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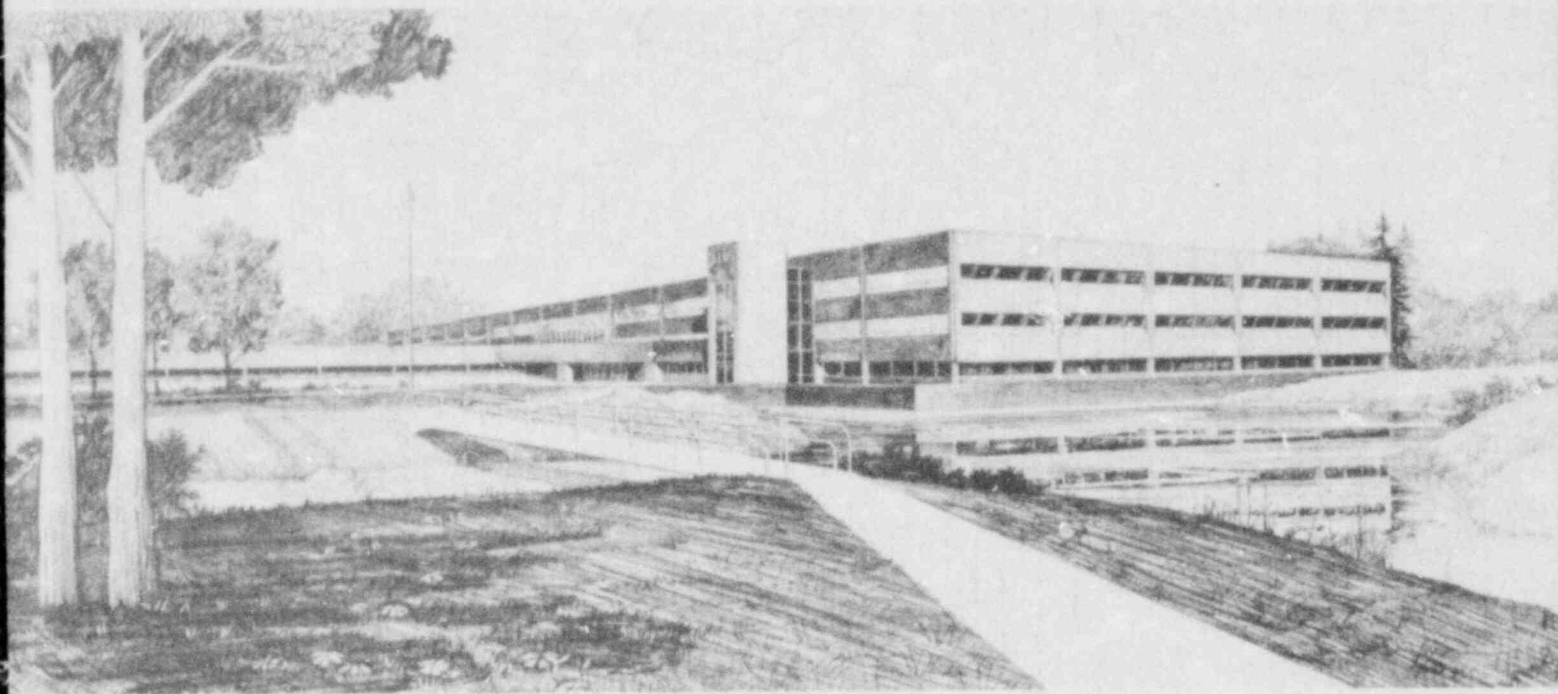

U.S. Department of Energy
Idaho Operations Office • Idaho National Engineering Laboratory

Power Burst Facility Thermocouple Effects Test Results Report, Test Series TC-1, TC-3, and TC-4

Richard W. Garner
Philip E. MacDonald

June 1982

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U.S. Nuclear Regulatory Commission
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POWER BURST FACILITY THERMOCOUPLE EFFECTS TEST RESULTS REPORT, TEST SERIES TC-1, TC-3, AND TC-4

Richard W. Garner
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EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

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ABSTRACT

Fuel rod cladding surface temperatures have been estimated in Loss-of-Fluid Test (LOFT) Facility and in Power Burst Facility loss-of-coolant accident (LOCA) tests using data obtained with thermocouples welded to the cladding outer surface. These cladding temperature estimates have been questioned because cladding surface thermocouples may act as cooling fins and local sites of cladding rewet, thereby delaying the time of occurrence of critical heat flux (CHF) and providing increased surface heat transfer. This report presents the results of three series of light water reactor fuel behavior tests (Thermocouple Effects Test Series TC-1, TC-3, and TC-4) that were performed in the Power Burst Facility to specifically evaluate the influence of cladding surface thermocouples on the thermal behavior of nuclear fuel rods under LOCA conditions. Twelve tests were performed in the three test series. Differences between tests included variations in system thermal-hydraulic conditions and in the initial test rod power level, as well as differences in design of the internal cladding thermocouples. This latter difference provided data for calibration of the surface thermocouples and evaluation of the influence of surface thermocouples on the time of occurrence of critical heat flux and post-CHF heat transfer.

