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Determination of the Bias in LOFT Fuel Peak Cladding Temperature Data from the Blowdown Phase of Large-Break LOCA Experiments

Prepared by
V. T. Berta, R. G. Hanson, G. W. Johnsen, R. R. Schultz

Idaho National Engineering Laboratory
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ABSTRACT

Data from the Loss-of-Fluid Test (LOFT) Program help quantify the margin of safety inherent in pressurized water reactors during postulated loss-of-coolant accidents (LOCAs). As early as 1979, questions arose concerning the accuracy of LOFT fuel rod cladding temperature data during several large-break LOCA experiments. This report analyzes how well externally-mounted fuel rod cladding thermocouples in LOFT accurately reflected actual cladding surface temperature during large-break LOCA experiments. In particular, the validity of the apparent core-wide fuel rod cladding quench exhibited during blowdown in LOFT Experiments L2-2 and L2-3 is studied. Also addressed is the question of whether the externally-mounted thermocouples might have influenced cladding temperature. The analysis makes use of data and information from several sources, including later, similar LOFT Experiments in which fuel centerline temperature measurements were made, experiments in other facilities, and results from a detailed FRAP-T6 model of the LOFT fuel rod. The analysis shows that there can be a significant difference (referred to as bias) between the surface-mounted thermocouple reading and the actual cladding temperature, and that the magnitude of this bias depends on the rate of heat transfer between the fuel rod cladding and coolant. The bias is positive valued when the actual (calculated) cladding temperature is greater than the measured cladding temperature. The results of the analysis demonstrate clearly that a core-wide cladding quench did occur in Experiments L2-2 and L2-3. Further, it is shown that, in terms of peak cladding temperature recorded during LOFT large-break LOCA experiments, the mean bias is 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ$ F). A thermocouple fin effect was not found in the blowdown phase (0-30 s). The best-estimate value of peak cladding temperature for LOFT LP-02-6 is 1104.8 K. The best-estimate peak cladding temperature for LOFT LP-LB-1 is 1284.0 K.

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EXECUTIVE SUMMARY

The Loss of Fluid Test (LOFT) Program conducted at the Idaho National Engineering Laboratory provided an important body of data on the behavior of pressurized water reactors during postulated loss-of-coolant accidents (LOCAs) and other transients. In particular, data from the LOFT Program played a significant role in helping to quantify margins of safety during design-basis, large-break LOCAs.

A total of five large-break LOCA experiments were carried out in LOFT, three under U.S. Nuclear Regulatory Commission (USNRC) sponsorship and two under joint sponsorship of the USNRC and the Organization for Economic Cooperation and Development (OECD). In three of these experiments (L2-2, L2-3, and LP-02-6), the thermal behavior of the core differed markedly from that in the other two experiments (L2-5 and LP-LB-1). Specifically, widespread cooling of the core occurred during the early part of the blowdown phase in the former experiments that was absent in the latter experiments. In fact, experiments LP-02-6 and LP-LB-1, which were conducted during the later OECD-LOFT program phase, were in part designed to better understand differences in blowdown core behavior noted in the earlier experiments.

The occurrence of significant core cooling during blowdown was initially unexpected, and was soon understood to be a consequence of the manner in which the primary reactor coolant pumps were operated during the experiments. In the experiments in which the coolant pumps continued to run (L2-2 and L2-3) or were tripped at the start of the test and followed a normal coastdown (LP-02-6), a short but significant period of positive core flow occurred between about 3 s and 8 s into the transient. Analysis showed that during this period, reactor coolant pump flow exceeded break flow, causing temporary reestablishment of positive (upward) flow through the core.

Because the LOFT fuel rod cladding thermocouples were mounted on the external surface of the cladding and protruded into the coolant stream, questions arose regarding the validity of the cladding temperature data, particularly the

extensiveness of the cooling of the clad during blowdown. Some hypothesized that cooling of the thermocouples may have occurred while the cladding remained at an elevated temperature. An alternative hypothesis was that the thermocouples may have enhanced the cooling of the cladding over that which would have otherwise occurred.

Because LOFT data have played an important role in reactor safety in general, it is important to understand the accuracy of the cladding temperature data. In particular, since the cladding temperature data were used to assess the uncertainty in best-estimate large-break LOCA (LBLOCA) calculations, it is essential to determine if any undue error was introduced into that study because of inaccuracies in the data.

In the study reported here, a systematic analysis of the LOFT large-break experiments and related information was undertaken. The principal objectives of the study were to determine:

- Whether the cladding thermocouples provided a reliable indication of core cooling during blowdown
- Whether the cladding thermocouples influenced the cooling of the cladding
- What bias exists in the cladding temperature data due to the external location of the thermocouples
- To what extent, if any, does the estimated bias in the data alter the conclusions of the LBLOCA Uncertainty Study.

To address these issues, this study relies primarily on the evidence provided by the LOFT data itself, supplemented by analyses using a detailed FRAP-T6 model of the LOFT fuel rod. The inclusion of fuel centerline temperature measurements in the last two experiments (LP-02-6 and LP-LB-1) provided key information upon which to build a coherent picture of the actual cladding temperature response during LOFT LBLOCA experiments.

Specifically, the issues were addressed by using data collected by thermocouples located at the centerline of several LOFT fuel rods in conjunction with the saturated fluid temperature in the LOFT core. These data alone are sufficient to calculate, by trial and error, the heat transfer mode that the LOFT fuel rods were subjected to during the enhanced cooling phase of the transient. The procedure was centered on the use of an assessed LOFT fuel rod model for the FRAP-T6 code. The fluid saturation data served as an initial and boundary condition, together with fuel rod physical properties, for the FRAP-T6 model, to determine the cladding surface heat flux required to produce a measured centerline thermocouple response. A number of calculations were required, using a trial and error approach, to match the measured centerline temperature. Following solution convergence, the corresponding calculated cladding surface temperature was then compared to the measured value to estimate the difference between actual (calculated) and measured cladding temperature. The method, therefore, not only provided further insight into the issue of blowdown rewet, but also a quantitative evaluation of thermocouple bias.

Clearly the LOFT LBLOCA cladding temperature data have instances in which the externally mounted thermocouples did not provide an accurate indication of actual cladding temperature. These instances generally occurred under conditions of rapid cooling in the core. During reflood, for example, some thermocouple data show several apparent quenching and reheating cycles prior to final quench of the fuel rod. The rate of reheating that occurs during these cycles is unphysically rapid (if it were representative of the cladding), from which it can be concluded that the thermocouple was quenching while the cladding was not. Given that this behavior can occur, the issue of the validity of the early blowdown cooling in L2-2, L2-3, and LP-02-6 is quite understandable.

That there was a period in which enhanced cooling could have taken place is of little controversy. Coolant flow balances and other corroborating data clearly show that a brief reestablishment of positive core flow had occurred. But based on the data from L2-2 and

L2-3 alone, it would be difficult to establish that the fuel rod cladding had been cooled as extensively as the thermocouple data implied. Fortunately, the similarity of experiments L2-3 and LP-02-6 (where the blowdown cooling occurred), and the similarity of Experiments L2-5 and LP-LB-1 (where no blowdown cooling occurred) created the opportunity to study the fuel centerline temperature data (available in LP-02-6 and LP-LB-1) as an independent source of information on fuel behavior during blowdown. Two key findings came from analyzing the fuel centerline temperature data in these latter experiments:

- The significant difference in fuel centerline temperature response between LP-02-6 (blowdown cooling) and LP-LB-1 (no blowdown cooling) was entirely consistent with the corresponding difference in indicated cladding temperature response.
- The similarity of fuel centerline temperature response in LP-02-6 of instrumented rods (cladding surface thermocouples) and uninstrumented rods (bare cladding surface) indicates clearly that the presence of external thermocouples neither precipitated nor enhanced cooling on rods equipped with them.

However, quantitative insight into external thermocouple behavior was gained by using the approach outlined above together with the data from the LP-02-6 and LP-LB-1 experiments. Successive iterations were performed to provide a cladding surface heat flux time history that produced the best agreement between the calculated and measured fuel centerline temperature for an instrumented fuel rod at the peak power elevation. The corresponding calculated cladding temperature was compared with the measured cladding temperature. For both LP-02-6 and LP-LB-1, the calculated cladding temperature exhibited the same behavior as the measured cladding data. However, the external thermocouple response tended to lag the response calculated for the cladding during the heatup (poor cooling), reach a lower peak temperature than the cladding (a bias that is positive by definition), and lead the response of the cladding during cooling.

To determine what systematic error in peak cladding temperature might be embedded in the LOFT LBLOCA data, the FRAP-T6 code was again employed. For LP-02-6, FRAP-T6 calculations were done using the heat flux profiles mentioned earlier, except that the model was revised to reflect the geometry of an uninstrumented rod (i.e., no centerline thermocouple). The resulting prediction of cladding surface temperature therefore represented best-estimate calculations of fuel rods with no instrumentation. The FRAP-T6 calculations of peak cladding temperature were compared with measured values in the 26–28 in. elevation region. A total of 10 measurements were compared with the FRAP-T6 calculations. The average systematic error in the PCT measurements was 8.0 K (14.4°F).

In LP-LB-1, there were 10 rods having both fuel centerline and cladding thermocouples at the 27 in. elevation. A FRAP-T6 calculation of the fuel centerline temperature was made for each of the rods. Iterations on the surface heat flux were carried out until the calculation agreed with the measured centerline temperature in each rod to within 2 K (3.6°F). Comparisons of the calculated and measured cladding temperatures gave 10 values which averaged 14.7 K (26.5°F). The twenty values from both experiments combined gave a mean systematic error, referred to as the mean bias in the thermocouples, of 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$).

The 2-sigma uncertainty in the mean bias was determined from 2-sigma uncertainty in (a) the population mean, (b) the fuel centerline temperature data, (c) the cladding temperature data, and (d) the FRAP-T6 calculation of cladding temperature. The 2-sigma uncertainty was calculated to be 16.2 K (29.2°F).

The mean bias of 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$) is considered to be applicable to the PCT data set obtained from all LOFT large-break transients, even though only two of the five large-break transients were used.

Other, less direct sources of information were investigated with regard to the bias question. In particular, data from experiments carried out in the Power Burst Facility (PBF) and in the COSIMA facility were examined, since in both LOFT-type external cladding thermocouples were used. Biases calculated from the PBF data are 85 K (153°F) during blowdown and 27 K (48.6°F) during reflood, and for the COSIMA experiments a blowdown bias of 15 K (27°F) was calculated. Finally, metallurgical examination of the zircaloy cladding from LOFT-type fuel rods showed reasonably close agreement between measured peak cladding temperature (external surface thermocouple) and that calculated (based on metallurgical composition). Differences in peak temperatures ranged from -14 to 33 K (-25.2 to 59.4°F).

The LBLOCA Uncertainty Study, mentioned earlier, made use of peak cladding temperature data from LOFT LBLOCA experiments. In that study, it was assumed that a 55.6 K (100°F) bias existed in the LOFT data. Since the bias determined in the present study, 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$), is bounded by the assumed bias, 55.6 K, there is no effect on the conclusions reached in that study stemming from the results of this study.

The analyses of the LOFT LP-02-6 and LP-LB-1 data in the blowdown phase indicated that there was no measurable fin effect of the thermocouple cables on the cladding temperature. Fuel rods with and without cladding external surface mounted thermocouples were found to have the same thermal behavior. This is in marked contrast to data from the same thermocouples in the reflood phase which show large fin effects during reflood.

The results of the analyses presented herein lead to a recommendation for the value of the peak cladding temperature attained in the LOFT large break transients LP-02-6 and LP-LB-1. The peak cladding temperature values are 1104.8 K for LP-02-6 and 1284.0 K for LP-LB-1.

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ACRONYMS

CSAU	Code scaling, applicability, and uncertainty	LOFT	Loss of Fluid Test
ECCS	Emergency Core Cooling Systems	LTSF	LOFT Test Support Facility
INEL	Idaho National Engineering Laboratory	OECD	Organization for Economic Cooperation and Development
LBLOCA	Large-break loss of coolant accident	UK	United Kingdom
LOCA	Loss of coolant accident	USNRC	U.S. Nuclear Regulatory Commission

Determination of the Bias in LOFT Fuel Peak Cladding Temperature Data from the Blowdown Phase of Large-Break LOCA Experiments

1. INTRODUCTION

During the blowdown phase of two early Loss-of-Fluid-Test (LOFT) Program experiments designed to study cold-leg pipe large-break loss-of-coolant accidents (LBLOCAs),^a the fuel cladding experienced an unexpected thermal quenching (apparently corewide) following initial dryout. Such behavior was indicated by fuel rod cladding thermocouples that were mounted on the cladding external surface. Immediately, questions arose concerning whether: (a) the thermocouple data were representative of the cladding temperature and (b) the thermocouples acted as cooling fins. The work described herein was designed to answer these questions.

1.1 Mission of the LOFT Program

The LOFT Program, carried out at the Idaho National Engineering Laboratory (INEL), was sponsored by the U.S. Nuclear Regulatory Commission (USNRC) as a major part of its water reactor research program.^b The LOFT facility was a unique, large-scale (1/48), integral nuclear experimental system that modeled the key features of a typical pressurized water reactor (PWR). The system was designed to simulate PWR response to various LBLOCAs but was also used to study small break LOCAs and other transients.

a. The instantaneous, double-ended-offset shear break of a primary coolant loop pipe.

b. After completion of the USNRC-sponsored portion of the LOFT program, a consortium of 10 countries, under the auspices of the Organization for Economic Cooperation and Development (OECD), cosponsored with the USNRC an extended research program, referred to as the OECD-LOFT Program.

The primary mission of the LOFT experimental program was to provide data that could be used to evaluate the adequacy of analytical methods (i.e., computer codes) employed to predict full-scale power reactor behavior. In particular, by modeling the LOFT experiments with these codes, insight was gained as to their ability to calculate overall LOCA response, the performance of Emergency Core Cooling Systems (ECCS), and the margin of safety afforded by the engineered safety features. A secondary objective of the program was to identify and understand any unexpected phenomena or thresholds in system behavior, which would ultimately require modeling by the codes.

1.2 Fuel Rod Cladding Surface-Mounted Thermocouple Instrumentation

Prior to conducting any LOFT experiments, extensive thermal-hydraulic analysis was done using the then current state-of-the-art codes, e.g., RELAP3 and RELAP4, in the late 1960s to mid 1970s. These analyses were used in part to guide the design of instrumentation for LOFT. Pre-LOFT experiment thinking, influenced by extensive calculations, predicted a LBLOCA scenario in which rapid depressurization, core heatup, and eventual reflood occurred. Early thermal quenching of the core during blowdown, followed by a second core heatup, was not foreseen nor predicted. Consequently, fuel rod thermocouple instrumentation design was driven by the reliability to provide adequate data for the expected depressurization/core heatup/reflood scenario. Of the two candidate thermocouple designs [(i.e., (a) thermocouples embedded in the interior wall of the cladding facing the fuel pellet gap versus (b) thermocouples attached to the outer surface of the cladding], the latter design was chosen as the more durable approach and was also judged

adequate to accomplish the mission objectives related to the LOFT core thermal-hydraulic response.^c The fuel rod cladding surface-mounted thermocouple design is described in detail in Section 2.

1.3 Enhanced Cooling of Fuel Rods Equipped with Surface-Mounted Cladding Thermocouples During LBLOCA Blowdown

The early focus of the experimental program was on the LBLOCA, which was believed to be the limiting, or most severe, design-basis accident. A total of five large-break LOCA experiments were carried out in LOFT, including three early experiments under USNRC sponsorship and two experiments conducted later under USNRC/OECD sponsorship.

In two of the early cold-leg pipe large-break LOCA experiments (L2-2, L2-3), an unexpected thermal quenching of the fuel rod cladding appeared to have occurred throughout the core during the blowdown phase. None of the computer code calculations had predicted this early quenching of the core. Analysis of the data^d from these and subsequent experiments led to the conclusion that there was a hydrodynamically-induced cooling of the core during blowdown that occurred when the reactor coolant pumps were left running following experiment initiation. Flow balance analyses at the cold-leg loop connections to the vessel showed that a net delivery of coolant to the vessel occurred for a short period following the transition from single- to two-phase flow at the break. This brief window of flow into the vessel (and up into the core) occurred when the reactor

c. As a matter of record, the surface-mounted thermocouple designer's expectations were confirmed in subsequent experiments that did not include a period of enhanced cooling. An example of such an experiment is the LOFT L2-5 experiment.^{1,2}

d. A summary of the analysis of the LOFT LBLOCA data is given in Subsections 3.1, 3.2, 3.3, and 3.4.

coolant pump flow exceeded the break flow. Other system data (e.g., core inlet coolant temperature) tended to substantiate this conclusion. However, because the LOFT fuel rod cladding thermocouples were mounted on the external surface of the cladding and protruded into the coolant stream,^e questions arose as to whether the thermocouples accurately represented the fuel rod cladding thermal behavior since the rates of cladding temperature change were quite large during the enhanced cooling period and the observed fuel rod thermal behavior was not a condition considered when the thermocouples were designed. Preliminary thoughts were that the nature of the thermocouple attachment to the cladding might cause the thermocouple to respond differently than the cladding. Moreover, the thermocouple might behave like a fin, thereby enhancing the cooling of the cladding.

