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GE POST-TEST ANALYSIS OF SLSF
EXPERIMENT W-1 THROUGH LOPI-4

By

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Prepared for the
U.S. Department of Energy
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By the
GENERAL ELECTRIC COMPANY
Advanced Reactor Systems Department
Sunnyvale, California

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Summary

SLSF experiment W-1 was designed to investigate fuel pin-to-coolant heat transfer during various LMFBR flow-coastdown events in the burnup interval from 0.0 atom percent to 0.5 atom percent. In the study reported here, data from in-fuel thermocouples and coolant (wire-wrap) thermocouples were evaluated during steady-state and transient operation from the beginning of the experiment through LOPI-4 (Loss-of-Piping-Integrity Transient Number 4).

The objective of the data evaluation was to determine how maximum coolant temperatures during successive LOPI transients were affected by burnup. A second objective was to identify the mechanisms responsible for this burnup effect.

It is concluded that the effects of fuel restructuring and gap closure on transient coolant temperature at very low burnup (i.e., before gap closure occurs) are comparable in importance to the effect of power. As fuel restructuring and gap closure occur, pin-to-coolant heat transfer during a subsequent LOPI transient is reduced, along with maximum coolant temperature during the transient.

At burnups corresponding to the final stages of gap closure and fuel restructuring (i.e., burnups above that of LOPI-2A in this experiment), the effect of increasing burnup is indistinguishable from the effect of decreasing pin power in the W-1 coolant temperature data.

Coolant temperature data from the last two LOPI transients in the W-1 experiment indicate that pin-to-coolant heat transfer during the final LOPI transient (LOPI-4) was lower than would be expected from the other W-1 data. This is believed to have been caused by increased fuel-cladding contact pressure prior to the LOPI-4 transient. Increased pressure was caused

by an increase in pin power of approximately 10% prior to this transient. Fuel cracking prior to LOPI-4 could also have had an effect.

Transient coolant temperature measurements taken just below the axial midplane of W-1 indicate that less fuel restructuring and gap closure occurred below the midplane. As a result, coolant temperatures just below the midplane were affected primarily by pin power; burnup effects were almost completely absent in coolant temperature data at this axial location.

Based on the observations summarized above, it is concluded that maximum coolant temperatures during a rapid flow-coastdown transient depend more upon pretransient fuel temperature than on transient fuel-cladding gap conductance. This conclusion was verified analytically. As fuel restructuring and gap closure occur, pretransient and transient gap conductance both increase, while pretransient fuel temperature decreases (assuming pin power remains constant). The W-1 data show that these changes produce lower transient coolant temperatures, despite the increase in transient gap conductance.

Analysis of steady state fuel temperatures during the W-1 experiment, performed using the LIFE-4 code¹, verifies that the LOPI transient tests were performed at distinctly different stages of fuel restructuring and gap closure, as intended. The analysis also suggests that the W-1 in-fuel thermocouples operated correctly during the entire period analyzed (i.e., through LOPI-4). Fuel temperatures predicted by the LIFE-4 code were in good agreement with the data at the highest burnups analyzed near the axial midplane. However, fuel temperature was predicted to decrease much too rapidly with increasing burnup near the beginning of the experiment. Near the top of the fuel column, LIFE-4 predicted rapid closure of the fuel-cladding gap, while post-test examination suggests that the gap was open

throughout the W-1 irradiation. It is concluded that the models describing initial fuel restructuring and gap closure rates in LIFE-4 require adjustment, while asymptotic temperature predictions appear reasonably accurate.

1.0 GE Analysis of Steady State Fuel Performance

A major objective of the W-1 experiment was to determine how fuel cracking, fuel restructuring, gap closure, and fission product generation affect heat transfer from fuel pin to coolant during flow-coastdown transients without SCRAM. To study these effects, the W-1 assembly was subjected to four Loss of Piping Integrity (LOPI) transients at selected intervals during the first 400 hours of the experiment. The LOPI transients were scheduled to occur at times when the test fuel pins were expected to have completed three distinctly different phases of restructuring. LOPI-1 was intended to provide transient performance data before any significant fuel restructuring or gap closure had occurred. LOPI-2 was scheduled to occur when fuel restructuring and gap closure had both been partially completed. LOPI-3 and LOPI-4 were both intended to occur after restructuring was nearly complete and the fuel-cladding gap had closed. The difference between LOPI-3 and LOPI-4 was intended to be that fuel cracks were healed prior to LOPI-3 and unhealed prior to LOPI-4. Each LOPI transient was designed to have the same fuel pin power level and the same flow coastdown, so that the effects of fuel structure and gap size on transient coolant temperatures could be observed directly.

The objectives of the steady state analysis were to confirm the existence of distinctly different fuel structures and gap sizes at the start of each LOPI transient and to quantify these differences in terms of fuel-cladding gap conductance and fuel temperature distributions. Viewed from a different perspective, the steady state analysis also provides evidence (i.e., calculated fuel temperature histories) that can be used to judge the validity of in-fuel thermocouple readings. Given data from in-fuel thermocouples

and coolant thermocouples during steady state operation, the main objective of the steady state analysis was to determine how much of the measured temperature difference between the fuel inner surface and the clad inner surface was associated with the gap and how much was associated with fuel conductivity and restructuring. This division is expected to vary with burnup, since burnup affects fuel-cladding gap size, the thermal conductivity of the material in the gap, fuel-cladding contact pressure, and fuel thermal conductivity. Although the thermocouple data and post-test fuel microstructural measurements are important sources of information regarding the validity of the steady state analysis, these measurements do not allow separation of the effects of gap conductance and fuel thermal conductivity. As a result, one must rely upon analytical models, and the confidence placed in the calculations depends upon one's confidence in the model employed, the model's ability to match all the available W-1 data, and the degree to which the model has been validated by analysis of previous experiments. This need to rely on the credibility of previously calibrated models is the primary reason that two independent steady state analyses are presented in this report. This section describes the results of W-1 analyses performed at GE-ARSD using the LIFE-4 code. HEDL calculations performed using the SIEX code are described elsewhere in this report. The LIFE-4 version used in the analysis was calibrated at WARD during January-April 1981. This version of the code will be frozen in June 1981 and documented by September 1981.

1.1 Results of the LIFE-4 Steady State Analysis

The approach adopted for the steady state analysis of W-1 was to provide nominal best-estimate operating conditions and pin geometry as input to the calibrated reference version of the LIFE-4 code. No adjustments were made to the code or to its calibration coefficients. Both annular and solid-pellet W-1 fuel pins were analyzed, although the primary focus was on the annular pin design which contained in-fuel thermocouples. Supplementary analyses of the annular pin were performed to determine if small changes in fuel-cladding gap conductance or fuel thermal conductivity could remove the observed discrepancies between predicted and measured fuel inner surface temperatures. In all cases, it was found that relatively large changes in these parameters were required to make predicted temperatures equal to measured temperatures. In addition, none of the supplementary calculations produced agreement between predicted and measured time histories of fuel temperature. Therefore, the reference case for each pin type is regarded as the most valid indication of fuel temperature distributions and gap conductance.

Figure 1 compares predicted and measured fuel inner surface temperatures for Pin 7 (typical of annular pins 3, 6 and 7)² near the axial midplane (35 cm below the top of the active fuel column) as functions of time. Figure 2 provides similar results for the same pin near the top of the active fuel column (5 cm below the top of the active fuel column). As shown in Figure 1, the thermocouple data indicate high fuel temperatures (2480°C to 2590°C) at the beginning of the irradiation period. Fuel inner surface temperatures indicated by the thermocouples decrease steadily, until they reach approximately 2150°C near the midpoint of ETR cycle 3 or the beginning of ETR Cycle 4. Very little change is evident in the data after the start of ETR Cycle 4. Thus, the

FIGURE 1

TEST SECTION POWER AND LIFE-4 FUEL CENTERLINE TEMPERATURE PREDICTION VS. THERMOCOUPLE DATA NEAR MIDPLANE (ANNULAR PIN)

thermocouple data show a substantial (330°C to 440°C) decrease in fuel temperature between the start of the irradiation period and the second half of Cycle 3.

The LIFE-4 predictions shown in Figure 1 show the same general behavior as the thermocouple data. Fuel temperatures at the start of the irradiation are relatively high (but 200°C below the thermocouple data). Predicted fuel temperature then decreases until it reaches 2150°C at approximately 190 hours in ETR Cycle 2. After this time, LIFE-4 predicts no significant change in fuel temperature, so that predicted and measured temperatures become essentially equal to one another near the end of ETR Cycle 3. These results indicate that LIFE-4 predictions agree very closely with the data after fuel restructuring and gap closure are essentially complete in the experiment. This suggests that the W-1 thermocouples provided valid absolute values of fuel temperature, since the LIFE-4 prediction reflects the temperatures that would be expected based on data from the experiments used to calibrate LIFE-4.