FIN No. A6041

TFBP Experiment Design and Analysis

SUMMARY

In-pile experiments are being conducted in the Loss-of-Fluid Test (LOFT) Facility and in the Power Burst Facility (PBF) at the Idaho National Engineering Laboratory to obtain data for understanding and modeling the behavior of light water reactors during a postulated large pipe break loss-of-coolant accident (LOCA). Fuel rod cladding surface temperatures have been estimated using data obtained with thermocouples welded to the cladding outer surface. These cladding surface temperature estimates have been questioned because the surface thermocouples may act as cooling fins and local sites of cladding rewet that delay the time of occurrence of critical heat flux and provide increased surface heat transfer.

Three series of thermocouple effects tests (TC-1, TC-3, and TC-4) were conducted in the PBF to evaluate the influence of external cladding thermocouples on the thermal and mechanical behavior of nuclear fuel rods during large pipe break loss-of-coolant accident conditions. Each of these tests was performed with four LOFT-type fuel rods contained in individual flow shrouds. The fuel rods were symmetrically positioned within a PBF test train in an environment similar to the LOFT experiment environment. Two rods in each test series were instrumented with LOFT cladding outside surface thermocouples, with junctions located near the high power region of the fuel rods. The cladding surface thermocouples were extended to the bottom of the fuel stack with dummy thermocouple wires. All four rods were instrumented with internal thermocouples, with junctions at the same axial elevation as the external thermocouples. The internal thermocouples were fitted in slots on the surface of the fuel pellets. Some of the thermocouple junctions were welded directly to the inside cladding surface, some were embedded in the inside cladding surface, and the remainder were fitted into holes near the surface of the fuel pellets.

Specific objectives of the PBF thermocouple effects tests were (a) to evaluate the ability of cladding surface thermocouples to accurately measure cladding temperature during a LOCA simulation, (b) to investigate the effects of cladding surface thermocouples on the behavior of light water reactor (LWR) fuel rods under large break LOCA conditions and evaluate the influence of test variables on these effects, and (c) to evaluate the behavior and durability of embedded internal cladding thermocouples. The behavior of fuel rods with and without cladding surface thermocouples during an LOCA was examined by comparing the response of the internal thermocouples. The error in the cladding surface thermocouple measurements was estimated by comparing the data from the embedded thermocouples with the surface thermocouple data.

The TC-1 Test Series consisted of four LOCA transients, the TC-3 Test Series consisted of only one transient, and the TC-4 Test Series consisted of seven transients. Each test included a power calibration, decay heat buildup, blowdown (with a slug of low quality, two-phase coolant forced past the test rods about 5 to 7 s after initiation of the transient), heatup, and reflood phase. The system conditions at the initiation of each blowdown were approximately 600 K inlet temperature, 15.5 MPa system pressure, and 50.0 kW/m maximum rod power, except for Tests TC-4E and TC-4G, for which the rod powers were 43 and 39 kW/m, respectively. In addition to variations in initial rod power (39 to 50 kW/m), the TC Test Series included variations in coolant slug flow rate (0.4 to 1.2 L/s) and coolant slug average quality (10 to 45%).

Evaluation of the measured temperature drops across the cladding indicates that the cladding surface thermocouples measured cladding surface peak temperatures during blowdown that were only slightly lower (17 to 27 K) than the actual cladding temperatures. However, the surface thermocouples influenced the cladding temperatures during the blowdown phase of the TC tests. Specifically, the surface thermocouples caused both a delay in the initial occurrence of critical heat flux (CHF) and improved the cladding surface heat transfer, subsequently reducing the cladding peak temperatures. Peak temperatures measured during blowdown were an average of about 73.5 K lower for each second of delay in CHF. An additional reduction in measured peak temperatures of about 50 K apparently resulted from the improved cladding heat transfer due to the surface thermocouples. The combined effects of the surface thermocouples reduced the average cladding peak

temperature during the blowdown phase of the PBF tests by 101 to 115 K.

The variations in the imposed coolant slug thermal-hydraulic parameters (slug quality and flow rate) and in test rod initial power (or stored energy) used during the TC-4 Test Series provided experimental data to evaluate (a) the effect of surface thermocouples on fuel rod thermal response during the blowdown quench phase of a large break LOCA and (b) the influence of system thermal-hydraulic conditions on surface thermocouple effects during the blowdown quench. Although the influence is relatively small, the effect of surface thermocouples on rod thermal response during blowdown quench appears to increase as the slug quality decreases and as the flow rate increases. However, the data also indicate that the thermocouple effect may disappear at very low quality slug flows. Also, the effect of surface thermocouples on LWR fuel rod thermal response during blowdown quench appears to decrease as the rod initial power decreases, and at low power the effect disappears. When the thermal behavior of the test rods with and without surface thermocouples in different tests, but with the same blowdown peak temperature (because of different initial powers), were compared, the blowdown quench behavior of the two types of rods was indistinguishable. This result suggests that the influence of the surface thermocouples on fuel rod thermal response during blowdown quench is primarily due to the initial delay in time to CHF and fin cooling of the rods with surface thermocouples (i.e., the lower cladding temperatures just prior to the blowdown quench).

