Thermocouple Calculation/Data Comparison BWT 2'
TE 3-7 35.7" above bottom of the fuel

BW2(1) COBRA NA VS. CHANNEL 9

Figure 38 BWT 2 TE 3-3 17.7"

BW2(1) COBRA NA VS. CHANNEL 19

Figure 39 Wire Wrap Thermocouple Calculation/Data Comparison BWT 2'
TE 4-6 37.7" above bottom of the fuel

Figure 40 BW4 COBRA NA VS. CHANNEL 13
BWT 4 TE 3-7 35.7"

BWG(2) COBRA NA VS. CHANNEL 13

Figure 41 Wire Wrap Thermocouple Calculation/Data Comparison BWT 6"
TE 3-7 35.7" above bottom of the fuel

BW7B COBPA NA VS. CHANNEL 13

Figure 42 Wire Wrap Thermocouple Calculation/Data Comparison BWT 7b'
TE 3-7 35.7" above bottom of the fuel

BW7B COBRA NA VS. CHANNEL 9

Figure 43 BW7 7b' TE 3-3 17.7"

BW7B COBRA NA VS CHANNEL 19

Figure 44 Wire Wrap Thermocouple Calculation/Data Comparison BWT 7b'
TE 4-6 37.7" above bottom of the fuel

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APPENDIX A

LIFE-4 CODE PARAMETERS

An early developmental version of the LIFE-4 code (i.e., the L4PL41 version, written September 11, 1978 on the CDC-7600 master file at Berkeley-LBL) was used in the post-test analysis of W-1 to determine fuel microstructure and thermal conductivity as functions of burnup. These quantities, in turn, were used to establish fuel porosity and fuel thermal conductivity values for use in the THTD transient analyses. The composition of the gas (i.e., the relative concentrations of helium fill gas and fission product gases) in the central void of each W-1 fuel pin was also estimated using this version of the LIFE-4 code. This was used in the THTD model to represent heat conduction between in-fuel thermocouples and the fuel inner surface. Finally, this steady state version of the LIFE-4 code was used to estimate fuel-cladding gap conductance as a function of burnup and axial location at the start of each W-1 transient.

Quantitative predictions of the LIFE code are sensitive to the set of material behavior constants used in the analysis. Approximately 300 of these constants are included in the code under the FORTRAN variable name QQ(I). For the W-1 analysis, 30 of the QQ values were adjusted to obtain agreement between predicted and measured values of fuel microstructural radii, fission gas release, and fuel-cladding gap size for the P23A-27 fuel pin. This EBR-II experimental pin was chosen for calibration because of its moderately high power level (418 W/cm) and because destructive examination data were available at five axial locations on this pin. The QQ values that were adjusted are shown in Table A-1. Values not shown were unchanged from the values in the reference code.

Prior to recalibration, the LIFE-4 code overpredicted fission gas release in the P23A-27 pin and underpredicted cold post-irradiation fuel-cladding gap size. After the QQ values were adjusted, these quantities agreed virtually exactly with the measured values. Analyses of W-1 steady state behavior using the two code versions displayed similar behavior. The unmodified code predicted very early gap closure in W-1, so that calculated

fuel inner surface temperatures were much lower than the thermocouple data indicated until very late in the W-1 irradiation. The modified LIFE-4 code predicted gap closure very late in the W-1 irradiation and lower gas release. The two solutions are believed to bracket the correct solution, based on a study of the W-1 thermocouple data. However, the modified code appears to give significantly better agreement with the thermocouple data.

By adding a transient heat transfer model to the steady state LIFE-4 code, it was possible to calculate fuel-cladding gap conductance values throughout each W-1 transient. These calculations provided initial estimates for gap conductances to be used in the THTD code for the final transient analyses. Since the LIFE-4 transient values had not been compared with experimental data from loss-of-flow transients prior to the W-1 analysis, they must be interpreted with caution. In the absence of these comparisons with data, LIFE-4 transient gap conductance values are believed to be on the low side in these calculations. The reasons for this are 1) the fuel-cladding gap is predicted to have been larger at the start of the transient calculations than the thermocouple data suggest, and 2) transient fuel swelling was not modelled. Note, however, that these considerations affect transient gap conductance predictions primarily at the start of the transient. Late in each W-1 transient, the predicted values are believed to have been reasonably accurate.