As noted above, the results shown in Figure 1 were obtained without adjustments to the code or to the input data. However, the method used to model fuel pin power history at the beginning of the irradiation has a significant influence on the LIFE-4 calculation. The results shown in Figure 1 were obtained by deleting the first 98 hours of ETR Cycle 2 from the analysis. Since pin power during this early period was never greater than 4kw/ft (131 w/cm), this should not have had an appreciable effect on the results. However, LIFE-4 predicted significant fuel restructuring when this 98-hour period was included in the analysis. As a result, the LIFE-4 prediction of 2300°C at 99 hours in Figure 1 becomes approximately 2240°C when the 98 hours at low power is included in the analysis. Very

rapid fuel restructuring is predicted by LIFE-4, even when the low-power interval is deleted from the analysis. For example, the columnar grain region radius is predicted to be 86 mils (0.22 cm) by the time full power is attained at the end of the initial 12-minute startup ramp! When the error causing this is found and corrected, LIFE-4 fuel temperature predictions at the start of the W-1 irradiation are expected to increase substantially without affecting predictions at the end of the irradiation.

As indicated by the preceding discussion, LIFE-4 results are clearly not valid near the beginning of the W-1 irradiation period, because fuel restructuring is predicted to occur much too rapidly. Near the end of the irradiation period, when LOPI-3 and LOPI-4 occur, LIFE-4 predictions appear to be valid based on the thermocouple data shown in Figure 1. Post-test destructive examination data provide additional information that can be used to judge the validity of LIFE-4 predictions near the end of the experiment. LIFE-4 predictions of fuel microstructural features from an annular pin (Pin 7) are compared with measurements in Table 1. As shown in this table for the near-midplane location, LIFE-4 predicts slightly greater fuel restructuring than was measured. However, the agreement is judged to be reasonably good. With regard to fuel-cladding gap size, note that the LIFE-4 prediction in Table 1 is hot gap size, while the measurement was obtained at room temperature. Based on previous experience comparing calculated values of hot gap size with cold PIE gap size measurements, GE believes that the cold gap measurement of 0.84 mils (.02 mm) certainly corresponds to a closed gap in the hot condition. This agrees with the LIFE-4 prediction.

To summarize the LIFE-4 results for the annular pin near the axial midplane, predicted values of fuel inner surface temperature, fuel microstructure,

Table 1

End of Steady State LIFE-4 Predictions of Fuel Temperature and
Microstructure Compared to Thermocouple and Post-Irradiation
Examination Data for Annular Fuel Pin No. 7

<u>Fuel Pin Location and Parameter</u>	<u>LIFE-4 Predictions</u>	<u>T.C. Data</u>	<u>P.I.E. Pin #7</u>
14" Below Top of Fuel Column			
Centerline Fuel Temperature (°F)	3876	3873	-
Central Void Radius (inches)	0.0390	-	0.0350
Columnar Grain Zone Radius (inches)	0.0885	-	0.0721
Equiaxed Grain Growth Zone Radius (inches)	0.0912	-	0.0834
Diametral Fuel-Cladding Gap (mils)	0.0*	-	0.84 [±]
2" Below Top of Fuel Column			
Centerline Fuel Temperature (°F)	3050	3041	-
Central Void Radius (inches)	0.0350	-	0.0360
Columnar Grain Zone Radius (inches)	0.0867	-	0.0000
Equiaxed Grain Growth Zone Radius (inches)	0.0887	-	0.0636
Diametral Fuel-Cladding Gap (mils)	0.0*	-	2.65 [±]

*hot
±cold

and hot gap size are in relatively good agreement with the thermocouple and PIE data near the end of the experiment. It is concluded that fuel thermal conditions prior to LOPI-3 and LOPI-4 are predicted correctly by LIFE-4 near the axial midplane of the annular pin, even though predictions early in the irradiation are clearly incorrect. The fuel-cladding gap conductance predicted by LIFE-4 for this axial location on an annular pin just prior to LOPI-3 is $0.79 \text{ w/cm}^2\text{C}$. Since fuel restructuring is predicted to be slightly too large at this axial location (see Table 1), this value of gap conductance may be slightly low.

Figure 2 compares LIFE-4 predictions near the top of the fuel column of an annular pin (Pin 7) with in-fuel thermocouple data. In contrast to the situation depicted in Figure 1, LIFE-4 overpredicts fuel temperature in Figure 2 near the beginning of the irradiation. At the end of ETR Cycle 4, LIFE-4 fuel temperatures agree exactly with measured fuel temperatures. The thermocouple data vary only slightly throughout the irradiation period, while LIFE-4 predicts a gradual decrease in fuel temperature. In this case, the agreement between predicted and measured fuel temperatures at the end of the irradiation appears to be fortuitous. This is shown by the PIE data in Table 1. At 5 cm below the top of the fuel column, the PIE data show no columnar grain formation and a small increase in central void size. In addition, the cold fuel-cladding gap measurement suggests that the gap was open in the hot condition (although some reduction in gap size appears to have occurred). Conversely, LIFE-4 predicts a closed gap in the hot condition and a large columnar grain region. The columnar grain formation predicted by LIFE-4 is caused by the code error discussed previously in this section.

FIGURE 2

TEST SECTION POWER AND LIFE-4 FUEL CENTERLINE TEMPERATURE PREDICTIONS VS. THERMOCOUPLE DATA NEAR TOP OF FUEL (ANNULAR PIN)

ETR POWER HISTORY FOR THE W-1 SLSF EXPERIMENT

If LIFE-4 predictions of gap closure and columnar grain formation were corrected to obtain agreement with the PIE data, predicted temperatures would be expected to be higher than the thermocouple data at the end of ETR Cycle 4 (as they are at the start of the irradiation), and little variation of predicted fuel temperatures with respect to time would be expected. Thus, predicted temperatures would be higher than measured temperatures at all times. This suggests incorrect operating conditions rather than incorrect thermal models, because the influential thermal models generally produce time variations in fuel temperature.

The possibility that local pin power is incorrect in Figure 2 suggests itself, because power at the top of the fuel column was recently increased by 8% to agree with the axial power profile determined via gamma scans. Prior to this change, LIFE-4 predictions agreed virtually exactly with measured fuel temperatures at the beginning of the irradiation. It is concluded that the axial power profile indicated by the gamma scan could be incorrect, and it is recommended that this possibility be considered in interpreting the transient segments of the W-1 experiment.

Since the LIFE-4 analysis is shown by PIE data to be incorrect at the top of the fuel column, the only estimate of gap conductance available from the analysis for this location is that gap conductance must be lower than the predicted value of $0.75 \text{ w/cm}^2\text{C}$. Fortunately, no analysis is necessary to qualitatively describe fuel structure and gap size prior to each LOPI transient. As shown in Table 1, very little restructuring or gap closure occurred near the top of the fuel column in the annular pins. Therefore, it seems clear that fuel structure and gap size were the same at this location for all LOPI transients, except for second-order effects caused by fission gas release and pin power level.

The preceding discussion of the LIFE-4 analysis of annular pins with in-fuel thermocouples suggests that LIFE-4 predictions provide good estimates of fuel temperature and gap conductance for high-power fuel near the axial midplane near the end of the W-1 irradiation. LIFE-4 predictions at earlier times near the midplane and at all times near the top of the fuel column are not valid, according to the annular-pin analysis. Therefore, LIFE-4 predictions of fuel temperature and gap conductance for the solid pin (Pin 14) are presented here only for the near-midplane axial location just prior to LOPI-3.

Table 2 compares LIFE-4 predictions of fuel microstructure with PIE data at the end of the W-1 irradiation. Near the axial midplane, predicted values are in excellent agreement with the data. The cold fuel-cladding gap size measurement is believed to correspond to a closed gap in the hot condition, which agrees with the predicted hot gap size. Because of the good agreement between measured and predicted values in Table 2 near the axial midplane, there is reason to believe that LIFE-4 predictions of gap conductance and fuel temperature near the midplane prior to LOPI-3 are accurate. The predicted gap conductance is $0.81 \text{ w/cm}^2\text{ }^{\circ}\text{C}$ and the predicted fuel inner surface temperature is 2433°C .