The measured cladding quench times and subsequent rewet times during the reflood phase of the TC-1 Test Series were also influenced by the cladding surface thermocouples, and fuel rods with external thermocouples quenched from 3 to 12 s before the other rods. However, the effects of surface thermocouples on fuel rod thermal response during the reflood portion of the TC-4 tests were small, and in some cases, no effects were detected.

The experience with the embedded internal cladding thermocouples proved them to be reliable and accurate cladding temperature measurement devices that can be used in future experiments.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Loss-of-Fluid Test Project (EG&G Idaho) for their technical and financial support in performing the Thermocouple Effects Test Series, to Dr. R. VanHouten (Nuclear Regulatory Commission) and Mr. Dave Rose (DOE-ID) for their encouragement and support of the test series, and to R. D. McCormick of EG&G Idaho for his help in developing the appendices.

CONTENTS

POWER BURST FACILITY THERMOCOUPLE EFFECTS TEST RESULTS REPORT, TEST SERIES TC-1, TC-3, AND TC-4

INTRODUCTION

The behavior of light water reactors following a postulated loss-of-coolant accident (LOCA) must conform to criteria specified in the Code of Federal Regulations. In-pile experiments are being conducted in the Loss-of-Fluid Test (LOFT) Facility and the Power Burst Facility (PBF) at the Idaho National Engineering Laboratory by EG&G Idaho, Inc., for the U.S. Nuclear Regulatory Commission to ensure that the behavior of both the cooling system and the nuclear core is understood and properly modeled. The LOFT Facility simulates the behavior of an entire, large pressurized water reactor (PWR) during a postulated LOCA. The PBF loss-of-coolant accident tests are providing in-pile information on the thermal and mechanical deformation behavior of nuclear fuel rods subjected to coolant conditions representative of those expected in a light water reactor (LWR) core during a double-ended cold leg break LOCA.

The coolant conditions during a postulated LOCA, such as a large cold-leg break in a four-loop pressurized water reactor, are characterized by an initial rapid system depressurization during which drastic changes occur in both mass flow and quality. Subcooled depressurization to saturation conditions occurs within approximately 100 ms. The subsequent depressurization is governed by saturated coolant conditions, with complete depressurization occurring within 20 to 30 s. The coolant flow stagnates within 1 to 2 s after saturation conditions have been attained and a condition of critical heat flux (CHF) occurs on the fuel rod cladding surface; heat transfer to the coolant is greatly reduced, and fuel rod temperatures rapidly increase. Core flow can be reestablished approximately 3 to 4 s after the break, terminating the rapid fuel rod temperature increase (blowdown peak temperature) and quickly cooling, and possibly quenching, the rods (blowdown quench) for a period of several seconds. However, the coolant will be depleted to the extent that CHF again occurs and fuel rod temperatures again increase 10 to 12 s after the break, but the temperatures will increase at a much slower rate, until terminated by core reflood and quench by the emergency core cooling systems.

The cladding temperatures measured during the LOFT large break loss-of-coolant experiments, L2-2 and L2-3, are shown in Figure 1 and substantiate the expected core cooling that occurs within 5 to 10 s after initiation of a simulated pipe rupture, well before the emergency core cooling systems were activated. However, fuel rod cladding temperatures have been estimated in the LOFT (and in the PBF) tests, using data obtained with thermocouples welded to the cladding outer surface. These cladding temperature estimates have been questioned because it has been hypothesized that the cladding surface thermocouples may be acting as cooling fins and local sites of cladding rewet that influence fuel rod thermal behavior by delaying the time of occurrence of critical heat flux and providing increased surface heat transfer. Therefore, due to its ability to provide in-pile subassembly testing with a wide range of coolant thermal-hydraulic conditions, the PBF was employed to obtain a better understanding of the LOFT test results and the influence of cladding surface thermocouples on LWR-type fuel rod thermal-mechanical responses during a large break LOCA.

This report presents the results of three series of LWR fuel behavior tests (TC-1, TC-3, and TC-4) that have been performed in the PBF to specifically evaluate the influence of cladding surface thermocouples on the thermal behavior of nuclear fuel rods under LOCA conditions. The PBF Thermocouple Effects (TC) Test Series was specifically designed to answer the following questions:

1. Do cladding surface thermocouples accurately measure LWR fuel rod cladding temperatures during a large break LOCA transient?