TABLE A

ADJUSTED CALIBRATION COEFFICIENTS
USED IN LIFE-4 CODE (9/11/78 Reference Version)
FOR W-1 ANALYSIS

QQ(2) =	0.70302E01
QQ(3) =	2.8950E-02
QQ(4) =	1.3805E-12
QQ(47) =	1.5E-01
QQ(56) =	2.50E-04
QQ(57) =	2.50E-04
QQ(67) =	1.80E00
QQ(71) =	7.00E09
QQ(82) =	-0.80E01
QQ(84) =	3.243
QQ(85) =	2.4288E04
QQ(86) =	0.60E03
QQ(88) =	1.0E04
QQ(89) =	0.19E01
QQ(90) =	0.03E00
QQ(138) =	2.111E+5
QQ(139) =	9.247E20
QQ(140) =	1.3157E05
QQ(141) =	9.59E11
QQ(142) =	2.029E07
QQ(143) =	2.9785E04
QQ(144) =	5.0
QQ(145) =	2.20E01
QQ(146) =	1.20E-1
QQ(150) =	1.25E+02
QQ(152) =	2.3600E-03
QQ(153) =	0.15300E00
QQ(156) =	4.2877E04
QQ(157) =	1.53600E05
QQ(172) =	0.10E01

APPENDIX B

Evaluation of Wire Wrap Thermocouple Response to Sodium Transient

Time constants for the wire wrap thermocouples were defined and measured in the classical sense relating the thermocouple response to an instantaneous change in environment. In application, the thermocouples are exposed to a continuously changing environment during a transient. This appendix gives a relationship for thermocouple response in terms of the measured time constant and the time dependent environment.

Thermocouple response with thermocouples treated as a "lumped mass," is determined from the equation:

$$\frac{dT}{dt} = - \frac{hA}{mc_p} (T - T_{\infty})$$

where: T = thermocouple temperature
 T_{∞} = Environment temperature
 hA/mc_p = heat transfer and thermocouple thermal properties

In the standard situation the initial temperature is T_0 and the environment is changed instantaneously to T_{∞} and held constant, i.e.,

@ $t = 0$, $T = T_0$; for $t > 0$, $T_{\infty} = \text{constant}$.

The solution is

$$T(t) = T_0 - T_{\infty})e^{-t/\tau} + T_{\infty} \quad (B-1)$$

where $\tau = \frac{mc_p}{hA}$ (assumed constant)

The time constant τ is determined experimentally from (B-1).

For the transient situation, the environment temperature is a function of time, $T_{\infty}(t)$, and the thermocouple response is determined from:

$$\frac{dT}{dt} + \frac{1}{\tau} T = \frac{1}{\tau} T_{\infty}(t)$$

$$@ t = 0, T = T_0 \text{ and } T_{\infty}(t=0) = T_0$$

The solution is

$$T(t) = \frac{1}{\tau} e^{-t/\tau} \int_0^t e^{t/\tau} T_{\infty}(t) dt + T_0 e^{-t/\tau} \quad (B-2)$$

with τ assumed constant.

In application to the W-1 experiment, analytical results for the environment temperatures are obtained from COBRA-3M as calculated sodium temperatures. These temperatures are then used in (B-2) with experimental values of τ , Table B-1, to calculate expected thermocouple response, $T(t)$. These results are compared to the wire wrap thermocouple data to provide a check on the sodium temperature transients.

TABLE B-1

Wire Wrap Thermocouple Time Constants

τ sec	TE
.0424	4-1,2,3,4,5,7,8,9,11
.0785	4-6, 10,12
.15	3-1,2,3,4,5,6,7

APPENDIX C

Description of Instrumentation

This appendix presents a brief description of the SLSF loop and test section instrumentation to facilitate use of the data analysis and evaluation.

Figure 1C is a cross section of the test section with thermocouple locations shown. The subchannels indicated in the fuel bundle are for the COBRA-3M model. Figure 2C is the corresponding layout of thermocouples in the axial direction.

SLSF instrumentation is shown on the SLSF schematic in Figure 3C.

NOTE: THERMOCOUPLES 7-4, 8 ARE AT 85 in.