1.4 Investigation of Cladding Surface-Mounted Thermocouple Response

An investigation of these questions was undertaken in the United States by the authors and in the United Kingdom (UK) by Coddington and Gill.³ Coddington and Gill's analysis suggested that the blowdown cladding quench observed in L2-2 and L2-3 may not have occurred, but rather the thermocouples were cooled while the cladding remained at an elevated temperature. Their analysis was based largely on data from the LOFT Test Support Facility (LTSF) and is summarized in Subsection 3.7 and Appendix B. The authors reviewed the LTSF data and concluded that LOFT core thermal-hydraulic conditions were not duplicated in the LTSF experiments.

e. The LOFT fuel rods, built with a 0.422-in. outer diameter and a 0.563-in. rod-to-rod pitch, had a flow area of 0.177 in.² for each subchannel of four rods. If cladding thermocouples were present, i.e., from one to three thermocouples could be present, the blockage would be 1.7% if one thermocouple were present, 3.4% if two were present, and 5.1% if three thermocouples were present. The thermocouples were located on the fuel rod center-to-center diagonal in a four rod subchannel. Each thermocouple occupied 0.062 in. of the 0.375-in. open channel width.

The LTSF experiments were designed to (a) evaluate the effect of cladding surface mounted thermo-couples on fuel rod thermal response and (b) evaluate the ability of a cartridge-type heater rod^f to simulate the thermal response of a nuclear fuel rod during a LBLOCA transient. These objectives were addressed by installing thermocouples embedded in the heater rod cladding inner diameter and attached to the cladding outer surface in the same manner as on the LOFT fuel rods.

The LTSF experiments were conducted with a range of test section inlet flow densities and velocities estimated to include those of the LOFT LBLOCA experiments. However, the test section pressure and noncondensable gas concentrations were not equivalent to those of the LOFT data. Further, the analysis, given in Subsection 3.5 for the first time, shows conclusively that the conditions present in the LOFT core were not duplicated in the LTSF experiments. Unfortunately, the calculations presented herein were not available to the LTSF researchers (see Gottula)⁴ nor to Coddington and Gill since the following work was done over four years after the LTSF experiments were completed.

1.5 Study Objectives

Since data from the LOFT program have played an important role in assessing reactor safety in general, it is important to understand what limitations exist in the accuracy of the cladding temperature data. In particular, since the data have been used to assess the uncertainty in best-estimate LBLOCA calculations,⁵ it is essential to determine if any undue error was introduced into that assessment.

Based on the above considerations, the study described in the following sections was undertaken to better understand the response of the LOFT cladding thermocouples during the

LBLOCA experiments. Specifically, the objectives of the study were:

- To determine whether the measured cladding temperature response during the blow-down phase of Experiments L2-2 and L2-3 was indicative of a genuine core-wide cladding quench.
- To determine if the externally mounted thermocouples enhanced the cooling of the cladding to the extent of precipitating cladding quench that would otherwise not have occurred.
- To determine the bias (temperature difference between the cladding of an uninstrumented rod and the external thermocouple reading on an instrumented rod) that existed when peak temperatures occurred during the LOFT LBLOCA experiments.
- To assess the impact of the cladding measurement bias on the conclusions reached in the best-estimate LBLOCA uncertainty study.⁵

1.6 Organization of the Report

The remainder of the report describes the analyses undertaken and results obtained to fulfill these objectives. Section 2.0 describes the design and as-built configuration of the LOFT fuel rod externally-mounted thermocouples, as well as the fuel centerline thermocouples employed later in the LOFT program. Section 3 presents an analysis of LOFT cladding thermocouple response during LBLOCA experiments, making use of several independent sources of information, and concluding with a determination of peak cladding temperature bias and peak cladding temperature (PCT) values for LOFT large break transients LP-02-6 and LP-LB-1. Section 4 examines the effect of peak cladding temperature bias on the use of LOFT data in the best-estimate LBLOCA uncertainty study. Section 5 presents conclusions from the study. Section 6 contains the references. Appendices A, B, C, and D furnish detailed information supporting the analyses given in Sections 3 and 4.

f. A REBEKA rod, provided by the Karlsruhe Nuclear Research Center in Germany, that features a simulated fuel pellet to cladding gap.

2. LOFT FUEL ROD INSTRUMENTATION

Fuel rod cladding temperature was considered to be the most important experimental measurement in the LOFT program. Accordingly, much effort went into designing an accurate, reliable, and durable thermocouple attachment scheme.^g Underlying, in part, the concept of mounting the thermocouples on the surface of the cladding, was the belief that during the large-break LOCA, the fuel rod heat transfer would remain poor throughout the blowdown until reflood began. This belief was based on the bulk of code predictions for large-break LOCAs at that time. Under such conditions, any fin effect due to the external mounting of the thermocouple would be minimal.

Cladding surface-mounted thermocouples were installed in six of the nine LOFT fuel assemblies. However, all of the discussion in the following sections pertains to the central fuel assembly since the central assembly had rod peaking factors at least 50% greater than those of the peripheral assemblies. The central fuel assembly used for the first large break experiments L2-2 and L2-3 was instrumented with 80 cladding surface-mounted thermocouples located in all four quadrants. The analysis of the data from these thermocouples led to the decision to construct new central fuel assemblies with fuel thermocouples in order to analyze the response of the cladding surface-mounted thermocouples. The fuel assembly used for large break experiments L2-5 and LP-02-6 included only 49 surface-mounted cladding thermocouples located

in two quadrants; however, additional instrumentation was installed, one type of which was the fuel centerline thermocouple. Lastly, the center assembly used for large break experiment LP-LB-1 included 74 cladding surface-mounted thermocouples and 17 fuel centerline thermocouples, located throughout all four quadrants. Axial locations ranged from 2-in. to 62-in.; however, approximately 50% of the thermocouples were located in the high power region of 22–34-in. elevation. This report includes the analysis of the 10 cladding surface-mounted thermocouples in the 26–28-in. (high power) elevation in Experiment LP-02-6, and 10 cladding surface-mounted thermocouples at the 27-in. elevation in LP-LB-1, in the determination of the thermocouple bias.

Following the results of experiments L2-2 and L2-3, which showed enhanced cooling in the blowdown phase, fuel centerline temperature measurements were added to the design of the succeeding LOFT central fuel assemblies. Fuel centerline thermocouples were installed in fuel rods with and without external cladding thermocouples. The purpose of the fuel temperature measurements was to help quantify the uncertainty of the cladding temperature data.

Fuel centerline thermocouples were only located in the center fuel assembly. Four fuel centerline thermocouples were located in two quadrants of the fuel assembly for the L2-5 and LP-02-6 experiments; however, one failed prior to the LP-02-6 experiment. Of the three operational fuel centerline thermocouples in LP-02-6, one was in a rod that had cladding surface-mounted thermocouples, and two were in rods that had no cladding instrumentation. Sixteen operational fuel centerline thermocouples were located in all four quadrants of the fuel assembly for the LP-LB-1 experiment. Ten of them were located at the 27-in. elevation in rods that also had cladding surface-mounted thermocouples, one was located at the 27-in. elevation in a rod that did not have cladding thermocouples, four were located at the 43.8-in. elevation in rods that also had cladding surface-mounted thermocouples, and one was located at the 43.8-in. elevation in a rod that did not have

g. To a degree, the merit of using surface-mounted thermocouples was borne out by subsequent efforts to embed thermocouples in the interior cladding surface of LTSF cartridge-type heater rods and LOFT fuel rods used in the USNRC/OECD cooperative effort. Of the three thermocouples embedded in the interior surface of the LTSF cartridge-type heater rod (using a prototype LOFT fuel rod design), all the primary junctions failed. Of the 28 thermocouples embedded in the interior surface of the LOFT fuel rod cladding for the LP-FP-2 experiment, eight had failed prior to the experiment. Thus, although development of embedded thermocouple technology has progressed, it is still immature.

cladding thermocouples. All operational fuel centerline thermocouples in LP-02-6 and LP-LB-1 are addressed in this report.

The following two subsections describe the cladding surface-mounted and fuel centerline thermocouples, respectively.

2.1 LOFT Cladding Surface Thermocouple Design

The cladding thermocouple cable cross-section is shown in Figure 1. Titanium tubing was used as the sheath material and the insulator material was magnesia (MgO). The thermocouple sheath was welded to the zircaloy fuel rod cladding using a systematic and precise laser welding technique,⁶ at a spacing interval of 1-in. with a weld length of 0.1-0.15 in. Four thermocouple sheaths were welded to the fuel cladding at 90-degree intervals on the surface to maintain symmetry and preclude bowing of the fuel rod with portions being dummy sheaths installed solely for structural considerations.

The thermocouple junction was designed to provide as intimate an attachment to the fuel cladding surface as could be achieved. Figure 2 shows that the flattened junction area provided intimate contact between the sheath, tantalum barrier, and junction weld. The attachment of the thermocouple junction to the cladding was investigated micrographically on a fuel cladding sample on which thermocouples had been welded according to the prescribed specifications. Figures 3 and 4 show cross-sections of two different thermocouple sheaths. In Figure 3, the cross section went through the thermocouple junction; whereas, in Figure 4, the sectioning process went beyond the junction weld and shows the two thermocouple wires. A small gap can be observed between the thermocouple sheath and the cladding in both cases. The gap is completely surrounded by the weld, so that it cannot communicate with the surrounding coolant. The size of the laser weld material assures a large metal area for heat transfer to the junction.

P829-WHT-189-02

Figure 1. LOFT cladding surface thermocouple cable design.

P829-WHT-189-03

Figure 2. LOFT cladding surface thermocouple junction detail.

2.2 LOFT Fuel Centerline Thermocouple Design

Fuel centerline thermocouples were installed at the 27-in.^h elevation in the central fuel assembly used for Experiments LP-02-6 and LP-LB-1, and also at the 43.8-in. elevation in the fuel assembly used for Experiment LP-LB-1. The thermocouples were developed at the Hanford Engineering Laboratory (HEDL). The design specifications for these thermocouples are listed in Table 1.

Prior to installation, HEDL conducted qualification testing on these thermocouples up to 2473 K (3992°F) to demonstrate their ability to remain structurally intact over a wide temperature range.⁷ Independent tests were conducted at the INEL⁷ that corroborated the HEDL data and extended the testing to 2700 K (4401°F). The results indicated that these thermocouples remain within 1/2% of reference temperature up to 2573 K (4172°F) but showed signs of shunting and calibration shift (ductile grain growth) beginning at 2673 K (4352°F).¹ On the basis of these results, the fuel thermocouples were expected to survive and provide accurate data covering the expected temperature range, including the fuel temperature during steady-state full-power operation at 50 MW [~ 2100 K (3321°F)].

h. The LOFT core was 66 in. tall and had a bottom-skewed cosine-shaped axial power distribution that was peaked at the 24 to 26-in. elevation above the bottom of the active fuel (BAF).

i. S. C. Wilkins, INEL (EG&G Idaho, Inc.) personal communication. The performance of the LOFT insulated thermocouple was at first surprising. The LOFT thermocouple was tested side by side with a BeO insulated thermocouple from the Power Burst Facility. The LOFT thermocouple performance was better. The results showed that although insulation resistance is an important factor, a more important factor is the ratio of insulation resistance to thermoelement loop resistance. The loop resistance is four times less in the LOFT thermocouple because the thermoelement diameter was twice that in the BeO insulated thermocouple.

Figure 3. Cross-sectional view of a typical LOFT thermocouple junction through the wire weld region.

Figure 4. Cross-sectional view of a typical LOFT thermocouple junction before the wire weld region.

Table 1. LOFT fuel centerline thermocouple description.

Operating temperature	2473 K (3992°F)
Thermoelement wires	Tungsten 5%, rhenium (W5Re) versus tungsten 26%, rhenium (W26Re) 0.010 ± 0.001 in. diameter
Insulator	Hafnia (HfO ₂) 0.044 ± 0.001-in. OD by two holes 0.012 ± 0.001-in. ID by 2 in. long and one hole 0.025 ± 0.001-in. ID by 1-in. long
Sheath	Re/W augmented ^a 0.063 ± 0.001-in. OD 0.048 ± 0.001-in. ID 39.37 ± 0.05 in. long
Junction type	Twisted, insulated weld spot at end
Total assembly length	342.49 in.

a. This sheath is used on the thermocouple located at the 27-in. elevation. The sheath material used on the thermocouple located at the 43.8-in. elevation is Mo/Re. The sheath dimensions are the same as for the Re/W augmented sheath.

Figure 5 shows the installation details of the fuel centerline thermocouples, while Figure 6 shows the uninstrumented fuel rod design. The principal differences between the fuel rods are (a) a shortened fuel pellet stack in the instrumented fuel rod to allow for the additional

hardware at the top of the fuel rod necessary to handle the thermocouple, and (b) the removal of fuel in the center of the pellets. The effect of the removed fuel was to decrease the maximum fuel temperature by approximately 17% and the stored energy by approximately 11% (Reference 9).

GENERAL NOTES: UNLESS OTHERWISE SPECIFIED

- 1 TOLERANCES: XX:015 XXX:005 ANGULAR:5°
- 2 DIMENSIONING AND TOLERANCING ARE IN ACCORDANCE WITH ANSI Y14.5, 1973
- 3 ONE SHORTERED LENGTH PELLET (200 MM) WITH A CONFIGURATION IDENTICAL TO PART NO 8 AND 9 MAY BE USED AT EITHER END OF THE COLUMN TO ACHIEVE THE TOTAL FUEL STACK LENGTH (PELLETS SHORTERED BY GRINDING ONE END (200 MM PELLET LENGTH) MAY ALSO BE USED PROVIDED THE GROUND SURFACE ON THE PELLET BE IN CONTACT WITH THE INSULATOR DISC.
- 4 A MINIMUM OF ONE FULL LENGTH ANNUAL PELLET (PT 8) SHALL BE REQUIRED BEYOND THE END OF THE THERMOCOUPLE PROBE.
- 5 SURFACE OF ROD IN THE LENGTH INDICATED SHALL BE GRINDED TO A FINISH (SEE APPLICABLE PRODUCT SPECIFICATION)
- 6 UPPER END CAP INSTRUMENT LEAD PENETRATION HOLE MAY BE REAMED TO A MAXIMUM 0.0005 INCH CLEARANCE WITH THE "MEASURED DIAMETER" OF THE INSTRUMENT LEAD
- 7 ASSEMBLY SHALL BE PRESSURIZED IN A 16 ATMOSPHERE AT 350.15 PSIG PER THE APPLICABLE PRODUCT SPECIFICATION

1 ASSEMBLY

QTY	ITEM	DESCRIPTION	REMARKS
1	1	ASSEMBLY	---
1	2	INSTRUMENTED END CAP (UPPER)	303.505-PT 1
1	3	TRANSITION PIECE	303.515
1	4	SPACER	303.516
1	5	SPRING WASHER	303.517
1	6	PLENUM STRING	303.511
2	7	INSULATOR DISC (ANNUAL)	303.512-PT 1
AR	8	FUEL PELLET (ANNUAL)	303.221
AR	9	FUEL PELLET	303.220
1	10	CLADDING	303.510-PT 3
1	11	LOWER END CAP	303.507
1	12	INTERNAL THERMOCOUPLE H-3 44408 PT 1	SUPPLIED BY CUSTOMER

Figure 5. LOFT fuel rod with a fuel centerline thermocouple.

1 ASSEMBLY

GENERAL NOTES (UNLESS OTHERWISE SPECIFIED)

1. DIMENSIONING AND TOLERANCING ARE IN ACCORDANCE WITH ANSI Y14.5, 1973
2. ONE SHORTENED LENGTH PELLET (200 MIN) WITH A CONFIGURATION IDENTICAL TO PART NO. 7 MAY BE USED AT EITHER END OF THE COLUMN TO ACHIEVE THE TOTAL FUEL STACK LENGTH. PELLET SHORTENED BY GRINDING ONE END (200 MIN PELLET LENGTH) SHALL BE USED ONLY AT THE PLENUM END OF THE COLUMN WITH THE GROUND SURFACE IN CONTACT WITH THE INSULATOR DISC.
3. ASSEMBLY SHALL BE PRESSURIZED IN A H₂ ATMOSPHERE TO 330-315 PSIG PER APPLICABLE PRODUCT SPECIFICATION
4. ANNULAR INSULATOR (PART 5) ONLY SHALL BE INCORPORATED IN FUEL RODS TO BE PRESSURIZED BY LASER DRILL/WELD PROCESS.

QTY	ITEM	2	DESCRIPTION	1	REMARKS
1	1	FUEL ROD ASSEMBLY			
1	2	UPPER END CAP		303.503	
1	3	PLENUM SPRING		303.511	
1	4	CLADDING		303.510 - PT 1	
AR	5	INSULATOR DISC (ANNULAR)		303.512 - PT 1	
AR	6	INSULATOR DISC (STANDARD)		303.512 - PT 2	
AR	7	FUEL PELLET		303.220	
1	8	LOWER END CAP		303.507	

Figure 6. LOFT standard fuel rod.

3. ANALYSIS OF LOFT FUEL ROD CLADDING THERMOCOUPLE RESPONSE DURING LBLOCA

This section presents an analysis of the behavior of the LOFT externally-mounted cladding thermocouples during large-break LOCA experiments. As an introduction, Subsection 3.1 creates a framework for the analysis by noting that, due to the cladding thermocouple design, at least three qualitative modes of thermocouple behavior might exist relative to that of the cladding: cladding-dominated, cladding-indicative, and coolant-dominated. Next, Subsection 3.2 reviews the data from Experiments L2-2 and L2-3 (in which an apparent early blowdown cladding quench occurred) as well as Experiment L2-5 (in which no early quench occurred). In Subsection 3.3, results from later experiments are presented and compared to L2-3 and L2-5. In these experiments (i.e., LP-02-6 and LP-LB-1), fuel rod centerline thermocouple data provided an additional, independent indication of fuel rod thermal behavior. LP-02-6 produced cladding temperature results very similar to L2-2 and L2-3, and analogously, LP-LB-1 gave results closely matching L2-5. The additional information offered by the fuel rod centerline thermocouples enables a clearer argument to emerge regarding the blowdown quench and the similarity of fuel rods with and without external thermocouples. The authors' best understanding of the early blowdown cladding quench, i.e., the enhanced cooling period, is given in Subsection 3.4.