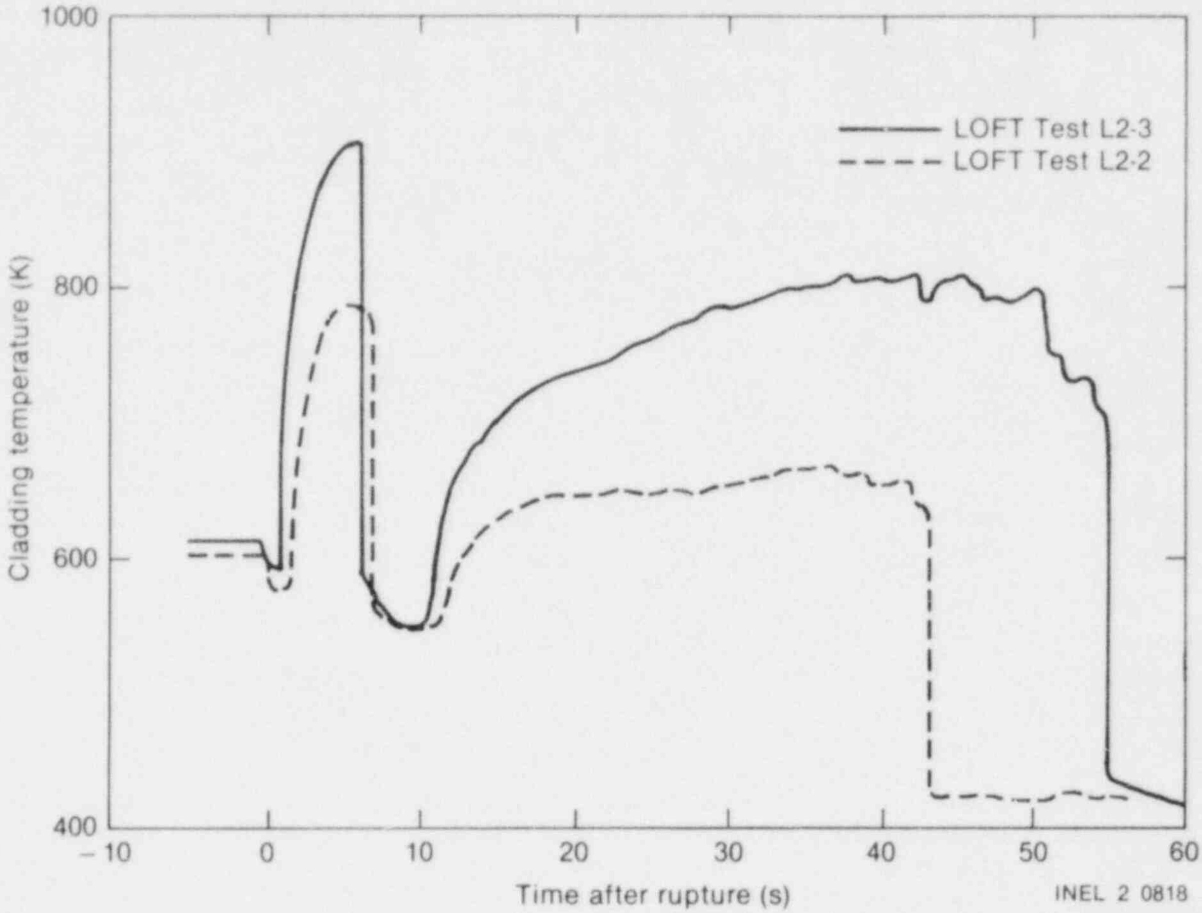


Figure 1. Cladding peak temperatures for LOFT Tests L2-2 and L2-3.

2. What correction factor should be applied to cladding surface thermocouple measurements to obtain the correct peak cladding surface temperature of uninstrumented rods; and how is the correction factor influenced by fin cooling and by delay in the time-to-CHF?

3. What is the effect of surface thermocouples on LWR fuel rod thermal behavior during a large break LOCA blowdown quench, and how is that effect influenced by the slug coolant conditions and the initial rod power?

4. Do cladding surface thermocouples significantly influence LWR fuel rod thermal response during reflood?

In addition, two of the test rods in the TC-4 Test Series employed an embedded thermocouple to measure cladding internal surface temperatures. An objective of the TC-4 tests was to evaluate the behavior and durability characteristics of the cladding embedded thermocouples under in-pile LOCA conditions.

The results from the TC-1 Test Series have been reported previously,[1] and it was concluded that surface thermocouples do influence fuel rod cladding temperatures during both the blowdown and reflood phases of a LOCA. However, the performance of Test Series TC-3 and TC-4 significantly expanded the range of thermal-hydraulic conditions and the amount of internal and external cladding temperature data, including the response of embedded internal cladding thermocouples. The results from the TC-1 tests are included in this report along with the results from the TC-3 and TC-4 tests to provide a broader basis for evaluating the effects of surface thermocouples and to emphasize the effect of improved measurement techniques (embedded cladding thermocouples) on the interpretation of the test results.

Subsequent sections of the report provide (a) a description of the PBF Thermocouple Effects tests design and conduct, as well as a description of the differences between tests; (b) a presentation of selected test results and a discussion of the specific questions posed above; and (c) a presentation of the conclusions based on the results of the TC tests. Details of the test designs and configurations are provided in Appendix A. Appendix B describes the conditions and conduct procedures for each test. Individual thermal responses during the TC Test Series are provided in the data plots of Appendix C. (The data for the TC-1 Test Series were not qualified; therefore, uncertainty values were not determined. The uncertainties for the TC-3 and TC-4 series are presented and discussed in Appendix C and identified on the individual data plots.) Descriptions of the RELAP-5 and FRAP-T5 computer codes and input data used to calculate system thermal-hydraulic conditions and fuel rod cladding temperature gradients, respectively, are provided in Appendix D. Documentation and record traceability information is provided in Appendix E. A description of the newly developed embedded internal cladding surface thermocouple is provided in Appendix F. (All of the appendices to this report are presented on microfiche attached to the inside of the back cover.)