As mentioned previously in this section, calculations were performed to determine how much fuel thermal conductivity or gap conductance would have to be reduced to increase predicted fuel temperature in the annular pin sufficiently to obtain agreement with the thermocouple data at the beginning of the irradiation period. As shown in Figure 1, an increase in fuel inner surface temperature of approximately 280°C would be required. The calculations indicate that fuel thermal conductivity would have to be reduced by 22% to obtain agreement with the thermocouple data just prior to LOPI-1.

Table 2

End of Steady State LIFE-4 Predictions of Fuel Temperatures and
Microstructure Compared to Thermocouple and Post-Irradiation
Examination Data for Solid Fuel Pin #14

<u>Fuel Pin Location and Parameter</u>	<u>LIFE-4 Predictions</u>	<u>T.C. Data</u>	<u>P.I.E. Pin #14</u>
14" Below Top of Fuel Column			
Centerline Fuel Temperature (°F)	4411	-	-
Central Void Radius (inches)	0.01800	-	0.0230
Columnar Grain Zone Radius (inches)	0.06997	-	0.0732
Equiaxed Grain Growth Zone Radius (inches)	0.07561	-	0.0789
Diametral Fuel-Cladding Gap (mils)	0.0*	-	1.26 [±]
2" Below Top of Fuel Column			
Centerline Fuel Temperature (°F)	3559	-	-
Central Void Radius (inches)	0.00855	-	0.0000
Columnar Grain Zone Radius (inches)	0.05135	-	0.0360
Equiaxed Grain Growth Zone Radius (inches)	0.05539	-	0.0580
Diametral Fuel-Cladding Gap (mils)	0.10*	-	2.78 [±]

*calculated when hot
±measured when cold

With fuel thermal conductivity at its nominal value, gap conductance was reduced by lowering the thermal conductivity of the gas in the gap. This was accomplished by changing the fraction of xenon in the fill gas. Nominally, 8% of the fill gas is xenon. To obtain agreement with the thermocouple data just prior to LOPI-1 near the axial midplane, it was necessary to increase the fill gas composition from 8% xenon to 65% xenon. These results are provided only to add perspective to the magnitude of the discrepancy shown in Figure 1. The calculation indicated that the temperature discrepancy is much larger than can be accounted for by uncertainties in either gap conductance or fuel conductivity for fuel with the low burnup or low degree of restructuring that is of interest here (i.e., at 120 hours in ETR Cycle 2, see Figure 1). These results confirm that the problem with the LIFE-4 calculation is the speed with which restructuring occurs, rather than the properties of restructured fuel.

1.2 Discussion of LIFE-4 Steady State Results

As noted previously in this section, an objective of the W-1 experiment was to determine the effect on pin-to-coolant heat transfer during a LOPI transient of fuel microstructure and gap size prior to the transient. LOPI-1 was to have occurred prior to significant fuel restructuring or gap closure, LOPI-3 and LOPI-4 were scheduled to occur after both restructuring and gap closure were essentially complete, and LOPI-2 was scheduled to occur when the test fuel was partially restructured and the gap was partially closed.

The LIFE-4 analysis confirms that each LOPI transient test was performed at a time when fuel structure and gap size had the intended characteristics near the axial midplane of each test pin. However, it is important to note that fuel was essentially unrestructured at the ends of the fuel columns and fuel-cladding gaps were open at the ends of the fuel columns. Since the transient response to coolant thermocouples is determined by axial average pin-to-coolant heat transfer characteristics, the effects of the fuel restructuring and gap closure would be difficult to observe unless fuel was restructured and the gap was closed along most of the length of each fuel pin. The LIFE-4 analysis did not provide insight regarding axial variations in fuel structure or gap size, because of the discrepancies noted in connection with Figure 2 and Table 1 at the top of the fuel column.

Ideally, the steady state LIFE-4 analysis would have duplicated the in-fuel thermocouple data at both axial sections at all points in time when best-estimate powers and measured coolant temperatures were used in the analysis. Ideally, these results would have been obtained without modifying any code calibration parameters. Such results would have

established with high confidence that the W-1 thermocouples operated correctly and that the effects of fuel restructuring, gap closure, and changes in fuel conductivity were modeled correctly. Such results would, therefore, have provided gap conductance and thermal conductivity values for the transient analyses that were validated by all the experiments in the LIFE-4 calibration data base, as well as by W-1 data.

Thermal calibration of the LIFE-4 code at low burnups such as that of W-1 (0.4 atom %) has been based almost entirely upon fuel microstructural radii measured in the P-19 and P-20 experiments³. Central void size, columnar grain radii, and fuel melt radii measurements provided approximate isotherms that could be used for thermal calibration. Only one experiment (P17A)⁴ exists with in-fuel thermocouples to show the time dependence of fuel restructuring and gap closure and to provide a direct temperature indication. Furthermore, since P-17A was the only experiment with in-fuel thermocouples prior to W-1, some uncertainty has existed regarding the validity of the P-17A thermocouple readings. Given this data base for calibration of LIFE-4, it is not surprising that the detailed early-life dynamics of fuel restructuring and gap closure are not predicted correctly by LIFE-4 while fuel temperatures are predicted correctly at higher burnups.

Figure 3 shows results for the P-17A experiment. LIFE-4 predicts "equilibrated" fuel temperatures to be approximately 100°C lower than the thermocouples indicate and fuel restructuring and gap closure are predicted to occur more rapidly than indicated by the thermocouples. Thus, the W-1 and P-17A data both indicate that fuel restructuring occurs too rapidly in the LIFE-4 model, while the LIFE-4 model predicts "equilibrium" fuel temperatures reasonably well in W-1 and less well in P-17A. The good agreement between LIFE-4 predictions and thermocouple data near the end of the W-1

experiment also indicates that the W-1 thermocouples registered temperatures that would have been expected based upon all the data used to calibrate LIFE-4. Therefore, it is concluded that W-1 in-fuel thermocouples provided accurate temperatures and that the best-estimate W-1 operating conditions are probably quite accurate.

FIGURE 3

LIFE-4 Fuel Inner Surface Temperatures for P-17A
vs. In-Fuel Thermocouple Readings

2.0 GE Thermal Analysis of LOPI Transients

Significant incentives exist for being able to predict correctly fuel-to-coolant heat transfer during LOPI transients, and to predict the timing of coolant boiling initiation and boiling duration. These are primary factors in the design of plant protection systems.

The objective of this analysis of the LOPI transient phase of the W-1 experiment was to quantify the effects of fuel restructuring and fuel-cladding gap closure on pin-to-coolant heat transfer during rapid flow coastdown transients. This was to be accomplished by analysis of the LOPI series of transient tests. In the LOPI tests, the pretransient fuel conditions ranged from fresh (as-fabricated) to completely restructured with closed fuel-cladding gap, as discussed in Section 1.0 of this report.

Although fuel-cladding gap closure is often regarded as part of fuel restructuring, in this report we distinguish between the two effects. The reason for this is the unique (compared to other aspects of fuel restructuring) ability of the gap to reverse its condition, depending on the relative temperatures of fuel and cladding. This changeability of the gap condition (open or closed) is particularly evident during a rapid flow coastdown event.

Fuel restructuring (as defined here) is, along with the gap condition, important in determining steady-state fuel temperature prior to the start of a transient flow-coastdown event. However, due to the fast-changing environment in the transient, the initial fuel structure and gap size have been considered prior to this study to be less important thermally than variations in gap size during transients. Testing the validity of this preconception was a main objective of the current analysis.

The analytical approach used to achieve the objectives discussed above was to attempt an interpretation of the data prior to performing any analysis.

This is described in Section 2.1. This exercise identified a number of questions that required analytical investigation to confirm the preliminary interpretation and to interpret second-order features of the data. These analyses are presented in Section 2.2. The majority of the analyses involved LOPI-3; parametric cases were defined to establish the relationship between LOPI-3 data and measurements from other LOPI transients.

The primary analytical tool used during the transient analysis was the THTD code⁵, which is a general-purpose, finite-element transient heat transfer program. This model treats coolant thermal-hydraulics in a very simplistic manner and models the fuel and thermocouples in detail. Detailed fuel structure and thermal properties were obtained from the LIFE-4 analysis described in Section 1.0.

2.1 Data Evaluation

Hypothesis

Fuel burnup effects reduce the severity of (i.e., peak coolant temperatures during) a LOPI incident.