Subsection 3.5 presents results obtained from a detailed FRAP-T6 model of a LOFT fuel rod. By reproducing the transient response of a centerline thermocouple using the model, the actual cladding temperature can be inferred. Here it is shown that the inferred cladding temperature during the blowdown quench lags behind the cladding thermocouple reading, but exhibits the same quench behavior. Having established that blowdown quenching did occur in LOFT Experiments L2-2, L2-3, and LP-02-6, but that a definite bias exists between the cladding thermocouple reading and

the actual cladding temperature, Subsection 3.5 goes on to present a determination of the magnitude of the bias at peak cladding temperature (PCT) in LP-02-6 and LP-LB-1. The analysis makes use of FRAP-T6 computed cladding temperatures as compared to the cladding thermocouple readings.

In Subsection 3.6 the separate PCT biases from LP-02-6 and LP-LB-1 are combined. Here the biases are evaluated considering uncertainties in the FRAP-T6 code calculations and the fuel centerline temperature measurement.

A short summary of the LOFT-thermocouple analysis done by Coddington and Gill is given in Subsection 3.7. Included also is a brief description of the relationship between the LOFT Test Support Facility experiments,⁴ Coddington and Gill's³ analysis, and the present study.

3.1 Potential Modes of LOFT Cladding Thermocouple Response

While the LOFT fuel rod cladding thermocouples, mounted as described in Subsection 2.1, will in general provide a good measurement of cladding temperature response, there are circumstances in which the thermocouple measurements can be misleading. This is because the thermocouple mounting arrangement creates a finite thermal resistance between the thermocouple junction and the cladding. Even though the resistance is very small, the potential exists for a significant temperature difference to occur between the cladding and the thermocouple. The cladding, thermocouple, and adjacent coolant constitute a thermally-coupled system that can exhibit different states. Conceptually, at least three modes of thermocouple response are possible:

Mode	Description
Cladding-dominated	The thermocouples measure the steady-state temperature with an uncertainty of 1.3% of the measurement range. The transient cladding temperature mean uncertainty is somewhat greater than the steady-state measurement uncertainty due to fin effects and thermal resistance between the thermocouple and the cladding.
Cladding-indicative	A high heat transfer environment causes the thermocouple temperature to decrease more rapidly than the cladding. The thermocouple may transition from film to nucleate boiling earlier than the cladding. The cladding exhibits the same general response as the thermocouple but appears to lag the thermocouple.
Coolant-dominated	The thermocouple temperature is very nearly equal to the adjacent coolant temperature; whereas, the cladding temperature is higher. A substantial temperature gradient about the cladding circumference may exist.

Figures 7 and 8 illustrate these three modes. Between -5 and 0 s in Figure 7 the difference in the thermocouple measurement and the true cladding temperature at steady-state conditions is seen to be on the order of 20 K. The transient is initiated at 0 s. Within 1 s after the transient is initiated, the cladding departs from nucleate boiling

and begins to heat up. Between 0 and 5 s, the heat transfer to the coolant is very poor (film boiling) and this causes the thermocouple measurement to closely follow the cladding temperature. At 5 s a large surge of coolant passes through the core, causing the thermocouple to begin transition to nucleate boiling. Two seconds later, the cladding also begins transition from film boiling to nucleate boiling. Both the thermocouple and the fuel rod cladding behave in a similar manner. However, the thermocouple is cooled to the adjacent fluid temperature; whereas, the adjacent cladding outer surface temperature remains elevated based on the fuel rod decay power level together with the process thermal resistance (i.e., of the fuel rod cladding, gap, fuel pellet, and the adjacent fluid film). By 10.5 s dryout occurs and the cooling potential of the adjacent fluid decreases with decreasing core coolant inventory.

The *cladding-dominant* mode is the desired operational mode of the thermocouple. The thermocouple will indicate the cladding surface temperature plus or minus a temperature offset that is a function of (a) the thermal resistance of the thermocouple (principally the braze and thermocouple sheath material), and (b) a cooling effect imposed on the thermocouple's sheath by the surrounding coolant. The *cladding-dominant* mode is illustrated in Figure 7 during the steady-state portion of the experiment, during the heatup phase, and after 10.5 s of the transient.

The *cladding-indicative* mode is an undesirable but expected behavior pattern. This mode exists after the thermocouple begins transition from film boiling to nucleate boiling. Because the thermocouple sheath is mounted external to the fuel rod, the thermocouple has the potential to transition from film to nucleate boiling independent of the fuel rod if the thermocouple to coolant boundary conditions are favorable. The *cladding-indicative* mode is characterized by the thermocouple and cladding exhibiting the same general behavior. However, the thermocouple-indicated cladding temperature magnitude is inaccurate. Since the thermocouple has the same behavioral characteristics as the cladding, but does not give a readily usable temperature, this mode is termed *cladding-indicative*.

Analysis of Thermocouple Response During LBLOCA

M618-WHT-692-07

Figure 7. Cladding-dominated and cladding-indicative thermocouple behavior.

S207-WHT-489-11

Figure 8. Coolant-dominated thermocouple behavior.

Finally, the *coolant-dominated* mode is also an undesirable but expected characteristic for an externally mounted thermocouple. The *coolant-dominated* mode occurs when the thermocouple measures the coolant temperature and does not provide any clue as to the behavior of the cladding temperature response. A clear example of the *coolant-dominant* mode is shown in Figure 8 (from LOFT Experiment LP-FP-1). The thermocouple TE-5G05-027 exhibits behavior that indicates rewetting and rapid reheating of the fuel rod. However, closer examination of the thermocouple data and comparison of its behavior to the other three thermocouples reveals that (a) the heatup rate shown by thermocouple TE-5G05-027 after 290 s is unphysically rapid and thus not representative of the fuel rod behavior, and (b) the behavior of thermocouple TE-5G05-027 is not typical. Consequently, the explanation of the thermocouple TE-5G05-027 behavior is that only the thermocouple was quenched at 280 s while the cladding continued to heat up.

If the above characterization of possible

thermocouple response is accurate, then an a-priori acceptance of the thermocouple readings as always being representative of the cladding cannot be made. Examination of other data and evidence is needed to gain further insight into cladding temperature behavior.

3.2 LOFT LBLOCA Blowdown Temperature Response

The early large-break LOCA transients demonstrated a range of transient responses, characterized by Experiments L2-3 and L2-5 (Reference 10). Figure 9 compares the measured maximum fuel rod cladding temperature for these two experiments, and shows a significant difference.

The experimental boundary conditions for L2-3 and L2-5 differed only in the operation of the primary coolant pumps. The pumps remained in operation throughout L2-3, while in L2-5 the coolant pumps were tripped at 0.94 s. Moreover, in the latter test, the pumps were also decoupled from the flywheel, which produced a very rapid pump coastdown following pump trip.

Figure 9. Maximum temperature on fuel rod cladding during Experiments L2-3 and L2-5.

The difference in hydraulic conditions between the two experiments during the early blowdown phase is explained by a simple coolant flow balance at the vessel inlet. At about 3.4 s in both experiments, the broken loop cold leg break location experienced a transition from subcooled to saturated fluid conditions, which resulted in a marked decrease in the critical flow at the break. The continued operation of the coolant pumps in L2-3, coincident with the flow transition at the break, resulted in the flow at the vessel inlet exceeding the flow at the cold leg break. As a result, a surge of low quality coolant was forced into the vessel and through the core. The condition was brief, since the coolant conditions at the pumps became saturated and degraded the intact loop flow by about 5.7 s. However, the surge of coolant moved through the core region at a high velocity (about 1.8 m/s as determined by analysis of the axial progression of temperature response) during a high pressure phase of the transient (8 to 5 MPa), which suggested the potential for significant heat transfer.

The data suggest that during L2-3 the fuel cladding underwent a short period of substantial cooling beginning at about 5 s, as evidenced by the turnover of the cladding temperature and a subsequent quench. In L2-5 no significant cooling is exhibited early in the blowdown phase, as the fuel cladding departed from nucleate boiling conditions early in the transient (similar to the response in L2-3) and remained in a film boiling regime until reflood of the core region began. The data suggest that a considerable amount of stored energy was removed from the fuel rod early in blowdown in L2-3.

The contrasting hydrodynamic conditions in L2-5 were due to the very rapid coastdown of the pump. In this case, the flow at the vessel inlet from the intact loop never exceeded the flow at the break location. Therefore, a core bottom-to-top surge of coolant did not occur in L2-5.

3.3 LOFT LBLOCA Data Analysis

The OECD-LOFT Project carried out two additional LBLOCA experiments. Experiment LP-02-6 was performed with a pump trip at the beginning of the transient. The pumps remained coupled to the flywheels and, therefore, followed a slower coastdown than that which occurred in L2-5. Figure 10 shows that the blowdown cooling in LP-02-6 was similar to L2-3. The differences between these experiments were in pump operation and initial power level. The pumps remained on in L2-3, while they were tripped and coasted down (with flywheels engaged) in LP-02-6. This resulted in a difference in the axial extent of the blowdown cooling. Leaving the pumps running in L2-3 resulted in cooling throughout the core, whereas it was primarily restricted to the bottom two-thirds of the core in LP-02-6. At the 27-in. elevation, the differences in peak cladding temperature reflect the differences in initial core power. L2-3 began from an initial power of 36.0 MW; whereas, LP-02-6 started from 46.0 MW. Figure 11 illustrates that in the lower two-thirds of the core, the effect of enhanced cooling is evidenced by a turnover in fuel cladding temperature response and, in some cases, actual quenching.^j Higher in the core early quench did not occur.

LP-02-6 provided key insight into fuel thermal response, because of the inclusion of corresponding fuel centerline temperature measurements. As mentioned earlier in this report, one possible interpretation of the LOFT large-break LOCA data is that the surface thermocouples may not have been indicative of the temperature response of the fuel clad (denoted in this report as coolant-dominated thermocouple response). If that hypothesis is correct, cooling of the fuel would not be significant.

j. The last three digits of each thermocouple identification shown in Figure 11 (and subsequent figures) denotes the axial position in inches above the bottom of the heated portion of the fuel rod.

Figure 10. Comparison of the temperature response at the 27-in. elevation in Experiments L2-3 and LP-02-6.

Figure 11. Fuel cladding temperatures measured on fuel rod 5G06 at several elevations during Experiment LP-02-6.

Figure 12 compares the temperature response of a surface-mounted thermocouple and the corresponding centerline thermocouple, at the 27-in. elevation for LP-02-6. The initial decrease in centerline temperature (0 to 4 s), coinciding with an increasing cladding temperature, reflects the radial redistribution of energy in the fuel following reactor scram. The increasing cladding surface temperature reflects both the redistribution of energy in the fuel rod and the degraded surface heat transfer resulting from the departure from nucleate boiling (DNB). At about 5 s into the transient the effect of enhanced cooling (resulting from coolant pump operation) was apparent as demonstrated by cladding surface quench accompanied by a slightly delayed but significant reduction of the fuel centerline temperature. The observed strong correlation between the surface thermocouple temperature response and the centerline temperature response indicates that the blowdown cooling observed in the LOFT facility during LP-02-6 resulted in the removal of a substantial amount of energy from the LOFT fuel. Such an effect could only occur with a return to nucleate boiling. Also shown in Figure 12 is the fuel centerline temperature response at the same

elevation and on the same fuel rod during LP-LB-1. (Note that the LP-LB-1 initial power level and maximum linear heat generation rates are higher than in LP-02-6. Thus the fuel centerline temperature for fuel Rod 5D07 was higher in LP-LB-1 than in LP-02-6 at steady-state conditions.) Comparison of the centerline temperature response in these two experiments clearly shows that the fuel was substantially cooled in LP-02-6 relative to LP-LB-1, consistent with the corresponding indications provided by the cladding thermocouples.

Figure 13 compares the centerline thermocouple temperature responses at the 27-in. elevation for three different fuel rods. Each of the fuel rods without surface thermocouples is remotely located relative to the rod with surface thermocouples. The data show a nearly identical response to the initial energy redistribution following reactor scram, and similarly, all three measurements indicate significant cooling during the period of observed cladding quench. The response of the rods without surface thermocouples lags slightly the response of the rods with surface thermocouples, suggesting that the

Figure 12. Fuel centerline and cladding temperature at the 27-in. elevation on fuel rod 5D07 during Experiment LP-02-6 and fuel centerline temperature during Experiment LP-LB-1.

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Figure 13. Fuel centerline temperatures at the 27-in. elevation on fuel rods 5D07, 5009, 5010, during Experiment LP-02-6.

surface thermocouple may indeed produce a small fin effect. However, the similarity of the data in Figure 13 clearly indicates that the observed cooling response in LP-02-6 during the blowdown phase was not limited to the surface instrumented rods. On the contrary, the response occurred core-wide (except at high core elevations as discussed earlier).

By design, LOFT Experiment LP-LB-1 demonstrated a very different transient response. The pumps were decoupled from the flywheel upon trip and experienced a very rapid coastdown, as they had in L2-5. The similarity in measured cladding temperature response in L2-5 and LP-LB-1 is shown in Figure 14. The higher peak temperature in LP-LB-1 reflects the higher initial power in that test (49.3 MW versus 36.0 MW in L2-5).

Figure 15 compares the surface thermocouple temperature response to two centerline

temperature measurements at the 27-in. elevation. One of the centerline measurements is for the same rod at the elevation of the surface thermocouple while the other centerline measurement is at the same elevation on a remote fuel rod without surface instrumentation. The same centerline temperature decrease occurs due to fuel rod energy redistribution following reactor scram and to degraded surface heat transfer conditions. The two centerline measurements during this initial phase were nearly identical. In LP-LB-1 limited cooling was observed during the blowdown phase of the transient and therefore the fuel cladding continued to heat up until such time as the ECCS began to operate. The centerline temperatures similarly did not exhibit further cooling during blowdown. The correlation of the centerline and surface thermocouples in LP-LB-1 confirms that the surface thermocouples were indicative of the fuel rod thermal response during the blowdown phase of the transient.

Figure 14. Comparison of the temperature response at the 27-in. elevation in Experiments L2-5 and LP-LB-1.

Figure 15. Fuel surface and centerline temperature in rods with and without cladding surface thermocouples at the 27-in. elevation during Experiment LP-LB-1.

The two centerline measurements shown in Figure 15 are seen to be different in magnitude following the initial energy redistribution phase, suggesting that the presence of surface thermocouples may result in a small fin effect. The difference in the two centerline temperatures implies that a corresponding cladding temperature difference exists. Before determining the bias for the blowdown phase temperature measurements, the refill/reflood phase of the transient will be addressed.

Figures 12 and 15 show that for LP-02-6 and LP-LB-1, respectively, the fuel exhibits significant cooling following the apparent observed cladding quench during refill/reflood. Figures 12 and 15 both show, prior to the quench, a delay of about 10 s between refill/reflood peak clad temperature and turnover of the centerline temperature. The 10 s delay represents a maximum delay between the surface and centerline response since the measured surface response includes the influence of the surface thermocouple fin effect. Figure 15 also compares the centerline temperature response for fuel with and without surface thermocouples and suggests about a 5 s difference between the two responses. This difference is due to the presence of surface thermocouples in a slow reflood environment. During the blowdown phase quench a similar, but shorter, delay was observed.

Summarizing this analysis of the LOFT external thermocouple response during LBLOCA experiments, we conclude that:

- Experiments L2-3 and LP-02-6 produced similar cladding temperature results (blowdown rewet). Analogously, L2-5 and LP-LB-1 produced similar results (no blowdown rewet). The consistent difference between these sets of experiments was the operation of the coolant pumps.
- The significant difference in fuel centerline temperature response between LP-02-6 and LP-LB-1 is entirely consistent with the corresponding difference in measured cladding temperature response, i.e., blowdown

quench occurred in LP-02-6, but not in LP-LB-1.

- In LP-02-6, the similarity of fuel centerline thermocouple response between rods with and without external clad thermocouples clearly shows that the presence of external thermocouples did not precipitate or materially affect the blowdown cooling.

3.4 Summary of the Enhanced Cooling Process

By its very nature, sites for locating diagnostic equipment in a nuclear core are severely limited. Consequently, the primary instrumentation used for evaluation of the thermal-hydraulic phenomena in the LOFT core were thermocouples (both fuel centerline and cladding surface-mounted) and flow measurements in the cold legs. Thus the local phenomena adjacent to the surface-mounted thermocouples can only be deduced from the global thermal-hydraulic behavior in the core.

Data analysis, presented in Subsection 3.3, has shown that a surge of coolant (beginning at 3 s in LP-02-6) moved bottom-up through the core as the primary coolant transitioned from a subcooled state to saturation in the L2-3 and LP-02-6 experiments. Prior to the flow surge, the core power had been reduced to about 3% by negative void reactivity induced by negative core flow. The core power remained at ~3% during the enhanced cooling phase of the transient. The flow surge consisted of low quality coolant and moved through the core in a relatively homogeneous fashion as indicated by the cladding thermocouples. That is, most of the thermocouples at a particular core elevation (thermocouple instrumentation plane) indicated an increase in the cooling rate at about the same transient time.