EXPERIMENT DESIGN AND CONDUCT

Four LOFT-type fuel rods were tested in each test, all of which were instrumented with internal fuel rod thermocouples (some directly attached to the cladding inner surface and some in the fuel near the pellet outer surface), and two of which were also instrumented with cladding external surface thermocouples. Detailed descriptions of the test rod and test train instrumentation for each test series are provided in Appendix A.

The fuel rods were symmetrically positioned within a test train in the PBF in-pile tube. Each test rod was surrounded by a flow shroud to direct coolant flow to the individual rods. A cross-sectional diagram of the TC-4 test train, illustrating the relative locations of the fuel rods and flow shrouds and the relative orientations of the fuel and cladding thermocouples, is shown in Figure 2. The axial position of all fuel rod thermocouple junctions was 0.53 m above the bottom of the test rod fuel stack, the elevation of peak power within the PBF.

All cladding surface thermocouples were grounded-junction Type K (Chromel-Alumel) thermocouples with a 0.1168-cm-diameter titanium sheath and magnesium oxide insulator, flattened to a thickness of 0.067 cm at the junction. The thermocouples contained a tantalum barrier between the thermal element and the sheath to provide a thermal conduction path from the sheath to the junction and to provide a ground. The cladding surface thermocouples were laser welded to the cladding at the junction and at several locations along the fuel rods. Dummy thermocouple wire extensions were provided below the thermocouple junctions to ensure an equal distribution of mass along the length of the fuel rods and to minimize coolant flow perturbations in the vicinity of the thermocouple junctions.

The embedded internal cladding thermocouples were grounded-junction Type K thermocouples with a 0.076-cm-diameter zircaloy sheath and aluminum oxide insulator, flattened to a thickness of 0.025 cm at the junction. These thermocouples also contained a tantalum junction barrier. The thermocouples were embedded in the cladding inside surface by removing an oval shaped section from the cladding, cutting a groove into the inside surface of a duplicate oval section, placing the thermocouple in the groove and laser welding it in place, and, finally, laser welding the duplicate oval section in place in the cladding. The internal welded cladding thermocouples were also Type K, but were Inconel sheathed, with a diameter of 0.051 cm, and were resistance welded to the inside surface of the cladding.

Figure 3 shows a diagram of the junction area of a cladding surface thermocouple, and a photograph of a cladding surface thermocouple and dummy extension attached to a fuel rod. Figure 4 shows a conceptual drawing of an embedded internal cladding thermocouple and a photograph of the cross section of an embedded thermocouple.

In addition to the fuel rod thermocouples, the instrumentation associated with each fuel rod and coolant flow shroud in the TC tests included a linear variable differential transformer (LVDT) at the bottom of each fuel rod to measure cladding axial displacement, turbine flowmeters at the inlet and outlet of each flow shroud to measure the coolant volumetric flow rate, and inlet and outlet thermocouples on each flow shroud to measure coolant temperature rise over the fuel rod length.

Each test series consisted of a power calibration and a fuel preconditioning phase, a decay heat buildup phase, and from one to seven blowdown and reflood phases. Initial system conditions of approximately 600 K inlet coolant temperature, 15.5 MPa system pressure, and 0.8 L/s inlet coolant flow rate were used in all the TC test series. The initial (immediately prior to blowdown) test rod peak power density was 50 kW/m during most of the tests. At about 5 to 7 s after initiation of blowdown, a slug of two-phase coolant was forced past the fuel rods to simulate the blowdown quench observed during the LOFT tests. Slug flow[a] was terminated at 11 s,

a. The "slug flow" discussed in this report is not necessarily the same as the flow regime characterized by a series of individual large bubbles that almost fill the available flow area of a given test apparatus and are separated by liquid, but is the mass of two-phase coolant introduced into the test rod flow shrouds at about 5 to 7 s after initiation of the transient to cool the fuel rods in a manner similar to the cooling observed during the LOFT L2 Test Series.