The above hypothesis has been proposed as a result of a preliminary examination of the W-1 data. This section describes the extent to which an examination of the data supports this hypothesis, and discusses the mechanisms that could be responsible for this behavior.

A detailed evaluation of coolant temperature changes during the LOPI tests was performed. The purpose was to determine how the maximum coolant temperature during a LOPI is affected by fuel burnup, gap closure, and restructuring and to quantify these effects. The approach was to isolate the burnup effect, as nearly as possible, by eliminating other variables between the LOPIs. Differences between initial coolant temperatures were eliminated by measuring temperature increases. Differences between SCRAM times were eliminated by removing LOPI-2 from consideration.

Figure 4 illustrates the method used to compare the maximum coolant temperatures during any two LOPI tests. In Figure 4, the temperature data from Thermocouple No. 3-2 are shown during LOPI-1 and LOPI-3. Instead of comparing absolute values of maximum coolant temperature during two transients, the temperature increase from steady state conditions to the time of maximum coolant temperature is compared. This eliminates the effect of initial steady state coolant temperature from the comparisons.

Maximum coolant ΔT 's for the LOPI tests are summarized in Table 3. The temperature data in Table 3 are arranged in columns, one column for each LOPI test of interest. Three numbers are shown in each column for each thermocouple. These numbers represent the temperature at time zero

Figure 4
Comparison of Temperature Records From
Thermocouple 3-2 During LOPI-1 and LOPI-3
(6.3 in. from top of fuel column)

Table 3

Measured Maximum Coolant Temperature
Increases During LOPI Transient Tests

<u>Thermocouple Number</u>	<u>Parameter Recorded</u>	<u>LOPI-1</u>	<u>LOPI-2A</u>	<u>LOPI-3</u>	<u>LOPI-4</u>
3-2	Temp. @ Time 0 (°F)	1175	1170	1155	1200
	Max. Temp.	1690	1650	1615	1690
	Δ Temp.	515	480	460	490
3-3	Temp. @ Time 0 "	975	975	965	990
	Max. Temp.	1375	1390	1360	1415
	Δ Temp.	400	415	395	425
3-6	Temp. @ Time 0 "	1190	1190	1180	1240
	Max. Temp.	1750	1730	1700	1750
	Δ Temp.	560	540	520	510
3-7	Temp. @ Time 0 "	1185	1200	1200	1250
	Max. Temp.	1710	1710	1670	1750
	Δ Temp.	525	510	470	500
4-6	Temp. @ Time 0 "	1225	1220	1210	1250
	Max. Temp.	1675	1610	1630	1715
	Δ Temp.	450	390	420	465

(initiation time of the flow coastdown), the maximum temperature recorded by that thermocouple during the LOPI, and the difference between the first two numbers. Only those thermocouples for which data were available from each of the four LOPIs are included in the tabulation.

Although, as mentioned above, initial coolant temperature was eliminated as a variable by the above method of comparison, initial power was still present as a variable between LOPIs. Since power was slightly different for each LOPI, it couldn't be eliminated from the analysis and the interpretation of the coolant temperature increases in the various LOPI tests became a matter of separating the effect of fuel burnup (the effect of primary interest) from that of initial power.

In the W-1 experiment, assembly power was determined by a calorimetric method, using data from coolant inlet thermocouples, flow meters, and coolant (i.e., wire-wrap) thermocouples⁵. Since there is scatter in the thermocouple data, it is possible to calculate different fuel assembly powers, depending on the data chosen as a basis for calculation. For example, Table 4 shows the results of three different calculations of the fuel assembly power at the start of each LOPI transient. Differences between the sets are due to: a) selection of different thermocouples for coolant outlet temperature determination, b) differences in reading the flowmeter data plots, and c) application of different correction factors to the coolant outlet temperature. The fuel bundle powers in Table 4 are presented both in absolute terms (total KW) and as normalized values referenced to the LOPI-1 power from each calculation set.

Calculation Set C is based on nine wire-wrap coolant thermocouples instead of the two or three used in the other two sets of calculations. Coolant outlet temperatures in Calculation Set C are based upon the same

Table 4

Three Different W-1 Fuel Assembly Power Calculations
for the LOPI Series Based on Flowmeter and Coolant
Thermocouple Data Immediately Prior to Each Transient

<u>Source of Calculation</u>	<u>Assembly Powers at Time = 0.0</u>			
	<u>LOPI-1</u>	<u>LOPI-2A</u>	<u>LOPI-3</u>	<u>LOPI-4</u>
Calculation Set A (GE)	670.8 kw (1.000)	667.1 kw (0.994)*	650.1 kw (0.969)	715.2 kw (1.066)
Calculation Set B (HEDL)	656.0 " (1.000)	668.0 " (1.018)	655.0 " (0.998)	714.0 " (1.088)
Calculation Set C (GE)	662.5 " (1.000)	687.9 " (1.038)	651.4 " (0.983)	714.1 " (1.078)

*Note: Values in parentheses are normalized assembly powers referenced to LOPI-1 power.

nine thermocouples in each LOPI test. Powers in Calculation Sets A and C were derived using coolant outlet temperature correction factors of 5 to 10 degrees while Calculation Set B does not contain any coolant outlet temperature correction. The coolant outlet temperature correction factors were deemed necessary by GE because, at zero power, the outlet thermocouples gave low readings. The problem appeared to be in the signal conditioning equipment.

The different sets of power calculations shown in Table 4 are similar in that they all show LOPI-3 as the lowest power and LOPI-4 as the highest power tests in the series. Calculation Set A differs from the other two sets in showing LOPI-1 to be a higher power test than LOPI-2A. Calculation Sets A and B indicate, in general, smaller differences in power between successive tests than does Calculation Set C. Note that each set of calculations shows power to be different for each LOPI, so that thermocouple data cannot be compared directly to determine the effect of burnup. The only exception is that, according to Calculation Set B, the power for LOPI-1 is virtually identical to LOPI-3 power. Unfortunately, Calculation Sets A and C indicate that LOPI-3 power was slightly lower than LOPI-1 power.

Table 5 shows how the coolant temperature increases indicated by the individual thermocouples compare in all the possible LOPI test combinations. In Table 5, there are 6 columns, corresponding to the 6 possible comparisons of LOPI transients. The axial location of each thermocouple is indicated in parentheses (inches above bottom of fuel column). The numbers in the columns opposite the thermocouple numbers are differences in the coolant temperature increases indicated by that thermocouple for two LOPI tests. The location of the temperature differences in the table indicates

Table 5

Coolant Temperature Increases Measured By Individual
Thermocouples In All Possible LOPI Test Matchups

TC No. and Location (in. above bottom of fuel column)	LOPI-1 vs. LOPI-2A		LOPI-1 vs. LOPI-3		LOPI-1 vs. LOPI-4		LOPI-2A vs. LOPI-3		LOPI-2A vs. LOPI-4		LOPI-3 vs. LOPI-4	
	LOPI-1 Higher	LOPI-2A Higher	LOPI-1 Higher	LOPI-3 Higher	LOPI-1 Higher	LOPI-4 Higher	LOPI-2A Higher	LOPI-3 Higher	LOPI-2A Higher	LOPI-4 Higher	LOPI-3 Higher	LOPI-4 Higher
3-3 (17.7)	--	15*	5	--	--	25	20	--	--	10	--	30
3-2 (29.7)	35	--	55	--	25	--	20	--	--	10	--	30
3-6 (33.7)	20	--	40	--	50	--	20	--	30	--	10	--
3-7 (35.7)	15	--	55	--	25	--	40	--	10	--	--	30
4-6 (37.7)	60	--	30	--	--	15	--	30	--	45	--	45
No. of TCs Indicating Each Result	4	1	5	0	3	2	4	1	2	3	1	4

*Note: Numbers are in °F, and represent the difference between thermocouple ΔT s (see Figure 4) during the two transients of interest.

the mathematical sign. For example, location of the 15 in the column headed "LOPI-1 vs. LOPI-2A" and opposite T.C. No. 3-3 signifies that T.C. No. 3-3 indicates a 15°F larger coolant temperature increase in LOPI-2A than in LOPI-1. The numbers at the bottom of each column are the total number of thermocouples indicating similar results in each LOPI test comparison. The 4 and 1 at the bottom of the column headed LOPI-1 vs. LOPI-2A, for example, show that 4 of the 5 thermocouples indicated larger coolant temperature increases in LOPI-1 than in LOPI-2A.