The core coolant flow surge was sufficiently large, as evidenced by the behavior of the fuel rod thermocouples, to first increase the film boiling energy transfer, then cause transition boiling, and finally result in nucleate boiling; all within the space of 1 s at a given elevation. Thus, the heat transfer coefficient at the rod surface increased an order of magnitude from $10^3 \text{ W/m}^2 \cdot \text{K}$ to

$10^4 \text{ W m}^{-2} \cdot \text{K}$. The mechanism for such a change is believed to be the same as the quench process that is experienced by a hot metal body (with initial temperature above the Leidenfrost temperature) as it is thrust into a cold coolant reservoir. However, in this case, the hot stationary fuel rods are cooled by a quickly moving low-quality coolant mass that rapidly disperses the steam blanket adjacent to the fuel rods, generated during the film boiling process, by a convection process. In essence, the moving coolant is envisioned to forcibly displace the film-boiling-generated steam by turbulent interphase drag such that the steam is carried with the moving fluid mass. Following removal of the steam blanket, film boiling to nucleate boiling transition is considerably enhanced. The timing of the flow upsurge following the power reduction was ideal for causing quench. Unfortunately, no data are available to support the above hypothesis for the coolant behavior adjacent to the fuel rods. Only the evidence provided by the fuel centerline thermocouples exists to substantiate that rapid film-boiling to nucleate boiling transition occurred, as described in Subsection 3.3.

A discussion of cladding thermocouple response characteristics for the condition of non-uniform cooling of fuel rods is contained in Appendix A. In conjunction with fuel centerline thermocouples, cladding thermocouple examples illustrate the characteristics for (a) cladding thermocouple only cooling, and (b) cladding thermocouple and cladding cooling in the presence of adjacent rods that experience very little cooling. These characteristics were not observed in the fuel centerline and cladding thermocouple data during the LP-02-6 enhanced cooling interval described in Subsection 3.3, thereby indicating that uninstrumented and instrumented rods all underwent a large cooling during this time.

3.5 LOFT Fuel Rod Model Analysis

In this subsection, a second approach is used to analyze the response of externally mounted cladding thermocouples during large-break LOCA experiments. Using the FRAP-T6 transient fuel

behavior code (Reference 11), a model of the LOFT fuel rod is developed. The model is then used to determine the cladding surface heat flux required to produce a measured centerline thermocouple response. The corresponding calculated cladding surface temperature is then compared to the measured value to estimate the difference between measured and actual cladding temperature. The method, therefore, not only provides further insight into the issue of blowdown rewet, but also a quantitative evaluation of thermocouple bias.

The LOFT facility did not contain sufficient instrumentation to provide information on the coolant conditions in the core as a function of time. Therefore, a direct determination of local surface heat transfer coefficient is not possible. However, it is not necessary to know the coolant conditions if the transient heat flux at the cladding surface is used as the boundary condition on the fuel rod model. Nevertheless, it is of interest to calculate an estimated heat transfer coefficient based on surface temperature, surface heat flux, and a reference coolant temperature. In the present study, a measured core inlet coolant temperature (TE-6LP-003) was used as a reference temperature during the blowdown phase. Recognizing that there will be a difference between coolant temperature at the core inlet and at any point in the core, a high degree of uncertainty must be attached to heat transfer coefficients inferred from using this temperature.

An iterative process, illustrated in Figure 16, was employed to arrive at a transient heat transfer coefficient (derived from the required heat flux) that produces a best fit between the calculated and measured fuel centerline temperature. The uncertainties associated with this process include the uncertainty in the fuel centerline temperature measurement and the uncertainty in the fuel rod model.

The base FRAP-T6 model of the LOFT fuel rod had been assessed against LOFT data (Reference 12). In its application in the present study, the hole drilled through the fuel pellets to accommodate the centerline thermocouple and sheathing was modeled, thereby accounting for the loss of fuel material and corresponding

P829-WHT-189-01

Figure 16. Analysis methodology to determine the LOFT cladding surface thermocouple measurement bias.

reduction in power. As illustrated in Figure 16, once a good fit to the centerline temperature was achieved, the resulting surface heat transfer coefficient history was then applied to a FRAP-T6 model without the centerline thermocouple. The resulting calculation of fuel rod response therefore represents a prediction for an uninstrumented rod. It is the cladding temperature from this latter calculation that is compared to a measured cladding temperature to arrive at an estimate of the bias introduced by the external thermocouple.

The above methodology was carried out for Experiments LP-02-6 and LP-LB-1. The following subsections describe the results for those experiments.

3.5.1 Fuel Rod Analysis of LP-02-6. A base case calculation was defined as the thermal response of a fuel rod containing a fuel centerline thermocouple and no cladding surface thermocouples. The FRAP-T6 model of the LOFT fuel rod was developed using (a) the information given in Reference 12, (b) the centerline thermocouple dimensional data, (c) fuel densification data (Reference 13), and (d) the power history, magnitude, and axial power profile for fuel Rod 5D07 in LP-02-6.

A time-dependent heat transfer coefficient was determined, by trial and error, that produced a fuel centerline temperature in close agreement with data as shown in Figure 17. The transient heat transfer coefficient required is shown in Figure 18.

M526-WHT-292-02

Figure 17. Comparison of calculated and measured fuel centerline temperature at the 27-in. elevation in fuel Rod 5D07 for Experiment LP-02-6.

M344-WHT-691-02

Figure 18. Time dependent surface heat transfer coefficient for the calculation shown in Figure 17.

At the initiation of the transient, the calculated surface heat transfer coefficient (HTC) was about $25,000 \text{ W/m}^2\cdot\text{K}$, typical of subcooled forced convection heat transfer. At about 1 to 1.5 s after the initiation of the transient, the fuel rod cladding experienced DNB and began a rapid heatup. The HTC decreased to a low value characteristic of film boiling. At 5 s, the core experienced a rapid influx of saturated liquid from the lower plenum, causing a large increase in the cladding HTC. The subsequent dryout of the cladding began at about 7 s, with an attendant decrease in HTC. At about 52 s, core reflood began to affect the fuel temperature at the 27-in. elevation. The cladding surface returned to nucleate boiling at about 55 s.

The FRAP-T6 calculated cladding temperature is compared with the external thermocouple data for fuel Rod 5D07 at the 27-in. elevation in Figure 19. The calculated behavior is very similar to the measured data. However, during the period of rapid temperature changes, 0 to 15 s, the measured data falls below the calculated temperature. The calculated and measured peak

cladding temperature (PCT) values are about 955 K (1259°F) and 931 K (1216°F), respectively. The difference, 24 K (43°F), is defined to be the approximate error in the cladding temperature measurement owing to its external location. This difference is also defined as the bias in the temperature. The bias is positive when the calculated value is greater than the measured value.

Notwithstanding the apparent error in the surface temperature measurement, the calculated cladding temperature at the 27-in. elevation clearly indicates that substantial cooling of the cladding occurred during the 5 to 10 s time frame in LP-02-6. The degree to which the calculated centerline and cladding temperatures are sensitive to the assumed heat transfer coefficient was explored next.

In the sensitivity study, the heat transfer coefficient was varied from a maximum of $11,000 \text{ W/m}^2\cdot\text{K}$ down to $500 \text{ W/m}^2\cdot\text{K}$ during the 5 to 10 s insurge period. The results are shown for the fuel centerline and cladding surface

M526-WHT-292-03

Figure 19. Comparison of measured and FRAP-T6 calculated cladding surface temperature in Experiment LP-02-6.

temperatures in Figures 20 and 21, respectively. The best agreement between measured and calculated data occurs for a maximum heat transfer coefficient of approximately $10,000 \text{ W/m}^2\cdot\text{K}$. Note the large degree of uncertainty associated with this coefficient, due to uncertainty in the coolant temperature (see above) as well as the centerline temperature and FRAP-T6 model.

It is interesting to see that the FRAP-T6 calculation using a maximum surface heat transfer coefficient of $1000 \text{ W/m}^2\cdot\text{K}$ during the 5 to 10 s interval is very similar to the calculation from the TRAC-PF1/MOD1 code¹³ as shown in Figure 22. This FRAP-T6 calculation is compared to the LP-02-6 data in Figure 23. The comparisons show that the TRAC-PF1/MOD1 code greatly under predicted the degree of cooling that took place in LP-02-6.

3.5.2 Cladding Thermal Response in LP-LB-1. The same methodology applied to LP-02-6 was repeated for LP-LB-1. The fuel rod

thermal response in this case was significantly different than that in LP-02-6, as shown earlier. Fuel Rod 5D07, containing a fuel centerline thermocouple, again is taken as the reference for the FRAP-T6 calculation. Figure 24 compares the measured fuel centerline and cladding surface temperatures on this rod in LP-LB-1. The FRAP-T6 calculation of the fuel centerline temperature is shown compared with the measured data in Figure 25, and the transient heat transfer coefficient required to produce agreement between the calculated and measured fuel centerline temperature is shown in Figure 26.

The associated calculated cladding temperature is compared with the measured cladding temperature for fuel Rod 5D07 in Figure 27. The calculated temperature exceeds the measured temperature during the initial heatup period in a manner similar to that in LP-02-6. The maximum difference between the calculated and measured cladding temperature in the first 10 s of the transient is $\sim 100 \text{ K}$ (180°F).

Figure 20. Effect of maximum blowdown heat transfer coefficient on fuel centerline temperature.

Figure 21. Effect of maximum blowdown heat transfer coefficient on cladding temperature.

Figure 22. FRAP-T6 with a maximum heat transfer coefficient of 1000 W/m²·K during blowdown compared with the TRAC-PF1/MOD1 calculation.

Figure 23. FRAP-T6 with a maximum heat transfer of 1000 W/m²·K during blowdown compared with measured data.

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Figure 24. Measured fuel centerline and cladding surface temperatures on fuel Rod 5D07 during Experiment LP-LB-1.

Figure 25. Comparison of measured and FRAP-T6 calculated fuel centerline temperature in fuel Rod 5D07 for Experiment LP-LB-01.

Figure 26. Time-dependent surface heat transfer coefficient for the calculation shown in Figure 26.

Figure 27. Comparison of the measured and calculated cladding surface temperature response for Experiment LP-LB-01.

3.6 LOFT LBLOCA Cladding Temperature Bias

The average temperature bias in the LOFT cladding thermocouples at peak cladding temperature is determined from comparisons of calculated and measured cladding temperatures in experiments LP-02-6 and LP-LB-1. All of the individual calculations from both experiments are taken together as a statistical representation of the performance of cladding thermocouples in the LOFT core. All significant contributors to the uncertainty in the average bias are statistically combined to determine the uncertainty in the mean bias.

The bias values from LP-02-6 were determined by first calculating the centerline temperature on Rod 5D07 to within 2 K agreement with data. Rod 5D07 also has a cladding TC which provides a comparison of calculated and measured cladding temperature, and consequently, one of the bias values. The other bias values, nine total, from LP-02-6 were determined by replacing the fuel centerline TC with fuel in the FRAP-T6 model and comparing the results of the calculation with measured cladding temperature data from those thermocouples in the 26-28 in. elevation. The ten bias values from LP-02-6, listed in Table 2, have an average bias value of 8.0 K (14.4°F).

Ten bias values were determined from LP-LB-1. However, in LP-LB-1 all ten fuel rods used in the calculations had both centerline and cladding TCS at the 27 in. elevation. Consequently, the bias value for each cladding TC was determined in the same manner as that for Rod 5D07 in LP-02-6; that is, calculating the measured centerline temperature with the FRAP-T6 code and then comparing the calculated cladding temperature with the measured cladding temperature. The ten bias values from LP-LB-1 are also listed in Table 2. The average bias value of these ten calculations is 14.7 K (26.5°F).

Taken together, the twenty bias values have an average of 11.4 K (20.5°F). The uncertainty in the mean is determined from four sources:

1. Uncertainty in the mean, $2\sigma_1$
2. Uncertainty in the fuel centerline TC, $2\sigma_2$
3. Uncertainty in the cladding TC, $2\sigma_3$
4. Uncertainty in the FRAP-T6 calculation of cladding temperature, $2\sigma_4$.

The uncertainty in the mean is determined from

$$2\sigma_1 = 2(\sigma^2/n)^{1/2} = 10.8 \text{ K (19.4°F)}$$

where

n = number of values, (20)

σ^2 = variance of the population, (590.2).

The uncertainties in the cladding and fuel centerline TCs were determined from data taken during hot standby conditions. The reference temperature instruments have a 2-sigma uncertainty of 3.75 K (6.75°F) Reference 15). All cladding and fuel centerline TCs were within the uncertainty band of the reference temperature instruments. Inspection of the polynomial calibration equation for the cladding and fuel centerline TCs showed that in the region of 1200 K (1700°F) the calibration error is 2 K (3.6°F) for the fuel centerline TC and 1 K (1.8°F) for the cladding TC. The 2-sigma uncertainty, then, is 4.25 K (7.65°F) for the fuel centerline temperature and 3.9 K (7.0°F) for the cladding temperature. Thermocouple calibration drift was also investigated as a possible source of uncertainty. The records of the LOFT data acquisition system (DAS) were examined during power operation prior to experiment initiation. The results showed that, from hot standby conditions to experiment initiation, the drift was insignificant.

The 2-sigma uncertainty in the FRAP-T6 calculation was determined from the assessment of the FRAP-T6 code in Reference 13. All sources of uncertainty interior to the cladding in the FRAP-T6 model were included to give a 1-sigma uncertainty in the calculated cladding temperature of 4.9 K (17.6°F). The calculated fuel centerline temperature agreed with the measured data to within 2 K (3.6°F). The 1-sigma uncertainty in the FRAP-T6 code for this application, then, is statistically given as 5.3 K (9.5°F). The 2-sigma uncertainty is 10.6 K (19.0°F).

Table 2. Cladding thermocouple bias values in LP-02-6 and LP-LB-1.

Thermocouple	Calculated/measured temperature at 5 s (K)	Bias at 5 s (K)
LP-02-6 ^a		
5D07-27	954.6/930.8	23.8
5F04-26	1031.6/1058.5	-26.9
5F07-26	1031.6/1017.5	14.1
5F08-26	1031.6/1008.0	23.6
5H06-28	1016.1/1015.4	0.7
5H07-26	1031.6/1018.6	13.0
5I04-27	1029.9/1002.9	27.0
5J08-26	1031.6/1002.7	28.9
5L06-26	1031.6/1073.2	-41.6
5M07-26	1031.6/1014.0	17.6
	Average bias	8.2
LP-LB-1 ^a		
5D07-27	1050.5/1018.6	31.9
5C07-27	1056.9/1050.6	6.3
5H13-27	1123.6/1099.4	24.2
5L10-27	1120.7/1064.4	56.3
5M09-27	1117.3/1105.9	11.4
5G04-27	1065.7/1019.7	46.0
5G08-27	1117.9/1139.7	-21.8
5E08-27	1058.2/1077.1	-18.9
5H06-27	1067.7/1059.2	8.5
5G02-27	1013.8/1010.8	3.0
	Average bias	14.7
Average bias in all values		11.4

a. Different center fuel assemblies were used in LP-02-6 and LP-LB-1.

The 2-sigma uncertainty for the mean bias is given by:

$$2\sigma = (2\sigma_1^2 + 2\sigma_2^2 + 2\sigma_3^2 + 2\sigma_4^2)^{1/2}$$

$$= 16.2 \text{ K } (29.2^\circ\text{F})$$

$$2\sigma_1 = 10.8 \text{ K } (19.4^\circ\text{F})$$

$$2\sigma_2 = 4.25 \text{ K } (7.65^\circ\text{F})$$

$$2\sigma_3 = 3.9 \text{ K } (7.0^\circ\text{F})$$

$$2\sigma_4 = 10.6 \text{ K } (19.0^\circ\text{F}).$$

The bias in the LOFT cladding thermocouple data at peak cladding temperature (PCT) is $11.4 \pm 16.2 \text{ K } (20.5 \pm 29.2^\circ\text{F})$.

The mean bias of 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$) is considered to be applicable to the PCT data set obtained from all LOFT large-break transients, even though only two of the five large-break transients were used. Transients L2-2 and L2-3 are very similar to LP-02-6 and transient L2-5 is very similar to LP-LB-1. A PCT data set would be expected to yield a very similar result, based on FRAP-T6 calculations of the five transients.

The thermal response of the cladding as a function of time is concluded to be bounded by the cladding thermocouple mean bias, except for time periods of very rapid cooling of the cladding. In this situation, the thermocouple surface can transition to a nucleate boiling regime earlier than the cladding.

To place the above evaluation of LOFT cladding temperature bias in a larger context, relevant data obtained in other facilities in which LOFT-type external thermocouples were used, were analyzed. In particular, data from Power Burst Facility (PBF) and COSIMA experiments were analyzed, the results of which are presented in Appendix B. Biases calculated from the PBF data are 85 K (153°F) during blowdown and 27 K (48.6°F) during reflood, and for the COSIMA experiments a blowdown bias of 15 K (27°F) was calculated.

Appendix B also describes the results from estimating peak temperatures on zircaloy clad rods using metallurgical examination. From several experiments using both an electrically heated rod and three nuclear fuel rods, an estimate was made of the difference between measured (LOFT external thermocouple) peak clad temperature readings and calculated (from metallurgical examination) peak temperatures. In terms consistent with the foregoing definition of bias, these results produced biases ranging from -14 to

33 K^k (-25.2 to 59.4°F), where the uncertainty of the calculational technique is $+70$ K (126°F) (95% confidence level).

3.7 Thermocouple Cable Fin Effect on LOFT Fuel Rods

The LOFT cladding surface thermocouple bias of $11.4 \text{ K} \pm 16.2 \text{ K}$ ($20.5^\circ\text{F} \pm 29.2^\circ\text{F}$), determined in Section 3.6, is the difference between true cladding temperature and the temperature indicated by the thermocouple attached to the external surface of the cladding. In this section the effect of the thermocouple mechanical component on the temperature of the cladding is addressed. This is referred to as the fin effect of the thermocouple cable on the surface of the fuel rod.