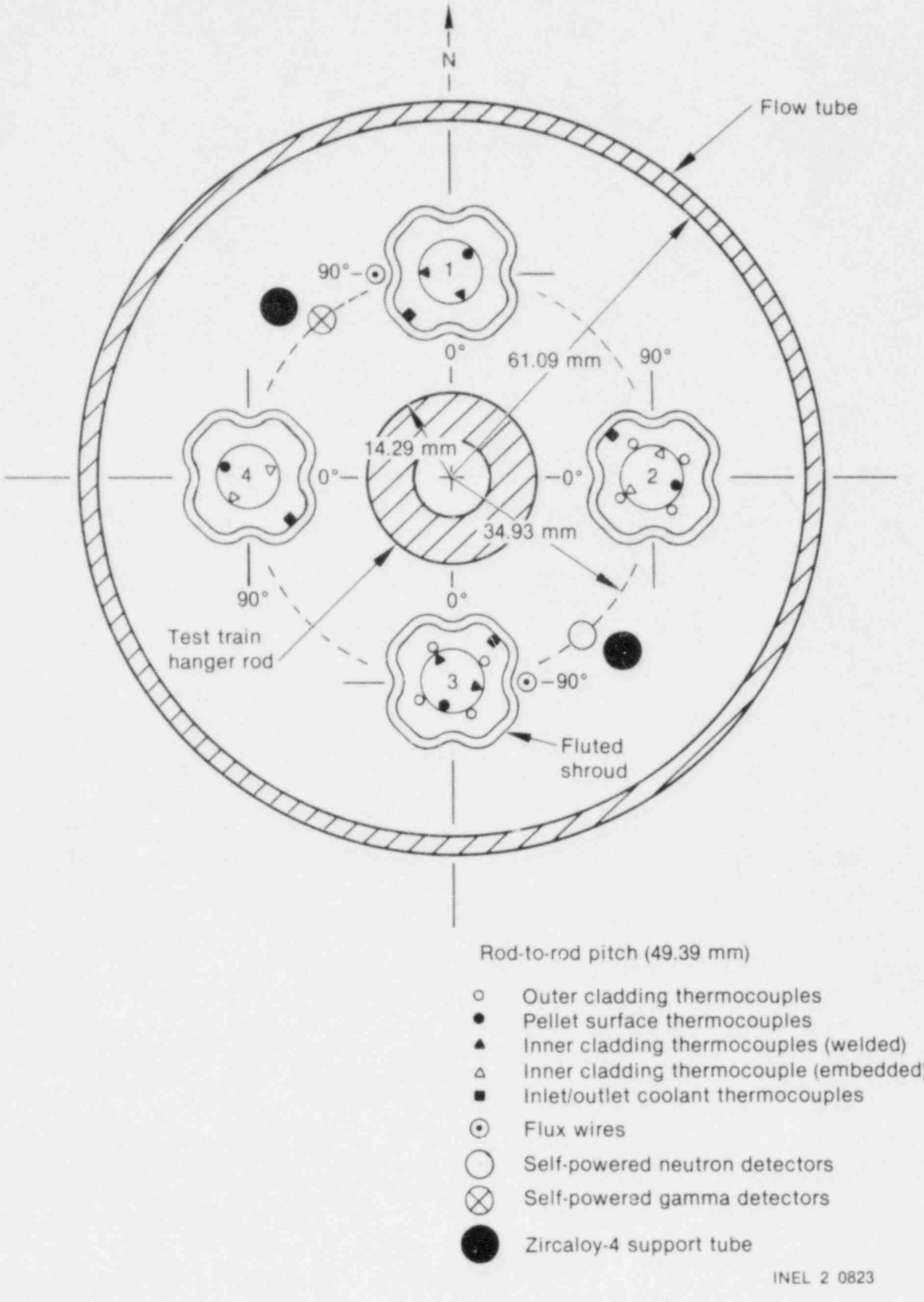
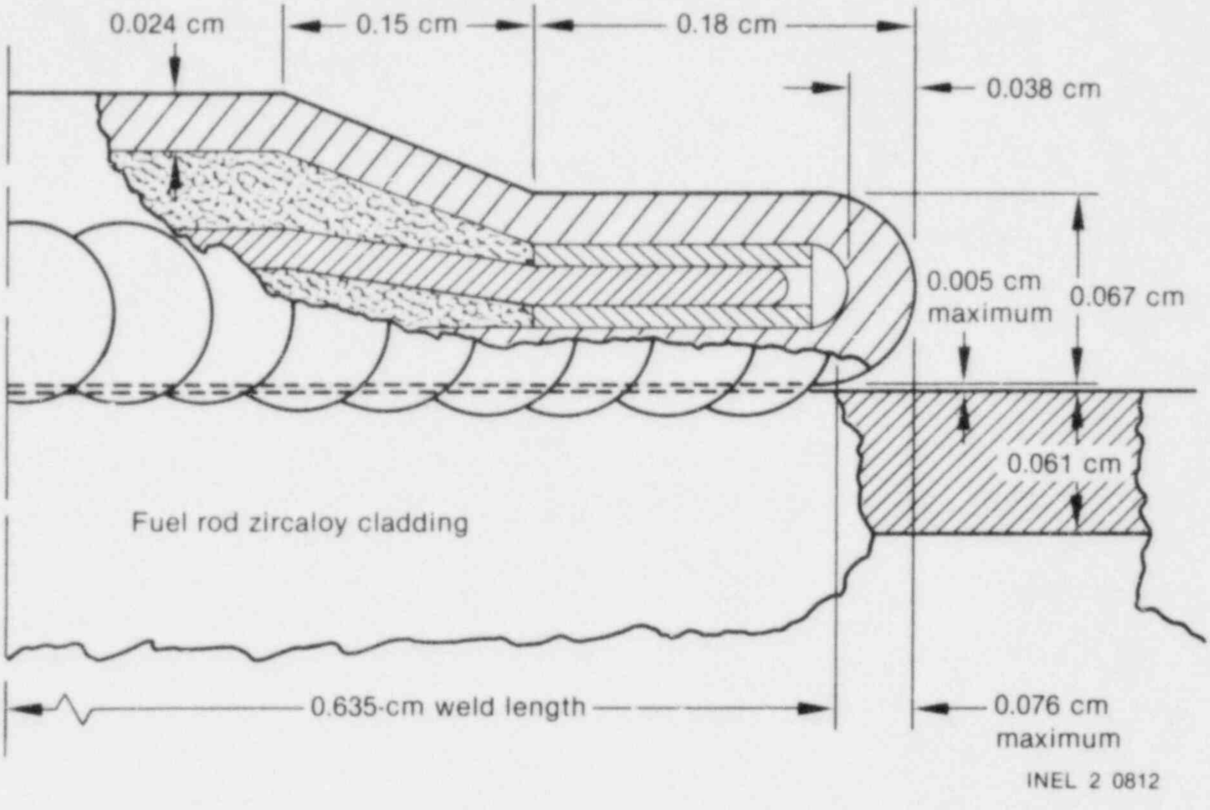