Figure 2C Axial Location of Test Section Thermocouples

Figure 3C Schematic of SLSF Loop with Instrumentation Locations

APPENDIX D

FUEL PIN POWER DISTRIBUTION CALCULATIONS

During the pre-test design phase, calculations were performed in order to determine fuel pin enrichments (Ref. 6) which would produce equal power in each of the nineteen fuel pins in the fuel pin bundle. The pre-test thermal hydraulic analyses (Ref. 5) were based on the assumptions of equal pin power, uniform power density in the radial direction within each pin and an axial power distribution based on data from the P-1 test.

Thermal hydraulic analyses for the post-test data analysis were done with detailed fuel pin power distributions provided by EG&G for the W-1 experiment. The fuel pin power distributions were obtained by EG&G from an extensive analysis of the fuel pin bundle including the in-fuel thermocouples and measured neutron flux data. This section presents a brief summary of the results and a presentation of the interpretation and synthesis of results into a form for use in the thermal-hydraulic analysis.

The analyses performed by EG&G included Monte Carlo RAFFLE calculations for three different models. The results have to be superimposed in order to obtain the complete detailed fuel pin power distributions. This approach involves approximations but was necessary due to the complexity of the problem and is consistent with the approximations used in the thermal-hydraulic models. An analysis with SCAMP was used to determine the gamma heating

The analyses performed by EG&G were done with the RAFFLE code with three separate models:

1. A single pin model was analyzed to determine the local effects near a thermocouple tip.
2. A 19 pin, x-y model was analyzed to determine the average fuel pin power for each fuel pin. This model was applied to four axial sections

to represent different lengths of thermocouples and the presence or absence of thermocouples in various pins.

3. A 30 region pin, quarter hexagonal model was analyzed to provide detailed radial and angular power distributions within each pin.

THERMOCOUPLE EFFECT

A two-dimensional analysis of a single pin was performed with a model which was detailed near the thermocouple tip. The objective was to determine the extent of the power perturbation due to the thermocouple and to guide the development of the multiple pin models. The results shown in Figure D-1 give the axial power distribution and show the power in a fuel pin to be approximately 6% lower in the region containing the thermocouple. The transition occurs from about -1.75 cm to +1.75 cm. The single pin analysis does not include the effects of adjacent pins so the results were not used directly. Multiple pin models did not include axial detail at the thermocouple tips so the ± 1.75 cm transition region from the single pin results was superimposed on multiple pin results.

Results from the 19 pin model give the effect of thermocouples on the magnitude of average power in each pin in each of four axial sections. Power differences in the different axial sections are due to thermocouple placement. Table D-1 summarizes the results.

The values given for each pin have been normalized with the power calculated in the lower section (below 14 inches from the top of the fuel) which contains no thermocouples. In the upper 2 inches where all the central seven pins have thermocouples, the power in these pins is reduced 4% to 5% by the presence of the thermocouples. The results in Table D-1 show that the primary effect on power in a fuel pin is due to the thermocouple within that pin with thermocouples in adjacent pins having a secondary effect.

80-554-59

**Figure D-1 AXIAL POWER DISTRIBUTION NEAR THERMOCOUPLE TIP
SINGLE PIN MODEL RESULTS**

80-554-48

Figure D-2 AXIAL DISTRIBUTION OF FUEL PIN BUNDLE TOTAL POWER

TABLE D-1

FUEL PIN POWER REDUCTION DUE TO THERMOCOUPLES
 19 PIN MODEL RESULTS FOR FUEL PINS WITH IN-FUEL THERMOCOUPLES
 POWER FOR EACH PIN NORMALIZED TO POWER IN THE LOWER SECTION

Pin	Location of Thermocouple	Axial Section (inches from top of fuel)		
		0-2"	2"-8"	8"-14"
1	8"	.944	.955	.996
2	8"	.956	.959	.993
3	14"	.953	.944	.976
4	2°	.951	.973	.993
5	2"	.969	.979	.984
6	14"	.945	.958	.965
7	14"	.960	.965	.982

- (1) Section from 0-2 inches contains thermocouples in 7 central pins.
 Section from 2-8 inches contains thermocouples in pins 1,2,3,6,7.
 Section from 8-14 inches contains thermocouples in pins 3,6,7
 Section below 14 inches does not contain thermocouples

FUEL PIN POWER AXIAL DISTRIBUTIONS

Axial power distributions were provided by EG&G (Reference 7) for each of the 19 pins for conditions corresponding to the LOPI 2, LOPI 3, LOPI 4 and BWT 6" tests. These distributions account for variations in the axial distribution of the ETR power due to different control rod positions for LOPI 3, LOPI 4, and BW 6" and include corrections for burnup and depletion. The LOPI-2 power distribution was calculated with the LOPI-4 ETR distribution with a different burnup and depletion correction. The distribution used for LOPI-1 is the same as that for LOPI-2, and all boiling window tests were assumed to have distributions the same as BWT 6".