A cursory review of Table 5 indicates that greater heat transfer from fuel pin to coolant occurred at low burnup than at high burnup in all comparisons not involving LOPI-4. The lower burnup transient also shows greater heat transfer in the comparison between LOPI-1 and LOPI-4, although the result is less clear in this case (3 thermocouples show LOPI-1 higher vs. 2 showing LOPI-4 higher). Since power was significantly higher during LOPI-4 than during the other transients, it is not surprising that the thermocouple data show higher heat flow to the coolant during LOPI-4 in Table 5. Neglecting the comparisons involving LOPI-4, one finds that at least 4 out of 5 thermocouples indicate greater pin-to-coolant heat transfer (and higher coolant temperatures) during LOPI-1 than during LOPI-2A or LOPI-3. Furthermore, the data clearly indicate greater pin-to-coolant heat transfer during LOPI-2A than during LOPI-3. Note, however, that Table 5 has not been corrected to account for the fact that power was different for each of the LOPI transients. Therefore, it is not clear from Table 5 alone whether pin-to-coolant heat transfer is always greater at low burnup or if this is true in W-1 only because power is greater at low burnup. Partial clarification of this issue can be obtained by considering Tables 4 and 5 together.

Since three different estimates of assembly power are shown in Table 4, the approach used in the discussion below is to interpret the data of Table 5 three separate times. First, it is assumed that the powers from Calculation Set A are correct, then the powers of Set B are assumed to be correct, etc. Only if all three interpretations of the data are the same can one state a definite conclusion. Otherwise, additional analysis is required to determine if power uncertainties are small enough for a burnup effect to be deduced from the W-1 data.

Table 5 shows that pin-to-coolant heat transfer was greater during LOPI-1 than during LOPI-2A. Since Calculation Set A assigns slightly lower power to LOPI-2A, Calculation Set A only mildly supports the hypothesis that fuel restructuring mitigates the effects of LOPI events (i.e., that burnup causes pin-to-coolant heat transfer to decrease). Calculation Sets B and C, however, both assign significantly higher powers to LOPI-2A than to LOPI-1. Therefore, both strongly support the above hypothesis. This follows because a higher power in LOPI-2A would be expected to result in a larger coolant temperature increase. The fact that the coolant temperature increase is lower in LOPI-2A means that the effect of burnup is more important than the effect of power in this part of the experiment, and this conclusion is not affected by the method used to estimate power.

In the comparison of LOPI-1 and LOPI-3, all of the thermocouples indicate larger temperature increases for LOPI-1. Calculation Set B assigns essentially the same powers to these LOPIs. Thus, Calculation Set B strongly supports the hypothesis that increasing burnup reduces pin-to-coolant heat transfer. Calculation Sets A and C assign higher powers to LOPI-1 than to LOPI-3 so further analysis is required to determine whether the observed behavior is caused by increasing burnup, or by decreasing power.

In the case of the LOPI-1 vs. LOPI-4 comparison, the thermocouples are 3-2 in favor of higher coolant temperature increases in LOPI-1. However, all calculation sets assign significantly higher powers to LOPI-4 than to LOPI-1. Therefore, all power estimates suggest that the effect of burnup is to decrease pin-to-coolant heat transfer.

The LOPI-2A vs. 3 comparison shows the T.C.s in favor of LOPI-2A by 4 to 1. All calculation sets assign higher powers to LOPI-2A. Because of this, further analysis is required to determine the relative effects of power and burnup.

Three out of five thermocouples indicate a larger coolant temperature increase for LOPI-4 than for LOPI-2A. Also, all of the calculation sets assign a higher power for LOPI-4 than for LOPI-2A. Therefore, analysis is required before a conclusion can be drawn from this set of data. The same situation exists for the LOPI-3 vs. LOPI-4 comparison.

In the above discussion, it has been shown that one or more of the power calculation sets do not support the hypothesis that fuel burnup effects reduce the severity of a LOPI event. In this context, nonsupport means that if that set of power calculations is assumed, a particular matchup of LOPIs cannot be used as evidence that the hypothesis is correct without further analysis. Table 6 summarizes the results of the LOPI temperature rise comparisons in terms of support given the hypothesis by each of the power calculation sets. For each LOPI test pairing, Table 6 indicates whether the data supports the hypothesis or not under a particular set of LOPI power assumptions. "True" means that the data from that LOPI comparison supports the hypothesis (clearly confirms the hypothesized burnup effect) under a given power calculation set. "Undetermined" means that the effects of power and burnup cannot be separated without further analysis. "False" means that the data indicates that the hypothesis is wrong.

Table 6

Summary of Conclusions Based on Simple Comparison
of Thermocouple Data From the W-1 LOPI Transients

	Power Calc. Set A			Power Calc. Set B			Power Calc. Set C		
	<u>True*</u>	<u>Unde- termined**</u>	<u>False</u>	<u>True*</u>	<u>Unde- termined**</u>	<u>False</u>	<u>True*</u>	<u>Unde- termined**</u>	<u>False</u>
LOPI-1 vs. LOPI-2A	x			x			x		
LOPI-1 vs. LOPI-3		x		x				x	
LOPI-1 vs. LOPI-4	x			x			x		
LOPI-2A vs. LOPI-3		x			x			x	
LOPI-2A vs. LOPI-4		x			x			x	
LOPI-3 vs. LOPI-4		x			x			x	

*"True" means that the data clearly support the conclusion that increasing burnup leads to reduced pin-to-coolant heat transfer during a LOPI transient.

**"Undetermined" means that the observed behavior could have been caused by the difference in power between two LOPIs as well as by burnup. In this situation, analysis (rather than a simple inspection of the data) is required.

Examination of Table 6 shows that each of the power calculation sets generally supports the hypothesis with Set B giving the strongest support. None of the power assumptions lead to data interpretations which would contradict the hypothesis.

An example of data which would contradict the hypothesis would occur if the coolant temperature rises during LOPI-1 and LOPI-3 were the same, or that of LOPI-3 was higher. This is not true, but if it were, it would argue strongly against the hypothesis under any of the power conditions (i.e., higher burnup would be clearly associated with greater pin-to-coolant heat transfer rather than less).

To summarize the results of Section 2.1 and Table 6, it has been determined by inspection of the data that pin-to-coolant heat transfer during a LOPI transient decreases as burnup increases, at least in the burnup-restructuring interval corresponding to LOPI-1 to LOPI-2A. This conclusion is not affected by uncertainties in assembly power. In other burnup intervals, the data are less conclusive. While the same conclusion may be drawn from a comparison of LOPI-1 data with LOPI-4 data, only 3 out of 5 thermocouples support this conclusion. Comparisons of data from other LOPI transients either depend on a particular estimate of assembly power (LOPI-1 vs. LOPI-3) or the effect of burnup cannot be separated from the effect of power without more detailed analysis. This analysis is described in Section 2.2.

Note that in Section 2.1 no attempt has been made to explain precisely how increased burnup causes lower pin-to-coolant heat transfer during a LOPI transient. The analyses of Section 2.2 are intended to provide this insight.

2.2 Analysis

2.2.1 Separation of Power and Burnup Effects

A difficulty encountered in evaluating the data of the previous section was that, in many of the LOPI comparisons, power effects obscured possible fuel restructuring effects. This was particularly true for the LOPI-2A vs. LOPI-3, LOPI-2A vs. LOPI-4, and LOPI-3 vs. LOPI-4 test comparisons. An analysis of the power effect on coolant temperature rise was performed using the THTD computer code⁵. The objective was to obtain information which would help to estimate the power effect in the LOPI comparisons mentioned above.

The first step of the THTD analysis was to test the code's ability to predict the maximum coolant temperature rise during LOPI-3. For this calculation, fuel-cladding heat transfer coefficients were obtained from the LIFE-4 code at the axial midplane. At other axial locations, LIFE-4 values were adjusted using measured post-irradiation gap sizes. The fuel-cladding h_{gaps} used at two axial locations in the fuel pin are shown in Figures 5 and 6. Figure 5 (nominal curve) shows the fuel-cladding gap conductance values used at the axial midplane and Figure 6 (nominal curve) shows the gap conductance values used at the top of the pin. The results of the THTD LOPI-3 calculation are shown in Figure 7. The maximum coolant temperature rise calculated by THTD during LOPI-3, using the power assumed in Calculation Set A, was 511°F compared to 520°F indicated by Thermocouple No. 3-6. This result is sufficiently accurate to establish the validity of the THTD model.