The temperature data relevant to the determination of the fin effect is summarized in Table 3 for LOFT LP-02-6 and in Table 4 for LOFT LP-LB-1. Supporting the information in these tables are the as-built instrument layout schematics for the center fuel assembly in each experiment, shown in Figures 28 and 29^l, that locate the thermocouples listed in Tables 3 and 4. The instrumented fuel rods shown in Figures 28 and 29 are referenced to the power distribution shown in Figure 30¹⁶. The LOFT core is symmetric on a 1/8 sector basis. Figure 30 shows the power distribution of a 1/8 sector of the entire LOFT core. Figure 31 contains a sample calculation of power density using the values in Figure 30.

k. Since in these examinations, the temperature difference is between the measured and calculated temperature on the same rod, this bias does not contain the temperature difference "component" between instrumented and uninstrumented rods.

l. The schematics show the fuel assembly instrument plan. Instrument failures are not indicated. The qualified data obtained from the instruments are contained in the NRC Data Bank maintained at the Idaho National Engineering Laboratory.

Figure 28. Instrumentation layout in the center fuel assembly in LOFT LP-02-6.

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Figure 29. Instrumentation layout in the center fuel assembly in LOFT LP-LB-1.

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- 1) Top numbers - Average pin power/average core power
- 2) Bottom numbers - Average power in fuel pin block at the hot plane/average core power

Therefore item (1) gives radial peaking factors and the ratio of item (2) to item (1) in any pin gives the axial peaking factor.

- 3) H identifies the hot pin.

Figure 30. LOFT core power distribution map—1/8 sector symmetric.

Power Density Calculation

Example:

Transient LP-LB-1

Total core Power:	49.3 MW
Number of fuel rods in the LOFT core	1300
Core average power/rod = $49.3 \times 10^6 / 1300 =$	3.7923×10^4 W
Core average power/rod/inch (66" rod length) =	0.575 kW/in.
Core average power/rod/cm =	0.226 kW/cm
Average pin power/average core power = (top number in core map)	1.511
Total power in that rod = $1.511 \times 3.7923 \times 10^4 =$	5.73×10^4 W
Average power in that rod =	0.868 kW/in. (0.342 kW/cm)
Axial peaking factor is $2.331 / 1.511 =$	1.543
Peak power density in that rod = $1.543 \times 868 =$ (0.527 kW/cm)	1.339 kW/in.

Figure 31. Power density calculation using values from Figure 30.

Table 3. Loft LP-02-6 fuel and cladding temperature information.

Fuel rod	Fuel TC axial location (in.) ^a	Cladding TC axial location (in.)	Fuel temperature at t=0 (K) ^b	Fuel temperature at 5 s (K)	Fuel temperature at 30 s (K)	Cladding temperature at 5 s (K) ^c
5D07	27	27	1769	1213	751	930.8
5D09	27	—	1765	1233	756	—
5D10	27	—	1858	1393	823	—
5F04	—	26	—	—	—	1058.5
5F07	—	26	—	—	—	1017.5
5F08	—	26	—	—	—	1008.0
5H06	—	28	—	—	—	1015.4
5H07	—	26	—	—	—	1018.4
5I04	—	27	—	—	—	1002.9
5J08	—	26	—	—	—	1002.7
5L06	—	26	—	—	—	1073.2
5M09	—	26	—	—	—	1014.0

a. Relative to bottom of fuel rod.

b.. Uncertainty in fuel thermocouple data is ± 4.25 K.c.. Uncertainty in cladding thermocouple data is ± 3.9 K.

Table 4. Loft LP-LB-1 fuel and cladding temperature information.

Fuel rod	Fuel TC axial location (in.) ^a	Cladding TC axial location (in.)	Fuel temperature at t=0 (K) ^b	Fuel temperature at 5 s (K)	Fuel temperature at 35–40 s (K, max)	Cladding temperature at 5 s (K) ^c	Cladding temperature at 35–40 s (K, max)
5D07	27	27	1933	1408	1141	1018.6	1118.6
5C07	27	27	1988	1410	1122	1050.5	1095.6
5H13	27	27	2060	1493	1239	1099.4	1198.6
5L10	27	27	2071	1464	1205	1064.4	1170.8
5M09	27	27	2049	1473	1207	1105.9	1178.0
5G04	27	27	2010	1442	1166	1019.7	1135.6
5G08	27	27	1999	1441	1196	1139.7	1190.1
5E08	27	27	1961	1430	1183	1077.1	1154.7
5H06	27	27	1903	1380	1218	1059.2	1196.1
5G02	27	27	1870	1348	1122	1010.8	1098.1
5F09	27	27	1927	1393	1210	—	—
5F04	—	26	—	—	—	1134.8	1168.8
5F08	—	24	—	—	—	1143.3	1223.2
5F08	—	28	—	—	—	1124.7	1205.5
5G06	—	30	—	—	—	1119.3	1201.8
5I06	—	21	—	—	—	1180.5	1219.4
5J04	—	26	—	—	—	1067.3	1185.0
5J04	—	30	—	—	—	1139.6	1185.0
5J08	—	24	—	—	—	1148.5	1252.5
5J08	—	28	—	—	—	1163.4	1230.5

a. Relative to bottom of fuel rod.

b. Uncertainty in fuel thermocouple data is ± 4.25 K.c. Uncertainty in cladding thermocouple data is ± 3.9 K.

There are two qualifications that are placed on the data shown in Tables 3 and 4 and Figure 30. First, there are local and global coolant flow asymmetries in the LOFT core. The local asymmetries are caused by the presence of instrument hardware that affects the flow area around the fuel rods. The global flow asymmetries are caused by the fuel assembly support structures in the upper plenum and the location of the broken loop hot leg relative to the core. This hot leg is located in the direction of fuel assembly 3 of the LOFT core, as shown in Figure 32. The coolant flow asymmetries cause variations in cooling among the fuel rods during the course of a large break transient.

The second qualification is that the power distribution map shown in Figure 30 was determined without inclusion of the instrumentation hardware. This would be a true 1/8 symmetry determination in this case. The presence of instrumentation hardware displaces coolant moderator which, in turn, affects the power in the rods. Therefore, rods that are instrumented, or near other rods that are instrumented, or near guide tubes that contain instruments, will have slightly different power densities relative to the case if no instrumentation hardware were present. The power variations will be small as indicated by the distribution in Figure 30 which shows only a small difference between a rod and the surrounding rods. However, as shown in Figure 13, the power variations can result in operating temperature differences that are large relative to the cladding thermocouple bias value, for example. Determination of the existence of a fin effect can be done only for the case where the fin effect is larger than the temperature variations caused by coolant flow variations and rod power density variations.

Several comparisons are now made to determine if a fin effect exists in the blowdown phase of the large break transient (0–30 s). The first comparison is between the calculated cladding temperatures on Rods 5D07 and 5D09 in transient LP-02-6. These two rods are in symmetric core locations; however, there is more instrumentation around Rod 5D07 which may cause the power in this rod to be slightly less than that in Rod 5D09. As shown in Figure 29, Rod 5D07 has surface

thermocouples whereas Rod 5D09 does not. The FRAPT6 calculated cladding temperatures for these rods, including the fuel centerline thermocouple, are these:

Rod 5D07	954.6 K $\pm$ 11.4 K
Rod 5D09	983.3 K $\pm$ 11.4 K

The difference, 28.7 K $\pm$ 22.8 K, may include a fin effect. Before the existence of a fin effect can be concluded, the thermal behavior of these rods with the fuel centerline thermocouple replaced with fuel must be calculated. The results of this calculation are as follows:

Rod 5D07 (no fuel TC)	1029.9 K $\pm$ 11.4 K
Rod 5D09 (no fuel TC)	1036.5 K $\pm$ 11.4 K

These calculations show no fin effect. Since the FRAPT6 fuel rod model contains a temperature dependent geometry, the combination of small variations in cooling and higher power levels in the rods resulted in a closer agreement at the higher rod temperatures. These higher temperatures for Rods 5D07 and 5D09 can be compared with the measured cladding temperature on Rod 5I04, which is in a symmetric core location:

Rod 5I04 (no fuel TC)	1002.9 K $\pm$ 3.9 K
	(measured)
	1014.3 K $\pm$ 20.1 K
	(TC bias value added)

The three rods are showing the same cladding temperatures if the uncertainties are considered. The instrumentation in the vicinity of Rod 5I04 is approximately the same as the instrumentation in the vicinity of Rod 5D07. These two rods are showing essentially the same cladding temperature; however, the lower absolute value of Rod 5I04 can also be attributed to the global flow asymmetry in the core. With reference to Figure 29, the global cooling asymmetry causes the cladding temperatures to decrease in the direction of lower row numbers and higher column letters. The difference between the cladding temperature values on Rods 5D07 and 5I04 can be attributed to the cooling asymmetry. The analysis of the thermal behavior of Rods 5D07, 5D09, and 5I04 shows no apparent thermocouple fin effect.

Figure 32. LOFT reactor vessel showing the orientation of the core.

The second comparison of data from LOFT LP-02-6 involves the degree of fuel centerline cooling in Rod 5D07 (with cladding TCs) and in Rods 5D09 and 5D10 (both without cladding TCs). For this comparison the 0–30 s time interval is chosen. This time interval covers the early thermal energy redistribution in the fuel rod following DNB and the enhanced cooling interval that began at approximately 5 s. The results are these:

Rod	Fuel Centerline Cooling [temperature differential 0–30 s, (K)]
5D07	1019 ± 4.25
5D09	1010 ± 4.25
5D10	1033 ± 4.25

This comparison shows no fin effect.

A third comparison of LP-02-6 data involves the calculated cladding temperature on Rod 5D10 (without cladding TCs) and measured cladding temperature on Rods 5F04 and 5L06. These three rods are in symmetric locations in the center fuel assembly. The comparison is made by first determining the $h(t)$ on the surface of Rod 5D10 with the FRAPT6 code and then replacing the fuel centerline thermocouple with fuel. The calculation with this geometry can be compared to the measurement of cladding temperature on Rods 5F04 and 5L06, neither of which have fuel centerline thermocouples. The results are these:

Rod	Cladding Temperature at 5s, (K)
5D10	1136.0 ± 11.4 (fuel centerline TC removed)
5F04	1069.9 ± 16.2 (includes thermocouple bias value)
5L06	1084.6 ± 16.2 (includes thermocouple bias value)

The instrumentation in the vicinity of Rod 5F04 is approximately the same as the instrumentation in the vicinity of Rod 5L06. The difference in the measured cladding temperature on these rods, therefore, is attributed to the global cooling asymmetry in the core. In terms of percentage, the temperature difference is only 1.4%. However, when considering the uncertainties, which are 95% confidence level, the cladding temperature is the same

on the two rods. Rod 5D10 is in a region that has very little instrumentation which would result in a higher power level in Rod 5D10. Also, the global cooling asymmetry in the core would cause Rod 5D10 to undergo less cooling than the other two rods. The difference between the minimum cladding temperature value on Rod 5D10, 1124.6 K, and the maximum cladding temperature value on Rod 5L06, 1090.8 K, is 33.8 K. This temperature difference, 3% of the 5D10 value, must be attributed to the effects of instrumentation hardware, global cooling asymmetry, and possibly a thermocouple fin effect. However, the comparison between Rods 5F04 and 5L06, and the power differences caused by the presence of instrumentation are considered to comprise the major part of the 33.8 K temperature difference, thus making the thermocouple fin effect very small.

Data from LOFT LP-LB-1 in Table 4 can also be used to investigate a possible fin effect in the 0–5 s interval. Comparing the fuel centerline cooling on Rod 5F09 (no cladding TCs) with the fuel centerline cooling on the rods with cladding thermocouples gives the following:

Rod	Fuel Centerline Cooling in the 0–5 s Interval, (K, ± 8.5 K)	
5F09	532	(no cladding thermocouples)
5C07	578	
5D07	525	
5E08	531	
5G02	522	
5G04	568	
5G08	558	
5H06	523	
5H13	567	
5L10	607	
5M09	576	
average:	556	minimum = 522 maximum = 607 4 values below 5F09 6 values above 5F09

These results show no fin effect; however, the variations in rod cooling are quite large, approximately 9% from the average. The variation at 5 s

is attributed primarily to the fuel temperature redistribution following DNB which is still underway. Therefore, the fuel centerline temperature data in this time interval would not be a good indicator of the presence of a fin effect.

The calculated cladding temperature at 5 s on Rod 5F09 (no cladding TCs) can be compared with the measured cladding temperature on the rods having cladding thermocouples (Table 4). The following results are obtained for the comparisons of (a) Rod 5F09 with Rod 5D07, and (b) Rod 5F09 with the average of the ten rods having both fuel and cladding thermocouples:

- (a) Rod 5F09 calculated cladding temperature = $1054.7 \text{ K} \pm 11.4 \text{ K}$

Rod 5D07 (with thermocouple bias added) = $1030.0 \text{ K} \pm 20.1 \text{ K}$

- (b) Rod 5F09 calculated cladding temperature = $1054.7 \text{ K} \pm 11.4 \text{ K}$

Average cladding temperature on the ten rods having both fuel and cladding thermocouples (with thermocouple bias) = $1075.9 \text{ K} \pm 20.1 \text{ K}$

The two values in (a) compare well and show no fin effect within the uncertainty of the data. Rod 5D07 was chosen for the comparison since the initial fuel centerline temperature in this rod is close to that for Rod 5F09. The data in (b) also shows no fin effect within the uncertainty of the data. However, a correction to the average value can be estimated from the average initial fuel centerline temperature, which is larger than the initial fuel temperature in Rod 5F09. The average initial fuel centerline temperature is 1984.4 K which is very close to the value of 1988 K for Rod 5C07. Rod 5C07 cladding temperature is measured to be $1062.0 \text{ K} \pm 20.1 \text{ K}$ at 5 s (including the thermocouple bias value). This value, when compared to the calculated value for Rod 5F09, indicates that there is no measurable fin effect.

In summary, the thermocouple data in the blowdown phase of the large break transients LP-02-6 and LP-LB-1 show that the fin effect, if

present, is small and within the uncertainties of the data and calculations. This conclusion is in sharp contrast to the large fin effect that appears in the data during the reflood phase of the transients. An example of a fin effect in this phase is included in Appendix A.

3.8 Peak Cladding Temperature in LOFT LP-02-6 and LP-LB-1.

The peak cladding temperature in LOFT LP-02-6 occurred at approximately 5 s into the transient. At this time an surge of coolant into the core from the lower plenum occurred that resulted in an enhanced convective cooling condition for a period of about 10–12 s. The enhanced cooling was corewide and sufficient to prevent the cladding thereafter from attaining the temperature at 5 s. In Section 3.6 the thermocouple bias was determined to be $11.4 \pm 16.2 \text{ K}$ ($20.5 \pm 29.2^\circ\text{F}$). In Section 3.7 the fin effect of the presence of the thermocouple attached to the cladding was determined to be insignificant. On the basis of these results, the peak cladding temperature that should be stated for LOFT LP-02-6 is the maximum measured cladding temperature in the 26–28-in. elevation plus the thermocouple bias. Therefore, the peak cladding temperature in LOFT LP-02-6 is the following:

$$\begin{aligned} \text{Peak Cladding Temperature} &= 1073.2 \pm 3.9 \text{ K} \\ &\quad (\text{LP-02-6}) \quad (\text{Rod 5L06}) \\ &\quad + 11.4 \pm 16.2 \text{ K} \\ &= 1084.6 \pm 20.1 \text{ K} \end{aligned}$$

The conservative upper limit value of 1104.8 K should be used in all analyses in which peak cladding temperature is important.

The peak cladding temperature in LOFT LP-LB-1 occurred just prior to the onset of the reflood phase in the 30–35 s interval. The enhanced cooling condition did not occur, by experiment design, in LP-LB-1. There was a short period of some top-down cooling followed by a continued heatup of the cladding due to decay heat. The determination of the peak cladding

temperature in LP-LB-1 is done in the same manner as for LP-02-6. The maximum measured cladding temperature is taken from the nine thermocouples listed in Table 4. The result is the following:

$$\begin{aligned} \text{Peak Cladding} \\ \text{temperature} &= 1252.5 \pm 3.9 \text{ K} \\ \text{(LP-LB-1)} &\quad \text{(Rod 5J08)} \\ &\quad + 11.4 \pm 16.2 \text{ K} \\ &= 1263.9 \pm 20.1 \text{ K} \end{aligned}$$

Again, the conservative upper limit value of 1284.0 K should be used in all analyses in which peak cladding temperature is important.

Since the determination of the thermocouple bias value involved data in LP-LB-1 from only the rods containing both fuel centerline and cladding surface thermocouples, checks were made to determine if this set of thermocouples was consistent with the set of thermocouples from rods containing only cladding thermocouples. The checks include accounting for the difference in operating power (approximately 11%) between rods with and without fuel centerline thermocouples. The following calculations were made using the data in Table 4.

Check 1

Average of the measurements on rods with both fuel and cladding thermocouples:

$$\begin{aligned} \text{Set 1} \quad t = 5 \text{ s} \quad &\text{cladding temperature} \\ &1064.5 \pm 3.9 \text{ K} \\ &\text{fuel temperature} \\ &1428.9 \pm 4.25 \text{ K} \end{aligned}$$

Average of the cladding measurements on rods with only cladding thermocouples

$$\text{Set 2} \quad t = 5 \text{ s} \quad 1135.7 \pm 3.9 \text{ K}$$

The thermal behavior on Rod 5E08 was taken to be representative of the set 1 rods since the fuel centerline temperature in Rod 5E08 at 5 s was $1430.0 \pm 4.25 \text{ K}$. Removing the fuel centerline thermocouple from the FRAPT6 model of Rod 5E08 resulted in a calculated peak cladding temperature at 5 s of $1144.1 \pm 11.4 \text{ K}$. This value agrees with the average value from set 2 within the uncertainty of the data.