The EG&G results also account for the variation due to thermocouple effects as determined with the 19 pin model. Transition zones of ± 1.75 cm were included between axial sections based on results of the single pin model.

FUEL BUNDLE AXIAL DISTRIBUTION

For analysis of sodium transients with the THYME and COBRA codes, an overall average power distribution for the whole fuel pin bundle was calculated from the individual fuel pin power. The power in pin j for test condition i may be written as $P_{ij}(z)$ which gives the linear power distribution (kW/ft) as a function of axial position z . The distribution of fuel bundle total power $PN_i(z)$, for test i is obtained as an average for the 19 fuel pins.

$$PN_i(z) = \frac{1}{19} \sum_{j=1}^{19} P_{ij}(z)$$

For convenience, a single distribution from averaging the four distributions was used.

$$PN(z) = \frac{1}{4} \sum_{i=1}^4 PN_i(z)$$

The result is shown in Figure D-2.

AXIAL POWER DISTRIBUTION FOR LIFE-4 AND THT-D ANALYSES

The LIFE-4 and THT-D analyses were performed for an annular pin, pin #7. Table D-2 gives the distribution of fuel pin power for pin #7 for the different test conditions as well as the average.

These values are normalized with the fuel pin total power.

RADIAL POWER DISTRIBUTION FOR COBRA ANALYSIS

A 30° sector of the fuel pin bundle was modeled for analysis of the test transients with the COBRA code. This model has five radial and six circumferential divisions similar to the 30 region pins used for the fuel pin power calculations. Figure D-3 shows a COBRA model overlay on the thirty region pin-quarter hex model and identifies the fuel pin types and sectors for which radial distributions are required for COBRA. Sample results for pin type B are given in Figure D-4. The values on the nodes are normalized such that the total for the thirty nodes is 1.0. Radial profiles for each of the sectors needed for the COBRA analysis have been taken from Figure D-4 and graphed in Figures D-5 and D-6 as nondimensionalized with the sector total power. These sector totals as a percentage of total fuel pin power are given in Table D-3 at the bottom of Figure D-3. The radial profiles in Figures D-5 and D-6 have been grouped and averaged together to form only four radial profiles. The resultant profiles for COBRA analysis are given in Figure D-7 and the application to different sectors of the COBRA model is identified in Table D-3.

TABLE D-2

AXIAL POWER DISTRIBUTIONS FOR LIFE-4 AND THD-D ANALYSES

Fuel Pin #7

X	LOPI 1 & 2	LOPI 3	LOPI 4	BW 6"	Average
TOP. 0"	.303	.334	.283	.346	.316
2	.498	.521	.468	.540	.507
4	.675	.695	.637	.716	.681
6	.830	.849	.787	.866	.833
8	.971	.988	.926	.999	.971
10	1.091	1.105	1.048	1.107	1.088
11	1.178	1.188	1.141	1.181	1.172
13.31*	1.223	1.228	1.192	1.216	1.215
14.	1.252	1.244	1.223	1.240	1.240
14.69*	1.279	1.279	1.254	1.262	1.268
16	1.302	1.298	1.284	1.277	1.290
18	1.317	1.306	1.312	1.283	1.304
20	1.309	1.293	1.317	1.270	1.297
22	1.278	1.258	1.298	1.239	1.268
24	1.225	1.228	1.256	1.193	1.225
26	1.152	1.134	1.192	1.132	1.152
28	1.059	1.047	1.105	1.053	1.066
30	.948	.941	.966	.956	.960
32	.821	.817	.868	.837	.836
34	.679	.671	.721	.687	.689
36	.524	.450	.557	.500	.508