The second step in the analysis was to evaluate the sensitivity to power of the coolant temperature rise during LOPI-3. These results were needed in order to compare the coolant temperature data in cases where power level differed between two LOPI transients. To accomplish this, fuel structure

Figure 5

Time Dependence of Fuel-Cladding Gap Conductance Assumed for the Fuel Column Axial Midplane During LOPI-3 in THTD Analysis

Figure 6

Time Dependence of Fuel-Cladding Gap Conductance Assumed For
the Top of the Fuel Column During LOPI-3 in THTD Analysis

FIGURE 7

Maximum Coolant Temperature. Increase During
LOPI-3 Compared to Data From Thermocouple No. 3-6

and gap conductance history were held at their nominal LOPI-3 values and power was allowed to vary over the range of interest in LOPI-1 through LOPI-4. Note that this procedure ignores the fact that fuel-cladding gap conductance is a function of pin power level. The procedure also ignores any changes in fuel pin heat transfer characteristics that might be caused by differences in burnup. As a result, the calculation indicates how LOPI coolant temperatures would change with power in the absence of any differences in gap conductance or fuel structure. By comparing the measured behavior with the predicted effect of power, this analysis can be used to deduce the existence in the data of some dependence on gap conductance or fuel structure.

Figure 8 shows the results of the power-sensitivity analysis. In Figure 8, the calculated maximum coolant temperature increase is shown as a function of fuel power. Fuel power is normalized to the LOPI-3 initial power level assumed in Calculation Set A with the calculated coolant temperature increase adjusted to 520°F rather than 511°F at that point. Also shown in Figure 8 are the average measured coolant temperature rises for all of the LOPI tests of interest. These are designated according to the LOPI test number and are plotted at three different power values corresponding to the three power level estimates shown in Table 4. For example, the point designated 1(A) represents the measured maximum coolant temperature in LOPI-1 and the power assumed for LOPI-1 in Calculation Set A. The measured maximum coolant temperature rise for each LOPI test in Figure 8 is an average value calculated from the data in Table 3. The algorithm used to compute the average is:

$$\text{Average Coolant Temperature Increase for LOPI-X} = 520^{\circ}\text{F} \times \frac{\sum_i \Delta T_i \text{ LOPI-X}}{\sum_i \Delta T_i \text{ LOPI-3}} \quad (2-1)$$

where

520°F = the LOPI-3 coolant temperature increase indicated by Thermocouple No. 3-6 (i.e., the increase from steady state pretransient temperature to the peak temperature during LOPI-3).

$\sum_i \Delta T_i$ = coolant temperature increase for Thermocouple i (steady state to peak transient) summed over all thermocouples in Table 3 for LOPI-X or LOPI-3.

Using Figure 8 as a reference, data from pairs of LOPI transients can be compared to see if differences in power between LOPIs are sufficient to explain differences in coolant temperatures, or if burnup effects appear to be present. The pairs of LOPIs discussed below are the pairings in which the effects of power and fuel burnup were not separable in Section 2.1 simply by inspection of the data.

LOPI-1 vs. LOPI-3

As noted in Section 2.1, LOPI-3 pin-to-coolant heat transfer was smaller than that during LOPI-1. However, LOPI-3 power was also lower than LOPI-1 power. Therefore, it was not clear whether reduced power or higher burnup caused LOPI-3 pin-to-coolant heat transfer to be lower. Figure 8 shows that LOPI-1 power would have to be 10% higher than LOPI-3 power to explain the observed difference in pin-to-coolant heat transfer. This is well outside the range of uncertainty in power. Therefore, it is concluded that the difference between LOPI-1 and LOPI-3 coolant temperatures was caused almost entirely by fuel structure effects (i.e., fuel restructuring and gap closure). Thus, this comparison supports the hypothesis of Section 2.1, and this conclusion is unaffected by the uncertainty in assembly power.

FIGURE 8
 THTD-Predicted Maximum Coolant Temperature Increases for LOPI-3 vs. Initial
 Power Compared to Measured Maximum Coolant Temperature Increase for Other LOPI's.

LOPI-2A vs. LOPI-3

The measured coolant temperature increase for LOPI-2A falls above the THTD-predicted coolant temperature increase for LOPI-2A at the powers assumed in Calculation Sets A and B and below the THTD-predicted coolant temperature increase for LOPI-2A using the LOPI-2A power assumed in Calculation Set C. The LOPI-2A power estimates from Calculation Sets A and B are so close to the predicted curve in Figure 8 that one must assume that coolant temperatures differ in LOPI-2A and LOPI-3 only because power differs. If fuel restructuring and gap closure had any effect in this burnup interval, that effect is too small to be significant in Figure 8.

A different interpretation results if one accepts the LOPI-2A power estimates from Calculation Set C. As shown in Figure 8, measured coolant temperatures during LOPI-2A are significantly lower than would be expected based on the power difference between LOPI-2A and LOPI-3 when Set C powers are attributed to LOPI-2A. This implies that increasing burnup caused an increase in pin-to-coolant heat transfer in the burnup interval between LOPI-2A and LOPI-3. This would be contrary to the burnup effect deduced from the rest of the W-1 data, and would contradict the hypothesis of Section 2.1. The majority of the available evidence suggests that LOPI-2A powers from Set C are incorrect. Therefore, the Set C data point in Figure 8 was neglected, and it is concluded that the effect of burnup cannot be distinguished by comparison of the LOPI-2A and LOPI-3 data.

LOPI-3 vs. LOPI-4

The measured coolant temperature increase during LOPI-4 in Figure 8 is well below the predicted value at that power (~715 kw). This could be due

to a) burnup-independent processes within the fuel pin which reduced the heat loss characteristics of the pin between the times of LOPI-3 and LOPI-4 (e.g., fuel cracking or fuel thermal expansion) or b) incorrect estimates of power for LOPI-4 by all three power calculation sets. Since it is unlikely that three independent estimates of power which agree so closely are very much in error, it is concluded that the estimated LOPI-4 power is correct and the ability of the fuel pin to lose heat during a LOPI transient was significantly impaired between the times of LOPI-3 and LOPI-4. The process(es) which caused this change are not burnup-related because there was no significant increment in burnup between the two LOPIs.

Since the W-1 experiment operated at full power for a significant length of time prior to LOPI-3, and for only a few minutes prior to LOPI-4, it is virtually certain that the W-1 fuel was extensively cracked prior to LOPI-4 and that cracking was less extensive prior to LOPI-3. This suggests that fuel cracking might have caused reduced pin-to-coolant heat flow during LOPI-4. In addition, the increased power in LOPI-4, relative to LOPI-3 would be expected to have increased fuel-cladding contact pressure and gap conductance. Fuel cracking may have reinforced the effect of the power increase, but uncertainties in the effect of power are too large to test this theory.

In summary, comparison of LOPI-3 data with LOPI-4 data provides reasonably clear evidence that pin-to-coolant heat transfer was lower during LOPI-4 than during LOPI-3. In our opinion, fuel-cladding gap conductance was higher prior to LOPI-4 than it was prior to LOPI-3, because power was higher prior to LOPI-4. If one accepts this, the LOPI-3 vs. LOPI-4 comparison indirectly supports the hypothesis of Section 2.1 by showing that high pretransient gap conductance leads to low pin-to-coolant heat transfer during a subsequent LOPI.

This is discussed further in Section 2.2.2. If one does not accept the opinion that gap conductance was higher prior to LOPI-4, then uncertainty regarding the effects of fuel cracking and increased power prevents firm conclusions regarding the cause of reduced heat transfer from being drawn from the LOPI-3 vs. LOPI-4 comparison.

LOPI-2A vs. LOPI-4

Power was higher during LOPI-4 than during LOPI-2A, and pin-to-coolant heat transfer was also higher during LOPI-4. Therefore, it is not clear by simple inspection of the data whether the increase in pin-to-coolant heat transfer during LOPI-4 was caused by the higher power or if a fuel structure effect was also present. Figure 8 suggests that LOPI-4 heat transfer was not as large as would be expected from the difference in powers. Therefore, one might conclude that burnup acted to reduce pin heat transfer between LOPI-2A and LOPI-4. However, based on the comparison between LOPI-3 and LOPI-4, we know that some mechanism unrelated to burnup acted to reduce LOPI-4 heat transfer. Because of this, no burnup effect can be proven based on comparison of data from LOPI-2A and LOPI-4.