A second check is the comparison of Rod 5F09 calculated cladding temperature, with the fuel thermocouple removed from the FRAPT6 model, to the average cladding temperature in the set 2 thermocouples. First, however, the calculated cladding temperature on Rod 5F09 is compared with the average cladding temperature of the set 1 measurements to determine if Rod 5F09 thermal behavior is near to the average of the set 1 rods. The result is the following:

$$\begin{aligned} \text{Rod 5F09 calculated cladding temperature:} \\ 1054.7 \pm 11.4 \text{ K} \quad t = 5 \text{ s} \end{aligned}$$

$$\begin{aligned} \text{Average cladding temperature of set 1:} \\ 1064.5 \pm 3.9 \text{ K} \end{aligned}$$

The average fuel temperature at 5 s in the set 1 rods is $1428.9 \pm 4.25 \text{ K}$ which is higher than that for Rod 5F09 ($1393 \pm 4.25 \text{ K}$). If the difference is added to the Rod 5F09 fuel temperature, Rod 5F09 becomes similar to Rod 5E08. The cladding temperature on Rod 5E08 at 5 s is $1077.1 \pm 3.9 \text{ K}$. On the basis of these results, Rod 5F09 thermal behavior can be concluded to be near the average of the set 1 rods. Comparison of Rod 5F09 with the set 2 rods gives the following result:

$$\begin{aligned} \text{Rod 5F09 calculated cladding temperature} \\ \text{(fuel thermocouple replaced with fuel):} \\ 1150.1 \pm 11.4 \text{ K} \quad t = 5 \text{ s} \end{aligned}$$

$$\begin{aligned} \text{Average cladding temperature from set 2:} \\ 1135.7 \pm 3.9 \text{ K} \end{aligned}$$

$$\begin{aligned} \text{With added thermocouple bias:} \\ 1147.1 \pm 20.1 \text{ K} \end{aligned}$$

The agreement in the two checks shows that the thermal behavior of the two sets of thermocouples in LP-LB-1 are consistent.

3.9 Relationship of the LTSF Data and Analyses to the LOFT Data

Following completion of the LOFT L2-2 and L2-3 experiment data analyses, researchers questioned the validity of the LOFT cladding surface-mounted thermocouple data since the thermal-hydraulic behavior observed during the "enhanced cooling" period was not anticipated and was outside the intended operational envelope of the thermocouples.

The first attempt to determine whether the cladding surface-mounted thermocouples were giving an accurate portrayal of the fuel rod cladding behavior was experimental. A series of tests were conducted in the LTSF,⁴ to duplicate the LOFT core thermal-hydraulic conditions, measure the actual cladding temperatures (using embedded thermocouples), and compare the actual cladding temperatures to the temperatures measured by LOFT-type cladding surface-mounted thermocouples. A description of the LTSF effort, in light of the analysis given in Subsection 3.5, is given in Subsection 3.9.1.

Using the available LTSF data, some researchers have analyzed the anticipated behavior of the cladding surface-mounted thermocouples during selected LOFT experiments. Foremost among these analysts are Coddington and Gill.³ A summary of their findings, in light of the analysis given in Subsection 3.5, is given in Subsection 3.9.2.

3.9.1 LOFT Test Support Facility (LTSF) Experimental Data. The LTSF experiments were designed to meet several objectives:

1. Measure the capability of two heater rod designs^m to simulate the thermal response of nuclear fuel rods
2. Evaluate the capability of the LOFT cladding-surface mounted thermocouple design to accurately measure LOFT fuel rod cladding temperatures
3. Evaluate the installation procedure for thermocouples embedded on the inner diameter of fuel rod cladding
4. Test the reliability and lifetime of embedded thermocouples under operating conditions.

Although only Objective 2 is directly applicable to the studies described herein, the four LTSF experimental objectives are so intertwined that each will be briefly addressed in the following paragraphs.

The strategy employed to evaluate the capability of the LOFT cladding-surface mounted thermocouples was centered first on obtaining a baseline measurement that could be trusted to give an accurate measure of the fuel rod simulator cladding temperature and second on duplicating the LOFT core thermal-hydraulic conditions. The baseline measurement was to be provided by thermocouples embedded on the inner cladding surface of a REBEKA heater rod, while the LOFT core thermal-hydraulic conditions were to be studied by obtaining a test condition envelope that included the LOFT data. In fact, neither of these goals was achieved.

m. FEBA and REBEKA heater rods: FEBA heater rods were solid-type rods with Inconel cladding, magnesia insulator, an internal heater element, and no simulated pellet-cladding gap. The REBEKA rods featured a simulated fuel pellet to cladding gap, i.e., 0.1 mm, that separated the Zircaloy cladding from aluminum oxide pellets and an internal heater assembly. The REBEKA rods are cartridge-type heater rods. Each LTSF three-by-three heater rod bundle had either nine FEBA rods or eight FEBA rods around the periphery and one REBEKA rod in the center. Both types of rods were provided by the Karlsruhe Nuclear Research Center in Germany.

3.9.1.1 Heater Rod Design. Experiments were conducted using the REBEKA rod both with and without the LOFT cladding-surface mounted thermocouples.ⁿ In both cases, it was intended that two prototype cladding-embedded thermocouples, installed prior to the experiments, would always be present on the inner surface of the cladding. Thus, data from the cladding-embedded thermocouples could be used to evaluate the effect of the cladding-surface mounted thermocouples on the heater rod quench behavior and also provide an accurate measure of the cladding temperature.

Unfortunately the cladding-embedded thermocouples proved to be unreliable. The primary junctions of these two thermocouples failed prior to the beginning of the first experiment and the experimentalists had to rely on other methods to meet their objectives such as evaluating the validity of the secondary junctions and using an analytical procedure based on an assumed known temperature in the heater rod (the location of which was determined by trial and error techniques) together with known fluid conditions adjacent to the heater rod wall. The revised procedure introduced unanticipated instrumentation uncertainty into the experiments. However, the additional uncertainty was not sufficient to render the data unusable. Due to the ingenuity of the experimentalists, the data were instrumental in partially meeting Objectives 1 and 2. Further, the unreliability of the thermocouples embedded in the cladding provided clear answers to Objectives 3 and 4, i.e., the thermocouple design and installation procedure required modification and was unreliable. Consequently, the surface-mounted cladding thermocouples were conclusively shown to be the most reliable means of measuring cladding temperature available in the first half of the 1980s.

3.9.1.2 Experiment Procedure. Because the exact thermal-hydraulic conditions in the LOFT

n. Whether the cladding surface-mounted thermocouples acted as cooling fins was investigated by conducting similar experiments using the REBEKA rod with and without the thermocouples attached.

core were unknown for the L2-3 experiment,^o a range of test section inlet conditions were specified for the LTSF experiments. The range was defined to bracket the suspected LOFT core thermal-hydraulic conditions. However, since the LTSF was a separate effects facility, some compromises were inherent to the experimental procedure; the test section pressure behavior and non-condensable gas concentrations were not equivalent to those of the LOFT data.

3.9.1.3 Comparison of LOFT and LTSF Core Thermal-Hydraulic Conditions. Extensive analyses by Coddington and Gill³ have shown that the heat transfer coefficients that describe the energy transfer between the LTSF heater rods and the LTSF test section coolant were on the order of 10^3 W/m²·K. For such an energy transfer level, a major result of the Coddington and Gill³ analysis is that the LTSF cladding surface-mounted thermocouples were probably in the coolant-dominated mode, i.e., the thermocouples measured the coolant temperature rather than the cladding temperature. In contrast to Coddington and Gill's³ findings, the present study has shown that the heat transfer coefficients adjacent to the LOFT fuel rods, during experiments comparable to those of the LTSF, were on the order of 10^4 W/m²·K, i.e., an order of magnitude greater than the rod heat transfer coefficients applicable to the LTSF test section. Thus, the LOFT fuel cladding surface-mounted thermocouples were in the clad-dominated or clad-indicative mode during the transient.

The difference in the peak heat transfer coefficients in the LTSF and LOFT experiments occurred because the LTSF experimentalists were unable to duplicate the LOFT core thermal-hydraulic conditions during the "enhanced cooling" portion of the transient. Unfortunately, this deficiency was not apparent until the analysis

o. The LTSF experiments were conducted specifically to investigate the performance of the LOFT thermocouple instrumentation under high-pressure thermal-hydraulic conditions typical of the L2-3 experiment.

described in Subsection 3.5 was completed four years after the LTSF experiments.

3.9.1.4 Comments—The Gottula Study and Surface-Mounted Thermocouples.

Although the conclusions in Gottula⁴ (see Conclusions 1 and 2, page 42) relating to the enhanced cooling period are erroneous, since the enhanced cooling period was not simulated in the LTSF, the LTSF data are nonetheless probably representative for other phases of the LBLOCA blowdown. However, since an enhanced cooling period was not simulated, Objectives 1 and 2 could not be completely satisfied (see opening paragraph under Subsection 3.9.1). If further use of the Gottula⁴ data are planned, a detailed study of their applicability should be made to define which portions of the LBLOCA transient that these data are representative.

Nevertheless, the data obtained by Gottula were useful in meeting Objectives 3 and 4, i.e., the thermocouples embedded in the inner cladding wall were found to be unreliable and the design immature. Consequently, Gottula's work showed that the only practical method for measuring fuel rod cladding temperatures in the early to mid 1980s was by using cladding external surface-mounted thermocouples.

In fact, the surface-mounted thermocouples have been shown to be very useful instrumentation that give valid information for much of a LBLOCA transient. Based on their original design objectives, as specified between the late 1960s and mid 1970s, the surface-mounted thermocouples have provided the information that was expected and thus have fulfilled their design expectations. For fuel rod cladding thermal response during LBLOCA transients without enhanced cooling, the thermocouples have delivered unambiguous data with a low uncertainty that clearly describes the fuel rod behavior.^{1,2}

3.9.2 UK LOFT Thermocouple Analysis.

Coddington and Gill³ analyzed the LOFT thermocouple response in LP-02-6 with an approach that utilizes data from the LOFT Test Support

Facility (LTSF) and initial and boundary heat flux conditions obtained from a calculation of LP-02-6 with the TRAC-PF1/MOD1 code. Their approach consisted of five steps:

1. Evaluation of heat fluxes, and thus heat transfer coefficients, from solid electrical heater rods to the coolant in the LTSF.
2. The assumption was made that under equivalent conditions the surface heat fluxes are the same for the rod and the thermocouple by making use of LTSF data from an equivalent experimental series that included heater rods with and without external surface thermocouples.
3. Using a two-dimensional finite element heat conduction model of the LOFT fuel rod, thermocouple, and fuel rod-thermocouple weld, together with the general purpose heat conduction code TAU, one of the LTSF experiments was simulated with surface heat fluxes as a boundary condition.
4. The Item 3 calculational technique was supplemented with a three-dimensional calculation to account for differential cooling along the thermocouple cable length and other associated axial conduction heat paths.
5. Using fuel rod-thermocouple initial state and heat flux boundary conditions extracted from a TRAC-PF1/MOD1 calculation of LP-02-6, the fuel rod thermocouple model was used to simulate the expected cooling and quench behavior of the cladding and thermocouple.

Coddington and Gill's³ approach is outlined in more detail in Appendix C. Their conclusion was: "The response of the thermocouples in LOFT Experiments L2-2, L2-3, and LP-02-6 therefore cannot be taken to be representative of the behavior of the uninstrumented fuel rods." However, the Coddington and Gill analysis rests on two assumptions:

Analysis of Thermocouple Response During LBLOCA

1. The LTSF experiments are phenomenologically equivalent to the LP-02-6 phenomena.
2. The TRAC-PF1/MOD1 code can accurately calculate the initial and boundary heat flux conditions in LP-02-6.

The present study focused rather on evidence of LOFT fuel temperature behavior taken directly from the LOFT experiments themselves. It does not rely, as the UK study does, on information (i.e., LTSF data, TRAC-PF1/MOD1 calculations) that cannot be proven to be relevant to the LOFT experiments.

4. IMPLICATIONS OF THE LOFT THERMOCOUPLE BIAS ON LBLOCA CSAU

The LOFT LBLOCA test data constitute a large portion of the experimental data base used in the Code Scaling, Applicability, and Uncertainty (CSAU) study⁵ to define the uncertainty in best-estimate code analyses of LBLOCA transients. Consequently, the extent to which the bias found in the present study affects the conclusions reached in Reference 5 is of some importance.

In the CSAU study a 55.6 K (100°F) bias was assumed for the LOFT peak cladding temperature data. The LOFT thermocouple bias, as explained in the previous subsection, is 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$). Thus, the CSAU assumed bias bounded the value obtained in this study. Further discussion of the role of LOFT data in the CSAU study is contained in Appendix D.

5. CONCLUSIONS

In this report an extensive analysis has been presented to address the general issue of LOFT surface-mounted cladding thermocouple behavior during large-break LOCA simulations carried out in that facility. From these analyses, the following conclusions have been drawn:

1. *Measured cladding temperatures during LOFT large-break LOCA experiments were generally indicative of actual cladding temperature response, in particular the blowdown cooling that occurred in Experiments L2-2, L2-3, and LP-02-6.*

The thermal and hydraulic behavior exhibited in Experiments L2-2, L2-3, and LP-02-6 was very similar, in that core-wide cooling occurred during the early phase of the blowdown due to the delivery of coolant from the reactor coolant pumps. The inclusion of fuel centerline thermocouples in LP-02-6 provided a clear picture of the core thermal response. Evidence supporting the above conclusion is provided by analyzing the relationship of the behavior of fuel centerline temperature data to that of the associated cladding temperature data in LP-02-6, as well as the relationship between fuel centerline data from LP-02-6 and corresponding data from LP-LB-1, in which no blowdown cooling occurred. Furthermore, analysis using a FRAP-T6 model of the LOFT fuel clearly indicates that the observed fuel centerline temperature response in LP-02-6 could only have occurred if the cladding had cooled, as was indicated by the surface-mounted thermocouples.

2. *The presence of surface-mounted cladding thermocouples on specific fuel rods neither precipitated the observed blowdown cooling nor materially affected the rate of cooling observed in LP-02-6 (and by association L2-2 and L2-3).*

Comparison of the fuel centerline thermocouple data for fuel rods with and without surface-mounted thermocouples in LP-02-6 shows the "fin" effect provided by the external thermocouple is small. Blowdown cooling occurred

regardless of the presence of the surface-mounted thermocouple.

3. *The mean bias in LOFT peak cladding temperature data during large-break LOCA experiments (i.e., the difference between calculated PCT on an uninstrumented fuel rod and measured PCT on an instrumented fuel rod, positive valued by definition when the calculated value is greater than the measured value) is estimated to be 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$).*

Analysis of the differences between calculated peak clad temperature (using the FRAP-T6 fuel model) and measured peak clad temperature from Experiments LP-02-6 and LP-LB-1 (54 points) resulted in a mean bias of 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$)

4. *The LOFT cladding thermal response as a function of time during large-break LOCA experiments, is bounded by the cladding thermocouple mean bias except for time periods of very rapid heating or cooling of the cladding.*

Comparisons of the FRAP-T6-calculated cladding temperature response with the measured temperature response show that the externally-mounted thermocouples can "lead" that of the cladding, owing to the fin effect or earlier transition of the thermocouple from film to nucleate boiling than the cladding.

5. *Since an enhanced cooling period was not simulated in the LTSF experiments, the LTSF data cannot be used to evaluate the capability of the LOFT cladding surface-mounted thermocouple design to accurately measure LOFT fuel rod cladding temperature. If further use of the Gottula⁴ data is planned, a detailed study of their applicability should be made to define which portions of the LBLOCA transient that these data are representative.*

Although the conclusions in Gottula⁴ (see Conclusions 1 and 2, page 42) relating to the

enhanced cooling period are erroneous, since the enhanced cooling period was not simulated in the LTSF, the LTSF data are nonetheless probably representative for other phases of the LBLOCA blowdown. In addition, the Gottula data give an important evaluation of the status of the technology for mounting thermocouples in the cladding inner diameter; the LTSF data show this technology was immature in 1984.

6. *The conclusions reached in the LBLOCA Code Scaling, Applicability, and Uncertainty (CSAU) Study, which made use of LOFT LBLOCA cladding temperature data, remain unaltered by the surface thermocouple bias computed in the present study.*

The CSAU Study assumed a 56 K (100°F) bias was applicable to the LOFT cladding temperature

data. Since this bounded the 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$) result of the present study, there is no impact on either the qualitative or quantitative conclusions of that study.

The analyses of the fuel and cladding thermocouple data in the LP-02-6 and LP-LB-1 transients did not indicate the presence of a measurable fin effect in the blowdown phase (0–30 s). This is in marked contrast to the data from the same thermocouples during the reflood phase of the transients. Large fin effects are indicated in the reflood phase.

The analyses presented herein provide the basis for recommending peak cladding temperature values for the LP-02-6 and LP-LB-1 transients. These values are 1104.8 K (1529.0°F) for LP-02-6 and 1284.0 K (1851.5°F) for LP-LB-1.

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Appendix A

**Nonuniform Cladding and Thermocouple
Cooling Phenomena**

Appendix A

Nonuniform Cladding and Thermocouple Cooling Phenomena

The upper part of the LOFT core experiences nonuniform top-down cooling from the gravitational fall of saturated fluid in the upper plenum during large-break transients. This cooling begins at approximately 18 s and is approximately 10–15 s in duration. The degree of cooling varies among the fuel rods because the amount of saturated water available is small. The effects of this kind of cooling can be analyzed from sets of fuel centerline and cladding thermocouples that were located at the 43.8-in. elevation in the center fuel assembly in LOFT large break transient LP-LB-1. These thermocouple sets are shown in the fuel assembly schematic in Figure 29 in Section 3.7.