*Detail near T/C

Table D-3
IDENTIFICATION OF PIN MODEL POWER VALUE AND DISTRIBUTION

PIN	SECTOR	POWER (%)	CURVE	PIN	SECTOR	POWER (%)	CURVE
C (1)	45°	16.6	c	D (4)	90°	17.5	a
B (2)	30°	17.6	a	D (4)	150°	15.9	b
B (2)	270°	16.0	d	D (4)	210°	7.7	b
B (2)	330°	16.3	b	E (3)	30°	18.3	a
D (4)	30°	9.2	a	E (3)	270°	15.1	b
				E (3)	330°	16.6	a

D-9

Figure D-4 PIN (B) FRACTIONAL POWER DISTRIBUTION (REGION POWER/PIN POWER) FROM MULTI-REGION MONTE CARLO CALCULATIONS FOR RUN NO. 1 (ALL T/C's ARE IN) ERRORS ENCLOSED IN PARENTHESIS ARE ONE FRACTIONAL PROBABLE ERROR (REF. 1)

80-554-40

Figure D-5 NORMALIZED RADIAL FUEL PIN POWER DISTRIBUTION FOR EACH SECTOR - Axial Section Below 14", No Thermocouples

Figure D-6 NORMALIZED RADIAL FUEL PIN POWER DISTRIBUTION FOR EACH SECTOR - Axial Section Below 14", No Thermocouples

80-554-10

80-554-62

Figure D-7 RADIAL POWER DISTRIBUTIONS FOR COBRA-3M

RADIAL POWER DISTRIBUTIONS FOR LIFE-4 ANALYSIS

The fuel pin thermal model for LIFE-4 analysis is a two-dimensional (r, z) model. The radial power distributions for use in LIFE-4 were obtained from the results from the quarter hex calculations such as given in Figure D-4. The values at each of the five radial locations were summed to obtain a circumferential average value for the two-dimensional (r, z) model. Radial distributions for each type of pin are shown in Figures D-8, D-9, and D-10 for each of the four axial sections normalized to unity.

A single radial distribution must be obtained for use in LIFE-4 analyses. The solid pins, types D and E, show very similar radial profiles for all axial slices. The profile variation due to axial location is slight compared to the radial variation. An average of the eight curves was selected for use with the solid pin LIFE-4 analysis. This profile is given in Figure 24.

For the annular pins, LIFE-4 temperature calculations at 2 inches from the top of the fuel will be compared with TE 22-5 data in pin 5 and at 14 inches with TE 22-7 data in pin 7. These are type B pins with the thermocouple locations as in run # 1, and run # 4 from Figure D-8. An average of the profiles in Figure D-8 was used for the LIFE-4 calculation for annular pins. This average, Figure D-11, is a good average for pin types B and C for all axial locations.

RADIAL POWER DISTRIBUTION FOR THT-D ANALYSIS

The THT-D fuel pin models are more detailed than COBBA and LIFE-4 models and use the most detailed fuel pin power distribution information. Radial power distributions can be input for each axial layer of nodes. The THT-D model is a two dimensional (r, z) model with conditions assumed uniform in the circumferential direction. Radial power distributions for analysis of annular pins are shown in Figure D-8 for the four axial sections of the fuel pin power analysis. Radial power distributions for the solid pin are shown in Figure D-9.

Figure D-8 NORMALIZED RADIAL POWER DISTRIBUTION FUEL PIN TYPE "B"

Figure D-9 NORMALIZED RADIAL POWER DISTRIBUTION FUEL PIN TYPE "D"

80-554-12

Figure D-10 NORMALIZED RADIAL POWER DISTRIBUTION FUEL PIN TYPE "E"

80-554-65

Figure D-1] RADIAL FUEL PIN POWER DISTRIBUTION FOR LIFE-4 ANALYSIS

TOTAL FUEL PIN POWER

The total power in each fuel pin was obtained by integrating the EG&G pin power distributions. The results are given in Reference 5.

In order to evaluate the power variation across the fuel bundle, the values were non-dimensionalized by dividing pin power by the average pin power. The pin to pin power variation is almost the same for all the test conditions so a single set of values was obtained by averaging for the four test conditions. Figure D-12 shows the total fuel pin power distribution. Pin 17 has the highest power, 3.2% higher than the average for the fuel pin bundle. Pin 2 has the lowest power, 2.1% lower than average.