Figure 2. Fuel train orientation for Test Series TC-4.



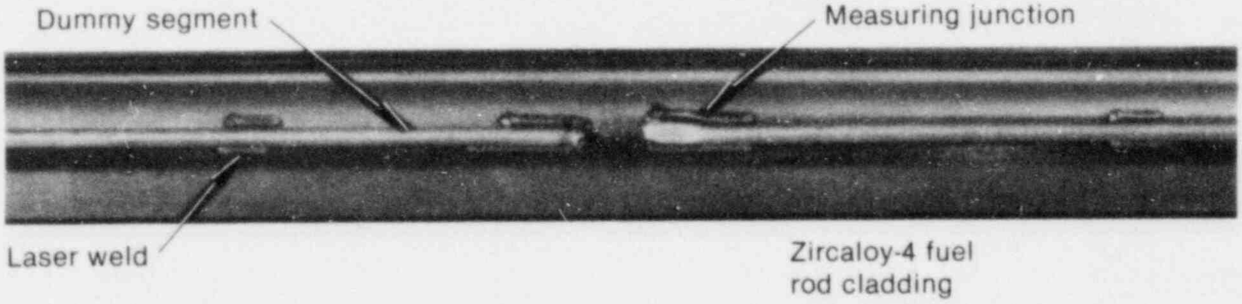


Figure 3. Diagram showing spade junction cladding surface thermocouple design, and photo of cladding surface thermocouple and dummy segment as attached to fuel rods in the TC Test Series.

and at 100 s, reflood coolant was injected to simulate emergency core coolant injection in a power reactor and to rewet and quench the fuel rods.

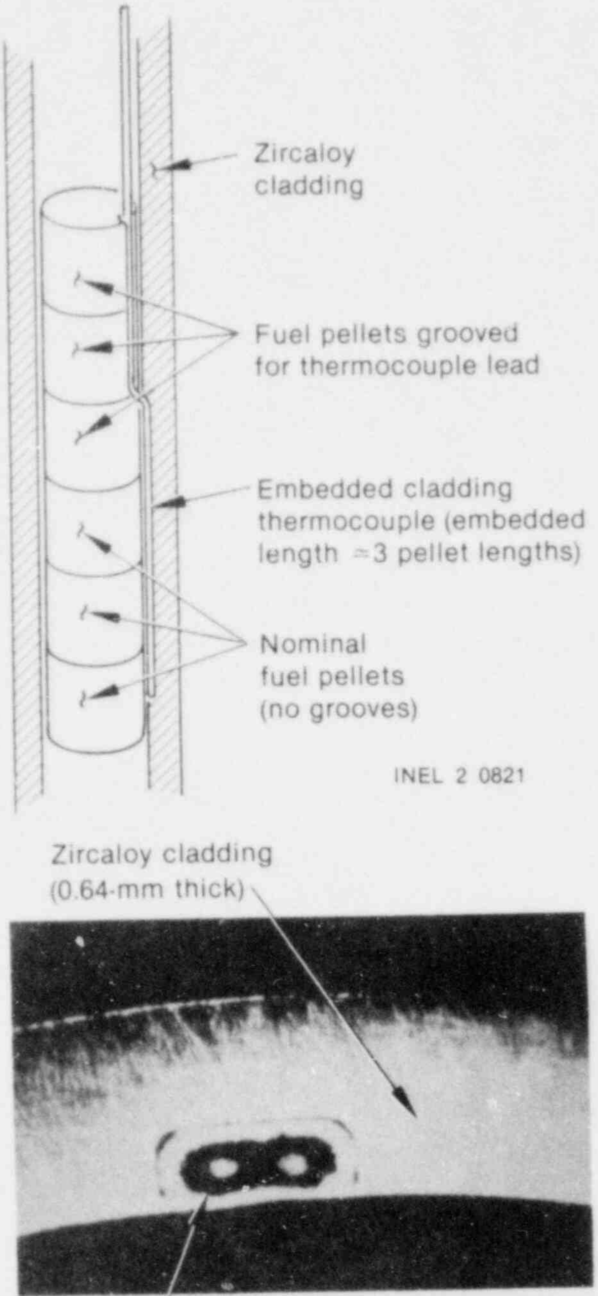


Figure 4. Diagram showing conceptual arrangement of embedded internal cladding thermocouple, and photo of embedded thermocouple cross section as used in the TC-4 Test Series.