Sets of fuel centerline and cladding thermocouples at the 43.8-in. elevation are shown for four fuel rods in the center fuel assembly in Figures A-1 through A-4. Rod 5L07 experiences very little cooling whereas Rods 5I04, 5I08 and 5I14 experience progressively larger cooling, respectively. The cladding thermocouple on Rod 5I04 experiences a quench of short duration which shows on the fuel centerline thermocouple as a small temperature decrease. The cladding thermocouples on Rods 5I08 and 5I14 experience longer duration quenches. In these two cases the cladding is also considered to undergo at least a near quench, as judged by the response of the fuel centerline thermocouple.

The fuel centerline temperature on Rods 5I04, 5I08, and 5I14 is less than the measured cladding surface temperature following the return to CHF conditions after the thermocouple quenches occurred. Further, on Rods 5I08 and 5I14 the cladding surface heatup rate following the return to CHF is higher than that for adiabatic conditions under decay heat input. These response characteristics indicate that fuel Rods adjacent to these instrumented Rods experienced less cooling and consequently became radiant heat sources. Adjacent fuel rods could have cladding

temperatures similar to that indicated by the cladding thermocouple on Rod 5L07 in Figure A-1.

The effect of a radiant heat source on fuel rod thermal behavior was studied by imposing a 6 s interval of high cooling on the FRAP-T6 calculation shown in Figure 25 in Section 3.5.2. The radiation heat source (adjacent fuel rods) was maintained at the fuel rod cladding temperature shown in Figure 27 in Section 3.5.2. The high cooling was imposed in the 15–21 s interval. The calculated fuel centerline and cladding surface temperatures are shown in Figure A-5. The calculated behavior is very similar to that measured on Rods 5I08 and 5I14 as shown in Figures A-3 and A-4, respectively. The calculated fuel centerline temperature is less than the calculated cladding surface temperature but the difference is less than that measured for Rods 5I08 and 5I14. This is expected since the cladding thermocouple was shown in Section 3.0 to be cooler than the cladding (thermocouple bias) for an internal fuel rod heat source (decay heat). A large external radiant heat source would produce the reverse effect; that is, a thermocouple indicated temperature that would be hotter than the cladding.

The calculated thermal behavior in Figure A-5 for LP-LB-1 can be compared to that measured for LP-02-6 in Figure 12 in Section 3.3. The area for comparison is the temperature behavior following return to CHF after the high cooling ends at approximately 14 s. There is no evidence of an external heat source in LP-02-6 since the heatup rate following thermal equilibration is near to and below adiabatic conditions for decay heat. Therefore, uninstrumented fuel rods adjacent to instrumented Rod 5D07 in LP-02-6 experienced similar cooling. The absence of measured heatup rates higher than adiabatic in LP-02-6 supports the conclusion that the bottom-up core-wide cooling beginning at approximately 5 s was real,

M618-WHT-692-02

Figure A-1. Fuel and cladding thermocouple data at the 43.8 in. elevation on Rod 5L07.

M618-WHT-692-03

Figure A-2. Fuel and cladding thermocouple data at the 43.8 in. elevation on Rod 5I04.

Figure A-3. Fuel and cladding thermocouple data at the 43.8 in. elevation on Rod 5108.

Figure A-4. Fuel and cladding thermocouple data at the 43.8 in. elevation on Rod 5114.

Figure A-5. FRAP-T6 calculated fuel centerline and cladding surface temperatures on a rod experiencing a period of significant cooling with adjacent rods experiencing no cooling.

affected all fuel rods, and was sufficiently large to make thermocouple fin effects negligible.

A fuel centerline thermocouple was also located at the 43.8-in. elevation in Rod 5J07. This rod did not have cladding thermocouples. The fuel centerline temperature data from Rod 5J07 compares best with the fuel centerline temperature data from Rod 5L07, as shown in Figure A-6,

which indicates that these two rods underwent similar cooling. This comparison is shown for the purpose of illustrating the kind of difference that can occur during reflood between rods with and without cladding thermocouples. As shown in Figure A-6, Rod 5L07 (with cladding thermocouples) was quenched approximately 15 s earlier than Rod 5J07 (without cladding thermocouples).

M618-WHT-692-01

Figure A-6. Fuel centerline temperature at the 43.8 elevation in Rods 5J07 and 5L07.

Appendix B

**Experimental Data: Other Facilities
and Metallurgical Studies**

Appendix B

Experimental Data: Other Facilities and Metallurgical Studies

In this Appendix, two approaches are taken to supplement the results of the LOFT surface-mounted thermocouple bias that is presented in Subsections 3.4 and 3.5. The first approach is to examine relevant data from other experimental facilities. The second approach is to obtain an independent estimate of the LOFT fuel rod PCT using zircaloy oxidation kinetics and microstructures information. The two approaches and summarized in Sections B.1 and B.2, respectively.

B.1 Experimental Data from Other Sources

Relevant data from other facilities were studied, from the standpoint of quantifying the potential bias exhibited by externally-mounted thermocouples in those facilities. The PBF, COSIMA, and NEPTUNE facility experiments were examined to identify the most prototypical experimental data using nuclear rods with and without LOFT-type externally mounted thermocouples (References B-1, B-2, and B-3). The PBF experiments (Reference B-1) and the COSIMA experiments (Reference B-2) appeared to be the most useful for quantifying a temperature bias relevant to the LOFT experimental data. The PBF and the COSIMA data analyzed in the following subsections.

B.1.1 Analysis of PBF Temperature Data.

The PBF experiments utilized four nuclear fuel rods in the configuration shown in Figure B-1. Two of the fuel Rods (2 and 3) had LOFT external thermocouples, as well as thermocouples welded to the cladding inner surface (Rod 3) and others embedded in the cladding near the inner wall (Rod 2). The other two rods (Rods 1 and 4) had no externally-mounted cladding thermocouples, but did have the thermocouples welded to the cladding inner surface (Rod 1), and embedded in

inner surface wall (Rod 4). For this analysis, the thermocouple data from fuel Rods 2 and 4 were analyzed, noting that both rods have the embedded thermocouples.

The PBF TC-4 experiment series provided the most useful data. In this series, the PBF system operated so as to subject the fuel rods to hydraulic conditions simulating a large break LOCA blowdown and refill/reflood. Since the shrouds shown in Figure B-1 were identical and shared a common upper and lower plenum, it could reasonably be assumed that all rods experienced the same hydraulic transient. Accordingly, rod-to-rod comparisons would show what, if any, effect the external thermocouples would have on rod behavior, and also the degree to which the external thermocouples were actually measuring cladding temperature.

In the present analysis, the objective was to assess the experimental bias in the external thermocouple measurements during these experiments. The bias of interest is that which occurred when peak temperatures were recorded. The method to calculate the external thermocouple bias was to estimate the clad outside surface temperature on fuel Rod 4 from the embedded thermocouple and then to compare the estimated blowdown and reflood peak temperatures with those measured with the LOFT external thermocouples on fuel Rod 2.

The method to estimate the peak cladding surface temperature for fuel Rod 4 was:

1. Subtract from the initial ($t \leq 0$) measured embedded inner wall thermocouple reading, the temperature drop across the cladding, utilizing the initial power, embedded wall thermocouple location, and the clad thickness and thermal property data. This is the estimated initial cladding surface temperature.

Figure B-1. Fuel train orientation for PBF TC-4 experiment series.

2. Assume that the external surface will undergo the same temperature rise (to either a blowdown peak or reflood peak) as the temperature rise measured by the embedded wall thermocouple.
3. Add to the estimated initial cladding temperature from (1) above the temperature rise noted in (2).
4. Subtract from the result of (3) the estimated temperature drop across the cladding at the peak temperature.

The estimated peak surface temperature for fuel Rod 4 (bard rod) becomes:

$$\begin{aligned}
 T_{\text{surface, peak Rod 4}} = & T_{\text{initial embedded T/C}} - \Delta T_{\text{clad initial}} \\
 & + (T_{\text{peak embedded T/C}} - T_{\text{initial embedded T/C}}) \\
 & - \Delta T_{\text{clad at peak}}
 \end{aligned}
 \tag{B-1}$$

This surface temperature was then compared to the measured LOFT thermocouple peak temperature on fuel rod 2 at the same location. Examples of thermocouple data are given in Figures B-2 and B-3. Figure B-4 illustrates the results obtained from Equation B-1 to estimate the outer cladding surface temperature from the embedded thermocouple data. Identical azimuthal thermocouple locations were compared for most of the experiments. The resulting data from these comparisons are given in Table B-1.

Figure B-2. Cladding surface temperature of fuel Rod 4, embedded thermocouples at 0.53 m and 340 degrees during Experiment TC-4A blowdown.

Figure B-3. Cladding surface temperature of fuel Rod 2 at 0.53 m and 340 degrees during Experiment TC-4A blowdown.

Figure B-4. Method of estimating the cladding surface temperature from the embedded thermocouple on fuel Rod 4.

Table B-1. LOFT thermocouple blowdown biases from PBF TC-4 experiments.

Experiment ^{a,b}	Rod 4 calc T _{initial} external [K (°F)]	Rod 4 embedded T/C temp rise [K (°F)]	Rod 4 calc external rod peak [K (°F)]	Rod 2 LOFT T/C peak [K (°F)]	ΔTemperature bias [K (°F)]
TC-4A	656.9 (723.4)	797 (976)	1193.0 (1688.4)	1098 (1517)	95.2 (171.4)
TC-4B	658.0 (725.4)	701 (803)	1098.0 (1517.4)	1025 (1386)	72.8 (131.0)
TC-4C	656.9 (723.4)	707 (814)	1103.0 (1526.4)	1025 (1386)	78.0 (140.4)
TC-4D	658.0 (725.4)	731 (857)	1128.0 (1571.4)	1040 (1413)	87.8 (158.0)
TC-4E	639.8 (692.7)	637 (687)	1015.4 (1386.7)	949 (1250)	65.6 (118.0)
TC-4G	643.1 (698.6)	580 (585)	962.0 (1272.6)	850 (1071)	111.7 (201.0)
Average					85.2 (153.3)

a. Reference B-1.

b. Experiment TC-4F was not used because of poor experiment and thermocouple conditions (Ref. B-1).

The average temperature bias for PCT in the blowdown phase was 85.2 K. This bias must be qualified by (a) uncertainty in the uniformity of coolant conditions in the four flow channels (Figure B-1) as noted by the authors of Reference B-1, and (b) measurement uncertainties in the temperature data used in Equation (B-1). Each source of uncertainty could contribute to a significant systematic error in the temperature bias. The authors of Reference B-1 state that the void fraction during the blowdown cooling was higher than in the LOFT LP-02-6 transients which, according to Nelson (References B-4 and B-5), can cause the heat transfer characteristics to differ from the low-void conditions when a low-void mixture is forced rapidly past a region in film boiling. Concerning measurement uncertainty, the uncertainty bars shown in Figures B-2 and B-3 in the high temperature region are larger than the average bias value determined from the as-measured data. Consequently, the bias values determined from the PBF data must themselves contain a large uncertainty.

When the same approach was used on the reflood peaks, the estimated cladding surface temperatures from fuel Rod 4 (bare rod) and fuel Rod 2 (with LOFT external thermocouples) were nearly identical. A different approach was used to assess the bias for the reflood peak. After CHF, when the rod is in film boiling, the external thermocouple would provide a fin effect on the cladding, and the thermocouple would measure a temperature somewhere between the true cladding surface temperature and the fluid temperature. Therefore, the measured embedded cladding temperature minus the clad temperature drop was compared to the LOFT external thermocouple reading on the same fuel rod. The LOFT thermocouple measured 17 to 27 K lower than what the true cladding surface temperature should be, based on the embedded thermocouple measurement. A bias of 27 K was then used to shift the measured LOFT reflood data. This value is consistent with the external to internal LOFT thermocouple effects observed in the NEPTUNE core uncover experiments (Reference B-3) which

showed a temperature difference of 20 K, between externally mounted and internal thermocouples.

B.1.2 Analysis of COSIMA Temperature Data. In the COSIMA experiments, electrical heater rods were used in a 9- rod bundle which was subjected to blowdown transients. LOFT external thermocouples were welded to the center rod in the same fashion as for the LOFT fuel rods. Repeat experiments were performed with a bare rod using optical pyrometers to measure the cladding surface temperature. There were also pyrometer readings for experiments in which the LOFT thermocouples were welded to the rod. The data that was used to characterize the LOFT thermocouple effect was for the blowdown phase. The peak temperature as measured with the LOFT external thermocouple was compared to the optical pyrometer reading on a bare rod for the same experiment conditions. Temperature plots from Reference B-2 are shown in Figures B-5 and B-6.

The COSIMA experiments provided two bias values that could be added to the data base for

blowdown LOFT thermocouple correction. The two bias values are listed in Table B-2. The average bias value is 15 K and is the bias to shift upward the measured LOFT blowdown average peak cladding temperature.

B.2 Temperature Estimates from Zircaloy Oxidation Kinetics and Microstructures

Metallurgical examinations of zircaloy cladding offer two independent techniques for estimating maximum cladding temperatures reached, i.e., zircaloy microstructures and zircaloy oxidation kinetics. Olsen (References B-6 and B-7) conducted experiments to add to the oxidation kinetics data base and established a state-of-the-art capability to estimate peak fuel rod cladding temperature in nuclear reactor thermal transients. The following discussion is a summary of this work and in large part is taken directly from References B-6 and B-7.

Figure B-5. Pyrometer and thermocouple measured temperatures for COSIMA at IN4 (blowdown).

Figure B-6. Pyrometer and thermocouple measured temperatures for COSIMA at IN6 (blowdown).

Table B-2. LOFT thermocouple average blow-down PCT bias from COSIMA experiments.

Experiment	Temperature bias [K (°F)]
IN4	25.0 (45.0) ^{A-2}
IN6	5.0 (9.0)
Average ^a	15.0 (27.0)

a. This value is used to shift upward the LOFT measured blowdown PCT.

B.2.1 Basic Research. Cladding microstructure characteristics permit determination of whether peak cladding temperatures achieved during abnormal thermal transients are within the α phase (<1100 K), the $\alpha + \beta$ phase (1100 to 1240 K), or the β phase (>1240 K). At temperatures below 1240 K, determination of the transition temperature through identification of the allotropic phases from microstructures is imprecise because of uncertainties associated with a multiple transient history and effects of cooling rate upon the

zircaloy microstructure for different cooling rates expected during the LOCA. However, the actual temperatures may be determined within ± 20 K from the fraction of β phase in the known two-phase $\alpha + \beta$ temperature region.

Cladding oxidation characteristics offer an alternative method to estimate peak cladding temperatures over a broad temperature range. High-temperature (>1270 K) oxidation is well characterized as a function of temperature and time-at-temperature, and with existing data and experience peak cladding temperatures between 1270 and 1770 K can be inferred within an estimated uncertainty of ± 40 to 70 K (95% confidence level), respectively.

For peak cladding temperatures below 1243 K, the limited oxidation data in the literature suggest that peak cladding temperatures in the high α and in the $\alpha + \beta$ region (970 to 1243 K) may be estimated by evaluating the extent of zircaloy oxidation. The current data in this temperature range were limited because (a) only one source of experimental data suitable for postirradiation examination (PIE) currently exists, and evaluation of potential systematic errors was not possible; (b) the data were not in a form that can

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be directly used for posttest metallographic analysis; and (c) the effect of multiple transients on oxidation characteristics was not evaluated.

Additional data for zircaloy oxidation rates in steam were obtained at INEL at temperatures of 961 to 1264 K and durations of 25 to 1900 s in order to overcome the above limitations and to calculate, in conjunction with measurements from postirradiation metallographic examinations, the prior peak temperatures of zircaloy fuel rod cladding in the $\alpha + \beta$ temperature region.

B.2.2 Application to Zircaloy Cladding with LOFT Thermocouples. Zircaloy oxidation rates determined at the INEL were used to evaluate the changes in a zircaloy-clad electrical heater rod that had been subjected to four transients and to three nuclear fuel rods that had variously been subjected to from one to four transients in the $\alpha + \beta$ temperature region.

Temperature estimates for the electrical heater rod from oxidation kinetics and the relative location of these temperature estimates are shown in Figure B-7, with the cross-section of the electrical heater rod taken at the junction of the thermocouples. The details of the microstructures and oxide layers for the different locations may be found in Reference B-7. Based on the oxidation kinetics, the peak cladding temperature was 1191 K and occurred opposite the two surface thermocouples. For the different oxide thicknesses, the temperature varied from 1141 K to 1191 K, resulting in a 50 K variation around the circumference of the zircaloy cladding. The temperatures near the two surface mounted thermocouples were 1159 K and 1145 K. The surface mounted thermocouple measurement was 1126 K which suggests a small thermocouple bias. Similarly, an estimated temperature of 1141 K at the

embedded thermocouple location (area 5 in Figure B-7) is slightly higher than the measured peak temperature of 1125 K. This difference suggests a small thermocouple effect (bias) on cladding temperature. At area 3, however, the difference is 41 K larger than at area 5. This is attributed to a combination of different oxide layer thicknesses at the two locations and the uncertainty in the temperature estimates based on oxide kinetics. The conclusion from this data, however, is that this data supports the small thermocouple bias and fin effect determined in the LOFT LP-02-6 data.

The first nuclear rod (Reference B-8) was subjected to three LOCAs, and a peak temperature of 1070 K was measured; the second nuclear rod was subjected to only one LOCA, during which a peak temperature of 1200 K was measured; and the third nuclear rod was subjected to four LOCAs, during which a peak temperature of 1125 K was measured.

The temperature estimates for the nuclear fuel rods were 1076 K compared with 1070 K measured for the first rod, 1186 K compared with 1200 K measured for the second rod, and 1145 K compared with 1125 K measured for the third rod. Calculated temperatures for two of the three rods were higher than the measured temperatures, which would be expected from thermocouple effects on cladding temperature. The low estimated temperatures for the second nuclear rod may be due to sloughed oxide or the lack of any thermocouple effect. All of these results appear consistent with the LOFT results for transients LP-02-6 and LP-LB-1 presented in Section 3. Also, the differences between calculation and measurement in Olsen's data are well within the variational range of differences between calculation and measurement in the LOFT transients.