Based on the steady state data from in-fuel thermocouples, it seems clear that some gap closure and fuel restructuring occurred between LOPI-2A and LOPI-4. As discussed in connection with the LOPI-3 vs. LOPI-4 comparison, the power increase prior to LOPI-4 is believed to have increased the pre-transient fuel-cladding gap conductance. This, in turn, is believed to have reduced pin-to-coolant heat transfer during LOPI-4. Although it is possible that heat transfer during LOPI-4 was low relative to that during LOPI-2A entirely because of some unidentified burnup-independent mechanism, it is most likely that heat transfer capability was reduced between LOPI-2A and

LOPI-4 by a combination of burnup-related changes in fuel structure and higher gap conductance caused by the power increase prior to LOPI-4. It is concluded that the LOPI-2A vs. LOPI-4 comparison indirectly supports the hypothesis of Section 2.1 in the same way that the LOPI-3 vs. LOPI-4 comparison supported this hypothesis.

LOPI-1 vs. LOPI-4

As discussed in Section 2.1, comparison of LOPI-1 data with LOPI-4 data provides a clear indication that pin-to-coolant heat transfer was lower during LOPI-4 than during LOPI-1. Even though LOPI-4 power was higher, pin-to-coolant heat transfer was lower during LOPI-4. While only 3 out of 5 thermocouples indicated larger coolant temperature increases during LOPI-1, the evidence is quite clear. Even if the thermocouple data showed no difference between LOPI-1 and LOPI-4, one would conclude that heat transfer was lower during LOPI-4 because of the higher LOPI-4 power.

Figure 8 strengthens the conclusion that heat transfer was lower during LOPI-4 than during LOPI-1 because it shows that LOPI-4 coolant temperatures would be expected to be 40°C to 60°C higher than measured based on the difference in powers. However, the comparison of LOPI-3 vs. LOPI-4 suggests that the cause of the LOPI-1 vs. LOPI-4 difference in heat transfer is not entirely related to burnup. The most likely explanation is that the observed effect is caused by a combination of burnup effects and the effect of the power increase prior to LOPI-4. This conclusion is similar to that derived from comparison of LOPI-2A and LOPI-4. In the LOPI-1 vs. LOPI-4 comparison, however, the burnup effect is known to be significant because of the comparison between LOPI-1 and LOPI-2A.

The results of the data comparisons made in this section are summarized in Table 7. Comparison of Tables 6 and 7 shows that the analysis of Figure 8 has strengthened support for the hypothesis that fuel restructuring and gap

closure lead to lower pin-to-coolant heat transfer during a LOPI transient. A significant result of the analysis is the finding that power differences between LOPI-1 and LOPI-3 are not large enough to explain the observed difference in heat transfer. A fuel structure-gap size effect must be postulated to explain these results.

Perhaps the most significant result of the analysis of Figure 8 is the finding that pin-to-coolant heat transfer is lower than expected when power increases prior to a LOPI transient, even when burnup is virtually unchanged. This suggests that reduced pin-to-coolant heat transfer during a LOPI transient is caused by low fuel temperature prior to the transient. This possibility is investigated in Section 2.2.2.

Table 7

Support for the Hypothesis
After Power and Burnup Effects are Separated

	<u>Calc. Set A</u>			<u>Calc. Set B</u>			<u>Calc. Set C</u>		
	<u>True</u>	<u>Unde- terminated</u>	<u>False</u>	<u>True</u>	<u>Unde- terminated</u>	<u>False</u>	<u>True</u>	<u>Unde- terminated</u>	<u>False</u>
LOPI-1 vs. LOPI-2A	x			x			x		
LOPI-1 vs. LOPI-3	x			x			x		
LOPI-1 vs. LOPI-4	x			x			x		
LOPI-2A vs. LOPI-3		x			x				x
LOPI-2A vs. LOPI-4	x*			x*			x*		
LOPI-3 vs. LOPI-4	x*			x*			x*		

*Supports the hypothesis indirectly, and only if pretransient gap conductance is assumed to be higher prior to LOPI-4 than it was prior to LOPI-3.

2.2.2 Effect of Fuel-Cladding Gap Conductance

The data evaluation and analysis presented in the first part of Section 2.0 have shown that maximum coolant temperature during a LOPI transient decreases as burnup increases. In the W-1 experiment, the burnup effect is reinforced by the effect of decreasing pin power, so the burnup effect is clearly observable only when comparing data from LOPI-1 with data from LOPI-2A, LOPI-3, and LOPI-4. The first-order effect of power is demonstrated analytically in Section 2.2.1. A second-order effect of power appears to be demonstrated by comparison of data from LOPI-3 with that from LOPI-4. However, fuel cracking occurs between LOPI-3 and LOPI-4, and this produces uncertainty in the interpretation of the data.

The analysis and discussion presented in this section are intended to clarify the mechanisms responsible for the observed trends in the data. First, it is helpful to review the changes in fuel structure and gap size that are believed to have occurred during the W-1 experiment, based on the analysis of steady-state in-fuel thermocouple data. Prior to LOPI-1, the steady state data indicate that fuel temperatures were very high, because fuel restructuring and gap closure had just begun to occur. Under these conditions, one would expect gap conductance to change very little during a LOPI transient, because a small amount of additional opening of the fuel-clad gap would be counteracted by the improved thermal conductivity of the gas in the gap caused by high gas temperature.

Prior to LOPI-2A, the steady-state data indicate that fuel restructuring and gap closure had progressed very close to completion (i.e., little change was observed between LOPI-2A and LOPI-3). As a result, fuel temperature was lower prior to LOPI-2A than it was before LOPI-1 and gap conductance was higher. During the LOPI-2A transient, gap conductance was almost certainly

higher than it was during LOPI-1 because of the smaller fuel-cladding gap. Fuel temperature was also lower prior to LOPI-3 than before LOPI-1, gap conductance was higher, and transient gap conductance was probably higher during LOPI-3 than during LOPI-1.

Since transient gap conductance (and fuel thermal conductivity) were almost certainly higher during LOPI-2A and LOPI-3 than during LOPI-1, these burnup-related changes do not explain the observed changes in coolant temperature, which indicate that pin-to-coolant heat transfer was lower during LOPI-2A and LOPI-3 than during LOPI-1. Apparently, the effect of high gap conductance (and fuel conductivity) during the transients was less important in the W-1 experiment than the effect of low pretransient fuel temperature. To test this interpretation of the data, analyses were performed to determine the relative effects of pretransient and transient fuel-cladding gap conductance on coolant temperatures during a W-1 LOPI transient.

Figures 9 and 10 show the results of a study performed to separate the effect of pretransient gap conductance from the effect of transient gap conductance during LOPI-3. Figure 9 shows three calculated coolant temperature histories during LOPI-3. The first calculation is the nominal prediction shown previously in Figure 7. As shown in Figure 7, this calculation produces reasonable agreement with Thermocouple No. 3-6. Gap conductance values used in this nominal case are best estimates based on LIFE-4 results. The second case illustrated in Figure 9 uses 150% of the nominal-case gap conductance values for steady state and throughout the LOPI-3 transient. As shown in Figure 9, maximum coolant temperature during the LOPI transient is approximately 20°F (11°C) lower when gap conductance is increased in this manner. This result confirms the interpretation of the W-1 data

FIGURE 9

Effects of Increased Gap Conductance During Steady-State and Transient, Increased Transient Gap Conductance Only, and Reference Gap Conductance During Steady-State and Transient on Maximum Coolant Temperatures Increase During LOPI-3.

discussed above, because it shows that coolant temperatures are expected to be lower during a LOPI transient, even though transient fuel-cladding gap conductance is higher, when some mechanism acts to increase both steady state and transient gap conductance. The third coolant temperature history in Figure 9 was obtained by increasing gap conductance to 150% of its nominal value during the LOPI-3 transient only. Steady state gap conductance and fuel temperatures were identical to those of the nominal case. This third case confirms the validity of the analysis by producing the expected result: all else being equal, an increase in transient gap conductance produces higher coolant temperatures during a LOPI transient. The magnitude of the effect is relatively large (approximately 60°F, or 33°C), indicating that the results of the second case were produced by two relatively large, but competing, effects. It is inferred from Figure 9 that coolant temperatures would have decreased by 44°C (80°F) if pretransient gap conductance had been increased to 150% of its nominal value.

Figure 10 confirms the results of Figure 9. In Figure 10, gap conductance was reduced to 50% of its nominal value. When both steady state and transient gap conductance values are decreased by this amount, coolant temperatures during LOPI-3 are predicted to increase. Note that the magnitude of the change in transient coolant temperature is consistent with the observed differences shown in Table 5 and the power effects illustrated in Figure 8; gap conductance is predicted to change coolant temperature by approximately 20°F (11°C), power is predicted to cause a change of 10°F to 40°F (5°C to 22°C), and the observed differences range from 5°F to 60°F (2°C to 33°C).