For the post-test analysis with the COBRA-3M code, the power for each of the four fuel pin types was taken as an average for the fuel bundle. For example, pins #2 - #7 were averaged to get the power for pin B(2) of the COBRA model. COBRA fuel pin powers expressed as a percentage of the average pin power are as follows:

Pin C	Pin Power	99.4%
B		98.4%
D		100.17%
E		100.15%

80-554-41

**Figure D-12 TOTAL FUEL PIN POWER DISTRIBUTION
ALL TEST CONDITIONS**

APPENDIX E

GAMMA HEATING RATES AND DECAY HEATING

The thermal-hydraulic analyses require input functions to describe heating rate in various components such as cladding and thermocouples in addition to the heating rates for the fuel. This information must be input for steady state condition and for the scram transient. The results of EG&G's analysis (Ref 8) are evaluated in this section and put into the proper form for the post-test calculations.

The test section power P_{TS} includes gamma heating in the thermocouples, cladding, wire wrap, sodium and hexcan and gamma heating in the fuel. For the full power condition, $P_{TS} = 668$ kW, produced at an ETR power of 145 MW, the total gamma heating rates are summarized in Table E-1.

TABLE E-1

TOTAL GAMMA HEATING RATES (kW) AT 145 MW ETR POWER

Thermocouples	0.68
Wire Wrap	1.19
Cladding	8.79
Sodium	2.71
Hexcan	<u>11.20</u>
Subtotal	24.47
Fuel	<u>60.13</u>
Total	84.6

Reference 9 gives values of delayed beta heating in the fuel which totals 17.65 kW for the fuel pins. Table E-2 summarizes the test section heating rates.

TABLE E-2

TEST SECTION HEATING RATES (kW) AT 145 MW ETR POWER

	Gamma	Beta	Fission	Total
Test Section Components	24.47	-	-	24.47
Fuel	<u>60.13</u>	<u>17.65</u>	<u>565.75</u>	<u>643.53</u>
Total	84.6	17.65	565.75	668

The major portion of the gamma heating in the test section comes from the ETR core and is 71.4% prompt and 28.6% delayed (Reference 9). Of the fission power, 6.5% is from fission product decay at steady state.

Variation of the fission product decay and the delayed gamma heating with time can be described with a fission product decay function. The remainder of the fission power as well as the prompt gamma heating is directly related to the ETR power.

During a scram, the ETR power can be described with the normalized function $F_S(t)$ such that

$$P_{ETR}(t) = P_{ETR}(0) \times F_S(t)$$

The fission product decay heat transient is described by a function $F_D(t)$ such that

$$P_D(t) = P_D(0) \times F_D(t) = .065 \times P_F \times F_D(t)$$

where P_D is the decay in the fission product heat and P_F is the fission heating rate. The function F_D is a normalized form of decay heat variation.

The values usually available (Ref 10) are for the case of an instantaneous reduction in fission power.

An analysis was performed to derive a modified function $f_D(t)$ which replaces $F_D(t)$ and accounts for the time variation of fission power for ETR as specified by the function $F_S(t)$.

Following a scram, the total power transient in the fuel pins at 145 MW ETR power is

$$P_{FP}(t) = 565.7 \times (1.0 - .065) \times F_S(t) + 565.7 \times .065 \times f_D(t)$$

$$+ 60.1 \times .714 \times F_S(t) + 60.1 \times .286 \times f_D(t) + 17.65 \times f_D(t)$$

$$P_{FP}(t) = 571.8 \times F_S(t) + 71.5 \times f_D(t)$$

The total test section power is due to the gamma and beta heating in the other test section components added to the fuel power, i.e.

$$P_{TS}(t) = 24.5 \times .174 \times F_S(t) + 24.5 \times .286 \times f_D(t) \\ + 571.8 F_S(t) + 71.5 f_D(t)$$

$$P_{TS}(t) = 576.1 F_S(t) + 78.5 f_D(t)$$

or $P_{TS}(t) = 668 [.862 F_S(t) + .118 f_D(t)]$

$$P_{FP}(t) = 643.5 [.889 F_S(t) + .111 f_D(t)]$$

The time dependence for the fuel power and for the test section power is very similar. Figure E-1 illustrates the variation with time for the test section power. The second term, the decay heat portion is about half the total after about 0.2 seconds and is dominate after about 30 seconds.

Figure E-1 DECAY HEAT TRANSIENT