Figure B-7. Estimated temperatures at thermocouple locations on the electric heater rod zircaloy cladding.

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Appendix C

Evaluation of UK LOFT Thermocouple Analysis

Appendix C

Evaluation of UK LOFT Thermocouple Analysis

Coddington and Gill (Reference C-1) have analyzed the LOFT thermocouple response in LP-02-6 with an approach that utilizes data from the LOFT Test Support Facility (LTSF) (References C-2, C-3) and initial and boundary heat flux conditions obtained from a calculation of LP-02-6 with the TRAC-PF1/MOD1 code. Specifically, their approach is summarized in the following steps:

1. Evaluation of heat fluxes (heat transfer coefficients) from solid electrical heater rods (with no external surface thermocouples) to the coolant in experiments in the LTSF. The heat transfer coefficients were evaluated as a function of rod temperature, fluid mass flow rate and equilibrium quality.
2. Use was made of the equivalent series of LTSF experiments on heater rods with and without external surface thermocouples. The assumption is made that the surface heat fluxes evaluated from the experiments with no external rod instrumentation would apply to rods with external thermocouples under equivalent conditions. That is, under equivalent conditions the surface heat fluxes are the same for rod and thermocouple.
3. A 2-D finite element heat conduction model of the fuel rod, thermocouple and fuel rod-thermocouple weld was constructed using the general purpose heat conduction code TAU, for the electrical fuel rod simulator. This was then used to simulate one of the LTSF experiments with an externally mounted thermocouple using a heat transfer surface (surface heat fluxes) evaluated from the parallel experiment on rods without an external surface thermocouple. An unknown parameter in this model was the thermal resistance of the weld, i.e., that between the thermocouple and the rod, and this was determined using the LTSF data.
4. To improve the calculation, a 3-D model was constructed to account for the spot welding of the thermocouple cable at intervals along the fuel rod. This allowed for differential cooling along the length of the thermocouple cable and any associated axial conduction heat paths.
5. The fuel rod thermocouple model was then used to simulate the expected cooling and quench behavior during the blowdown phase of LP-02-6. To do this the fuel rod-thermocouple initial state and heat flux boundary conditions were taken from a TRAC-PF1/MOD1 transient calculation. These conditions were from a calculation in which the fuel rod (uninstrumented) did not quench.

The results of their analysis of LP-02-6 are shown in Figure C-1 which is taken from Reference C-1. To quote their conclusions:

“The above analysis shows therefore that it is possible to explain the behavior of the LOFT thermocouples, on the basis of a model in which the surface heat flux to the passing fluid is consistent with that deduced from separate effects experiments and does not necessarily quench either the clad or the fuel rod; but because of the poor coupling of the thermocouple—first since the thermocouple is intermittently welded to the rod and second because the weld is restricted to a small fraction of the apparent area of contact, the response of the thermocouple is detached from that of the rod. The response of the thermocouples in LOFT experiments L2-2, L2-3, and LP-02-6 therefore cannot be taken to be representative of the behavior of the uninstrumented fuel rods.”

Figure C- 1. TRAC-PF1/MOD1 calculation of the centerline and surface temperature for Experiment LP-02-6.

The results obtained by the analyses in the current study lead to entirely different conclusions. The TRAC-PF1/MOD1 and TAU code calculations shown in Figure C-1 lead to a calculated fuel centerline and cladding response in LP-02-6 as shown in Figure C-2. The calculation of the fuel centerline temperature in Figure C-2 does not agree with the measured fuel centerline temperature on either surface instrumented or uninstrumented fuel rods in LP-02-6 as shown in Figure C-3. The Coddington and Gill analysis depends heavily on two assumptions:

1. The LTSF experiments are phenomenologically equivalent to the LP-02-6 phenomena
2. The TRAC-PF1/MOD1 code can accurately calculate the initial and boundary heat flux conditions in LP-02-6.

The present study focuses on evidence of LOFT cladding thermocouple behavior taken

directly from the LOFT experiments themselves. It does not rely on information (i.e., LTSF data, TRAC-PF1/MOD1 calculations) that cannot be proven to be relevant to the LOFT experiments. It is for this reason that the conclusions drawn in the present study are considered to be more defensible.

What can be said about the UK study is that it provides a basis for questioning the robustness of the LOFT surface thermocouples throughout a wide range of coolant conditions. In effect, what their results show is that conditions could arise in which the thermocouples might provide a false indication of cladding cooling that is an important finding, and is not inconsistent with the discussion of possible thermocouple behavior in Section 3 of this report. However, the root issue is what core cooling phenomena actually occurred in Experiments L2-2, L2-3, and especially LP-02-6. The results of the present study are considered to be of sufficient substance to put that issue to rest.

Figure C- 2. Comparisons of calculations and measurement of cladding surface temperature in Experiment LP-02-6.

Figure C- 3. Fuel centerline temperatures at the 27-in. elevation during Experiment LP-02-6.

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Appendix D

Compatibility of Calculated LOFT Thermocouple Bias with LBLOCA CSAU Evaluation and Implications of LOFT LBLOCA Data on Core Behavior in Full-Scale Systems

Appendix D

Compatibility of Calculated LOFT Thermocouple Bias with LBLOCA CSAU Evaluation and Implications of LOFT LBLOCA Data on Core Behavior in Full-Scale Systems

D-1. Introduction

The U.S. Nuclear Regulatory Commission (USNRC) recently issued a revised rule (see Reference D-1) for loss-of-coolant accident emergency core cooling system (LOCA/ECCS) analysis that is based on 15 years of research. The revised rule allows the use of a best-estimate computer code safety analysis method to meet licensing requirements, but requires the licensee to quantify the uncertainty of the code analysis and include the uncertainty when comparing the calculated results with acceptance limits provided in 10 CFR 50. The USNRC has developed and demonstrated an uncertainty evaluation methodology called Code Scaling, Applicability, and Uncertainty (CSAU) in support of the revised ECCS rule. The methodology is described in detail in Reference D-2.

An important element of the CSAU methodology is the assessment of the best-estimate computer code against qualified experimental data bases. However, since test data typically is obtained from scaled facilities, code assessments must include the inherent scaling compromises that may exist for unique data sets. The following section (Section D-2) discusses the conclusions of the CSAU studies relative to (a) LOFT data compared to data in other scaled facilities and (b) the applicability of data recorded in scaled-facility cores (for rate-dependent processes) to full-scale cores. In addition, calculational evidence is given showing similar core inlet mass flow behavior during blowdown in a full-scale system and the LOFT facility for similar LBLOCA transients. Section D-3 discusses the implications of the LOFT thermocouple bias

values (reported in the main body of this report) on the CSAU methodology application to PWRs. Finally, Section D-4 contains key conclusions relative to application of LOFT data to full-scale systems and the compatibility of the LOFT thermocouple bias values.

D-2. Applicability of LOFT LBLOCA Data to PWRs

The LOFT LBLOCA core-related data can be shown to be applicable to postulated commercial PWR LBLOCA behavior in two ways:

1. The CSAU methodology, in relating the behavior of core phenomena for a number of power-to-volume scaled facilities, demonstrated that LBLOCA core rate-dependent processes are well simulated in such facilities.
2. Advanced thermal-hydraulic code calculations of commercial PWR LBLOCA transients demonstrate similar coolant flow to the core as observed in the LOFT experiments.

The following discuss the above two approaches.

CSAU-Based Approach: The CSAU methodology application to the LBLOCA for PWRs required the use of experimental data from a wide spectrum of test facilities (both integral and separate effects) that include scales ranging from 1/30,000 to 1/48. The maximum measured cladding temperature from each LBLOCA experiment from each facility is plotted as a function of the specific linear heat generation rate in Figure D-1. The data shown in the figure are from

Figure D-1. Maximum measured cladding temperature from several scaled experimental facilities during blowdown.

facilities that adhered to a power-to-volume scaling criteria in their design. This is expressed as:

$$\frac{P_{\text{Test}}}{P_{\text{PWR}}} = \frac{V_{\text{Test}}}{V_{\text{PWR}}}$$

where P_{Test} and P_{PWR} are the power in the test facility and a typical Westinghouse four-loop PWR, respectively, and similarly, V_{Test} and V_{PWR} are the total primary coolant system volume for the test facility and the nuclear power plant. For idealized volume scaling, the time scale, fluid mass and energy distributions, velocities, accelerations, and lengths are preserved in the scaled facility as in the prototype plant. Since the time scale and the mass and energy distributions are maintained prototypical, rate dependent phenomena should be accurately simulated in the scaled facility.

The LOFT facility (and each of the other facilities represented in Figure D-1) was designed using a power-to-volume scaling criteria. However, since the LOFT core was 66 in. in

length, rather than the prototypical 144 in., the LOFT core flow area was, of necessity, enlarged to preserve the coolant-volume-to-power ratio. Figure D-1 shows the maximum cladding temperature recorded from numerous experiments in different facilities, including LOFT. Examination of these data show no systematic difference owing to scale. Indeed, the CSAU Technical Program Group concluded that:

“Any and all scale effects (if present) on blowdown peak cladding temperature are included with the 95% tolerance lines of Figure D-1”

Figure D-2 shows the LOFT data also agree with the measured reflood-related trends of other facilities. Figure D-2 presents data from a wide range of scaled facilities:

“Rate-dependent processes that occur in the core during a LBLOCA are well simulated in test facilities designed and operated according to the power-to-volume scaling criteria.”

Figure D-2. Measured temperature rise data from scaled experimental facilities during reflood.

Approach Using Advanced Codes: Analysis that ensued following LOFT Test L2-2 (Reference D-3) determined that the occurrence of significant core cooling during the early blowdown phase of the LBLOCA transient in the LOFT facility was directly related to the manner in which the coolant pumps were operated during the transient. If the coolant pumps continued to run throughout the blowdown phase of the transient, significant cooling was experienced throughout the core (L2-2, L2-3). Similarly, when the coolant pumps were allowed to coast down, beginning at the initiation of the transient, significant cooling was observed through the lower two-thirds of the core during the early blowdown phase (LP-02-6). Finally, when a locked rotor simulation was performed (pumps stopped very rapidly), no evidence of early blowdown phase cooling was observed (L2-5, LP-LB-1).

Analysis of the observed behavior indicated that the key to the occurrence of significant cooling during certain transients is associated with a coolant flow balance on the downcomer. For the cases of powered pumps and coasted-down pumps, early in the blowdown phase of the transient the intact loop flow exceeded the break flow for a brief period immediately after the

coolant reached saturation at the break. Thus, the "excess" intact loop flow was forced into the downcomer and upward through the core. Figures D-3 and D-4 show comparisons of the intact and broken loop-mass flows during the blowdown phase of the transient for Tests L2-3 and LP-02-6, respectively. Figure D-5 shows a contrasting response from LOFT Test LP-LB-1 in which the coolant pump rotors were locked causing a very rapid flow coastdown. Figure D-5 clearly shows that the break flow rate was always greater than the intact loop flow, causing reverse flow in the core throughout the blowdown phase.

Best-estimate calculations were performed for a typical Westinghouse four-loop PWR using the RELAP5/Mod 1 code (Reference D-3). The study objective was to determine the corresponding effect of coolant pump operation on thermal-hydraulic response during a LBLOCA transient. The calculated response with the coolant pumps on throughout the early blowdown phase is shown in Figure D-6. Comparison of the calculated and experimental results shows that the same hydraulic response observed in the LOFT facility was calculated to occur in the PWR

Figure D-3. Comparison of the intact and broken loop cold leg mass flow for LOFT Experiment L2-3.

Figure D-4. Comparison of the intact and broken loop cold leg mass flow for LOFT Experiment LP-02-6.

Figure D-5. Comparison of the intact and broken loop mass flow for LOFT Experiment LP-LB-01.

Figure D-6. Calculated intact and broken loop, cold leg mass flows during a LBLOCA with pumps powered for a PWR (RELAP5).

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(see Figure D-3). Figure D-7 shows the hydraulic response of the PWR when all coolant pumps are unpowered at the initiation of the transient and coast down normally. Again, the figure shows that between about 3 s and 7.5 s, a positive core flow was predicted. This result is consistent with the results for LOFT Test LP-02-6 shown in Figure D-4.

Similarly, a calculation was performed for the case analogous to LOFT Test LP-LB-1 in which the coolant pumps simulated a locked rotor condition. Figure D-8 presents a comparison of the cold-leg flows. The figure indicates that, as in LOFT Test LP-LB-1 (Figure D-6), the break-flow exceeded the intact loop flows throughout the blowdown phase of the transient, thereby maintaining a continuous reverse core flow.

The above discussion shows that the break-related hydraulic response expected in a typical PWR is expected to be the same as the response observed in the LOFT LBLOCA experiments, and, therefore, the core inlet flow response is expected to be similar. Comparison of the calculated and measured amount of coolant mass that was available to cool the core during the observed

blowdown quench period of the transient indicates that the amount of coolant in the LOFT facility and in the PWR calculation were consistent with the scaling ratio between the two facilities. For the case of coolant pumps on throughout the transient, the ratio of the PWR coolant mass-to-LOFT coolant mass was about 61. For the case where the pumps were allowed to coast down normally, the coolant mass ratio was about 40. (The values of the coolant mass available for core cooling was determined by integrating the curves shown in Figures D-3, D-4, D-6, and D-7 during the period that the intact loop flow exceeded the break flow.)

D-3. Implications of The LOFT PCT Bias on CSAU LBLOCA Results

The analysis in the body of this report (see Section 3.5) has determined that the mean bias for the LOFT LBLOCA PCT data is 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$). The CSAU methodology applied to the LBLOCA scenario was based on a data base in which the LOFT data played a significant

Figure D-7. Calculated intact and broken loop cold leg mass flows during a LBLOCA with coolant pumps unpowered for a PWR (RELAP5).

Figure D-8. Calculated intact and broken loop cold leg mass flows during a LBLOCA with pump shafts locked for a PWR (RELAP5).

role. Therefore, it is important to understand the impact of the above bias on the CSAU analysis and conclusions. Accordingly, the following discussion is provided to summarize the compatibility of the LOFT-TC bias values and the CSAU LBLOCA results.

Sensitivity calculations relative to peak cladding temperature during blowdown were performed using a TRAC-PF1/Mod1 computer code model of a Westinghouse nuclear power plant. A code-related bias was determined based on these calculations. Figure D-9 illustrates how the numerous TRAC sensitivity calculations for PCT (noted as CSAU-NPR) compared to the experimental PCT data base presented earlier in Figure D-1. The figure shows that the TRAC calculations agreed reasonably well with the experimental data base. Figure D-10 presents the probability density function of the data base points and of the TRAC calculated data from Figure D-9. Note that the TRAC PCT distribution function is conservative when compared to the probability distribution function for the experimental PCT data. As a result of the sensitivity analysis performed with the TRAC code (see

Reference D-2), a summed bias of 316 K (110 F) was determined appropriate. Figure D-9 shows added conservatism when the summed bias is added to the TRAC distribution function. At the time the work reported in Reference D-1 was underway, the credibility of the LOFT cladding surface thermocouples was an unresolved issue. At that time, indications were that the LOFT PCT data might have a bias of about 56 K (100°F). Accordingly, each LOFT PCT data point was increased by 56 K and Figure D-10 shows the probability density function for the revised data set. The figure shows that the TRAC plus summed bias remained conservative relative to the revised experimental data base. Further, Reference D-2 also concluded that the TRAC probability density function without summed bias is also conservative.

Completion of the work reported in this study indicates that the mean bias to be applied to the PCT measured by LOFT cladding surface thermocouples is actually 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$). The assumed bias of 56 K in Reference D-2 therefore provided a bounding

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Figure D-9. Maximum measured cladding temperature from several scaled experimental facilities during blowdown.

condition to the actual LOFT PCT data bias. As a result, the conclusions stated in the application of the CSAU methodology to the LBLOCA scenario are unaffected by the findings of this study.

applicable to, and indicative of, expected thermal-hydraulic response in a prototype nuclear power plant.

D-4. Conclusion

The conclusions that can be stated from the discussions presented in Appendix D are:

1. The LBLOCA core thermal-hydraulic response data from LOFT experiments is

2. The mean bias of 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ\text{F}$) for the LOFT LBLOCA PCT data determined in this study does not impact the conclusions drawn from the application of the CSAU methodology to the LBLOCA scenario in a PWR.

Figure D-10. Comparing the effect of a 100°F adjustment to the LOFT data and its effect on the data histogram when compared to the TRAC distribution function during blowdown ($7.5 < \text{LHGR} < 10.5 \text{ kW/ft}$).

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11. ABSTRACT (200 words or less)

Data from the Loss-of-Fluid Test (LOFT) Program help quantify the margin of safety inherent in pressurized water reactors during postulated loss-of-coolant accidents (LOCAs). This report analyzes how well externally-mounted fuel rod cladding surface thermocouples in LOFT accurately reflected actual cladding temperature during large-break LOCA experiments. The analysis shows that there can be a significant difference (referred to as bias) between the surface-mounted thermocouple reading and the actual cladding temperature, and that the magnitude of this bias depends on the rate of heat transfer between the fuel rod cladding and coolant. Further, it is shown that, in terms of peak cladding temperature recorded during LOFT large-break LOCA experiments, the mean bias is 11.4 ± 16.2 K ($20.5 \pm 29.2^\circ$ F). The best-estimate value of peak cladding temperature for LOFT LP-02-6 is 1104.8 K. The best-estimate peak cladding temperature for LOFT LP-LB-1 is 1284.0 K.

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