The analysis of Figures 9 and 10 supports the conclusion that the decrease in pin-to-coolant heat transfer during the W-1 LOPI transients that is observed as burnup increases is caused by a decrease in pretransient

FIGURE 10

Effects of Reduced Steady-State and Transient Gap Conductance
Reduced Transient Gap Conductance Only, and Reference Steady-
State and Transient Gap Conductance on Maximum Coolant Temper-
ature Increase During LOPI-3.

fuel temperature rather than some unforeseen burnup-related reduction in transient gap conductance. The analysis also suggests an explanation for the fact that pin-to-coolant heat transfer during LOPI-4 was found in Figure 8 to be lower than would be expected based on pin power during LOPI-4. The absolute value of heat transfer to the coolant was higher during LOPI-4 than during LOPI-3 and fuel temperatures were higher before the transient, but coolant temperature was not as high during LOPI-4 as the high power would suggest. Since the analysis of Figure 8 was performed by assuming that gap conductance was constant at all powers, one need only hypothesize that gap conductance was higher prior to LOPI-4 than it was before LOPI-3 to explain why transient heat transfer was lower than predicted during LOPI-4. Figure 9 shows that increased pretransient gap conductance would be expected to have this effect.

Gap conductance did increase substantially between LOPI-3 and LOPI-4. This is shown by the in-fuel thermocouple data. Fuel inner surface temperatures indicated by the midplane thermocouples showed that fuel temperatures prior to LOPI-4 were 100°F (55°C) higher than they were prior to LOPI-3. However, an analysis of the expected increase in fuel temperature showed that fuel temperatures would have increased by 300°F (167°C) if gap conductance had been held constant. It is concluded that the 10% power increase that occurred between LOPI-3 and LOPI-4 produced a substantial increase in fuel-clad gap conductance. Figure 9 indicates that this pretransient gap conductance effect is sufficient to explain the lower-than-expected heat transfer to the coolant that was observed during LOPI-4. Therefore, reduced transient gap conductance or fuel conductivity due to fuel cracking or other mechanisms need not be postulated in order

to explain the data. Figures 9 and 10, along with the W-1 data discussed above, indicate that coolant temperatures during a LOPI transient are reduced whenever pretransient fuel temperatures are reduced, whether this is caused by fuel restructuring associated with increasing burnup or by shorter-term phenomena such as power cycling.

Additional evidence that coolant temperatures during the W-1 LOPI transients were affected by pretransient fuel temperatures, rather than burnup-related reductions in transient gap conductance or fuel conductivity, is provided by an analysis of data from Thermocouple No. 3-3 (see Table 5). This thermocouple was located lower along the active fuel column than any of the thermocouples analyzed by G.E. Therefore, coolant temperatures recorded by this thermocouple would be expected to be least affected by fuel with a high degree of fuel restructuring and gap closure. In fact, this thermocouple might be expected to record the behavior of fuel near the bottom of the pin, where little restructuring and gap closure occurred. The data from Thermocouple No. 3-3 were evaluated assuming that little gap closure or fuel restructuring occurred below this thermocouple. In this situation, one would expect little or no effect of burnup to be apparent in the data, which would make other effects easier to identify.

As shown in Table 5, the data from Thermocouple No. 3-3 appear to be inconsistent with the data from the other four thermocouples. However, in the absence of gap closure and fuel restructuring, the data interpretation described above suggests that these data should be explainable by considering pretransient pin power alone. Between any two LOPI transients, one would expect higher coolant temperatures to occur during the transient with higher pin power (i.e., fuel temperature). From Table 4 and Figure 8, the correct power to be assigned to each LOPI transient was taken to be the

middle estimate from among Sets A, B and C. This yields estimates of 651.4 Kw, 662.5 Kw, 668.0 Kw, and 714.1 Kw for LOPIs-3, -1, -2A, and -4, respectively. Using these powers, one would expect LOPI-2A transient coolant temperatures to be higher than LOPI-1 temperatures, LOPI-1 to be higher than LOPI-3, LOPI-2A to be higher than LOPI-3, and LOPI-4 to be higher than any other temperatures. This is precisely what was recorded by Thermocouple No. 3-3, as shown in Table 5. These results are regarded as confirmation that coolant temperatures during a LOPI transient are primarily dependent on pretransient fuel temperature, and that burnup effects other than gap closure and fuel restructuring are relatively unimportant under the conditions of the W-1 experiment.

2.2.3 Transient Central Fuel Temperature Histories

The in-fuel thermocouple records indicate that some very different processes occur at the axial midplane than occur at the upper end of the pin. Figure 11 shows the temperature histories of the central fuel region at the axial midplane during LOPIs-I, -2A, -3, and -4, as recorded by Thermocouple No. 22-6. An interesting feature of this comparison is the presence of progressively larger increases in temperature during the initial 1-1.5 sec of successive LOPI tests. Because of the monotonic nature of these temperature surges, they are believed to be valid evidence of actual physical changes in this region of the fuel. The data from Thermocouple No. 22-5, near the top end of the fuel, is very different from that shown in Figure 11. Figure 12 shows the central fuel temperature histories at the top of the fuel pin during LOPIs-1, -2A, -3, and -4, as recorded by Thermocouple No. 22-5. Aside from the lower temperatures, another difference from the histories shown in Figure 13 is apparent. The curves are generally very smooth, with none of the upward surges in temperature noted in Figure 11. This means that the fuel temperature required to activate the processes indicated by the temperature histories of the axial midplane region is higher than that of the top end of the fuel column.

The detailed thermal model in THTD allows analysis of the effects of changes in geometry and materials properties during a transient. Therefore, attempts were made to duplicate the central fuel temperature history in-

licated at the axial midplane for LOPI-3 using THTD. Figure 13 shows how the central fuel temperature at the axial midplane of the pin is predicted by THTD to respond to step changes in the fuel-cladding gap conductance at 0.0 sec. into the transient. In Figure 13, a step reduction of 50% in the gap conductance at 0.0 seconds causes the central fuel temperature at the axial midplane to increase 40°F. This is much less than the 204°F rise indicated by Thermocouple No. 22-6 in LOPI-3 and the 600°F rise in LOPI-4. Step changes in the conductance of the fuel-cladding gap do not appear to be the cause of the central fuel temperature increases observed in LOPI-3 and LOPI-4.

Other attempts to duplicate the central fuel temperature history at the axial midplane were made by adjusting the conductance of the gap between the thermocouple and the inner surface of the fuel (the inner gap) and by increasing the heat generation rate in the thermocouple. The results of these calculations are shown in Figure 14. In Figure 14, the data from Thermocouple No. 22-6 are compared to two THTD-predicted central fuel temperature histories. These temperature histories are based on a reduced inner gap conductance (by a factor of 4) in one case and the combination of reduced inner gap conductance (by a factor of 8) and increased heat generation (by a factor of 3) in the thorium insulation of the in-fuel thermocouple in the second case. In both THTD cases, the changes in gap conductance and heat generation rate were assumed to occur at 0.0 seconds into the transient. In neither case, as shown in Figure 14, was the predicted central fuel temperature increase even close to that indicated by the thermocouple data.

These results indicate that changes in outer (fuel-cladding) or inner (thermocouple-fuel) gap conductance are not the cause of the observed fuel temperature surges in the axial midplane region. It is possible that the operative mechanism was the opening of a circumferential crack in the fuel near the fuel inner surface soon after the beginning of the transient. A second (and perhaps equivalent) possibility is that fuel vapor deposition on the midplane thermocouple occurred, so that heat generation near the thermocouple was much larger than was assumed in the analysis. This would explain the burnup-related increase in the magnitude of the temperature peak recorded by the in-fuel thermocouples. Unfortunately, post-test examination revealed no significant fuel deposition on the thermocouples, so this theory cannot be proven.

FIGURE 11

In-Fuel Temperature Data For LOPI-1, 2A, 3, and 4
From Thermocouple #22-6, 14" Below Top of Fuel Column

FIGURE 12

In-Fuel Temperature Data For LOPI-1 2A, 3, and 4
From Thermocouple #22-5, 2" From Top of Fuel Column

Figure 13

Dependence of Predicted In-Fuel Thermocouple Temperatures
on Fuel-Cladding Gap Conductance During LOPI-3

Figure 14

THTD Predicted In-Fuel Thermocouple Temperatures at Axial
Midplane Compared to Data From Thermocouple #22-6 During LOPI-3

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