Light water reactor fuel rod thermal response to a LOCA transient is primarily dependent on: (a) the initial state of the rod (i.e., initial stored energy, rod size, and cold internal gas pressure), (b) the system depressurization rate, and (c) the cladding surface heat transfer coefficient history (which is controlled by coolant mass flow, quality, and pressure). Test parameter variations for Test Series TC-1, TC-3, and TC-4 included variations in initial test rod power, coolant slug flow rate, and coolant slug average quality, as shown in Table 1. The slug average quality values shown in Table 1 were obtained from RELAP5/MOD1[a] computer calculations using measured flows and temperatures as input. The RELAP-5 input and system model are described in Appendix D.

A schematic illustration of the PBF in-pile tube loop and associated piping and components for performing LOCA blowdown transients is shown in Figure 5. A PBF LOCA blowdown transient is initiated by isolating the in-pile tube loop from the primary system loop. This is accomplished by closing both the hot and cold leg isolation valves and opening the loop bypass valve shown in Figure 5, then opening one or both of the cold leg or hot leg blowdown valves. Following the initial subcooled depressurization, the desired system depressurization can be obtained by selectively opening and closing the cold leg blowdown valves (and hot leg valves, if necessary).

An objective of the PBF Thermocouple Effects Test Series was to provide system thermal-hydraulic and depressurization conditions comparable to the conditions that existed during the LOFT L2 power ascension test series. Figure 6 provides comparisons between the measured system pressures as functions of time for the LOFT L2-3 test and the TC-1C, TC-3A, TC-4A, and TC-4D tests. (The data for the TC-1 Test Series were unqualified; therefore, uncertainty values were not determined. The uncertainties for

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a. RELAP5/MOD1, Cycle 17. Idaho National Engineering Laboratory Configuration Control Number F00708. The hydrodynamic model developed for the RELAP5 code includes the important physical phenomena of two-phase and non-equilibrium thermodynamics. Evaluation of uncertainties in the hydrodynamics calculations has been limited because existing homogeneous flow, thermal equilibrium test conditions, and the calculational capabilities of the RELAP5 code under two-phase nonequilibrium conditions are not accurately known.

Table 1. Test parameter variations for PBF Thermocouple Effects Test Series

Test Identification	Initial Rod Peak Power (kW/m)	Slug Quality[a] (%)	Slug Flow Rate Through Shrouds (L/s)
TC-1A	50	35	0.8
TC-1B	50	35	0.8
TC-1C	50	35	0.8
TC-1D	50	35	0.8
TC-3A	50	17	1.0
TC-4A	50	45	0.4
TC-4B	50	45	0.4
TC-4C	50	14	0.4
TC-4D	50	35	1.2
TC-4E	43	10	1.2
TC-4F	50	10	1.2
TC-4G	39	10	1.2

a. Calculated with the RELAP5/MOD2 computer code.

the TC-3 and TC-4 series are discussed in Appendix C and shown on the individual plots presented on the microfiche cards). Generally, the system depressurization during the PBF Thermocouple Effects tests was slightly faster than during the LOFT L2-3 test; however, this is not expected to have influenced fuel rod thermal-mechanical behavior or the effect of surface thermocouples on the fuel rod thermal response.

Other measured system conditions during the LOFT L2-3 test were a slug flow rate of approximately 0.4 L/s and an inferred slug coolant quality of approximately 2%. Slug flow was accomplished at 7 s into the TC-1 blowdown transients by simply closing the cold leg blowdown valves and opening one of the hot leg blowdown valves. Slug flow was terminated at 9 s into the TC-1A test by closing the hot leg valve and opening a cold leg valve to continue blowdown. The calculated coolant quality in the in-pile tube test space during slug flow was approximately 35%. The slug duration was increased to 4 s for Test TC-1B, and to 6 s for Tests TC-1C and TC-1D. A comparison between the measured cladding surface temperature response during Test TC-1A and the measured temperature response during the LOFT L2-3 test is provided in Figure 7. The comparison indicates that coolant quality during the TC-1 Test Series was too high to provide sufficient cooling during the slug period and the surface thermocouple response in the PBF did not simulate the LOFT L2-3 test blowdown quench.

Although the desired thermal-hydraulic conditions were not achieved during the TC-1 Test Series, the TC-1 data indicated that cladding surface thermocouples clearly influence LWR fuel rod thermal response during the blowdown phase of a LOCA and may also have a small influence during the reflood phase. The surface thermocouples caused a slight delay in time-to-CHF and they improved the cladding surface heat transfer during blowdown, subsequently reducing the cladding peak temperatures, as postulated. The measured cladding quench times, and subsequent rewet times during reflood, were also somewhat sooner for rods with cladding surface thermocouples than for rods without surface thermocouples. On the other hand, it was also concluded that the limited data from the internal and external cladding surface temperature measurements were not sufficient to precisely evaluate the actual cladding temperatures.

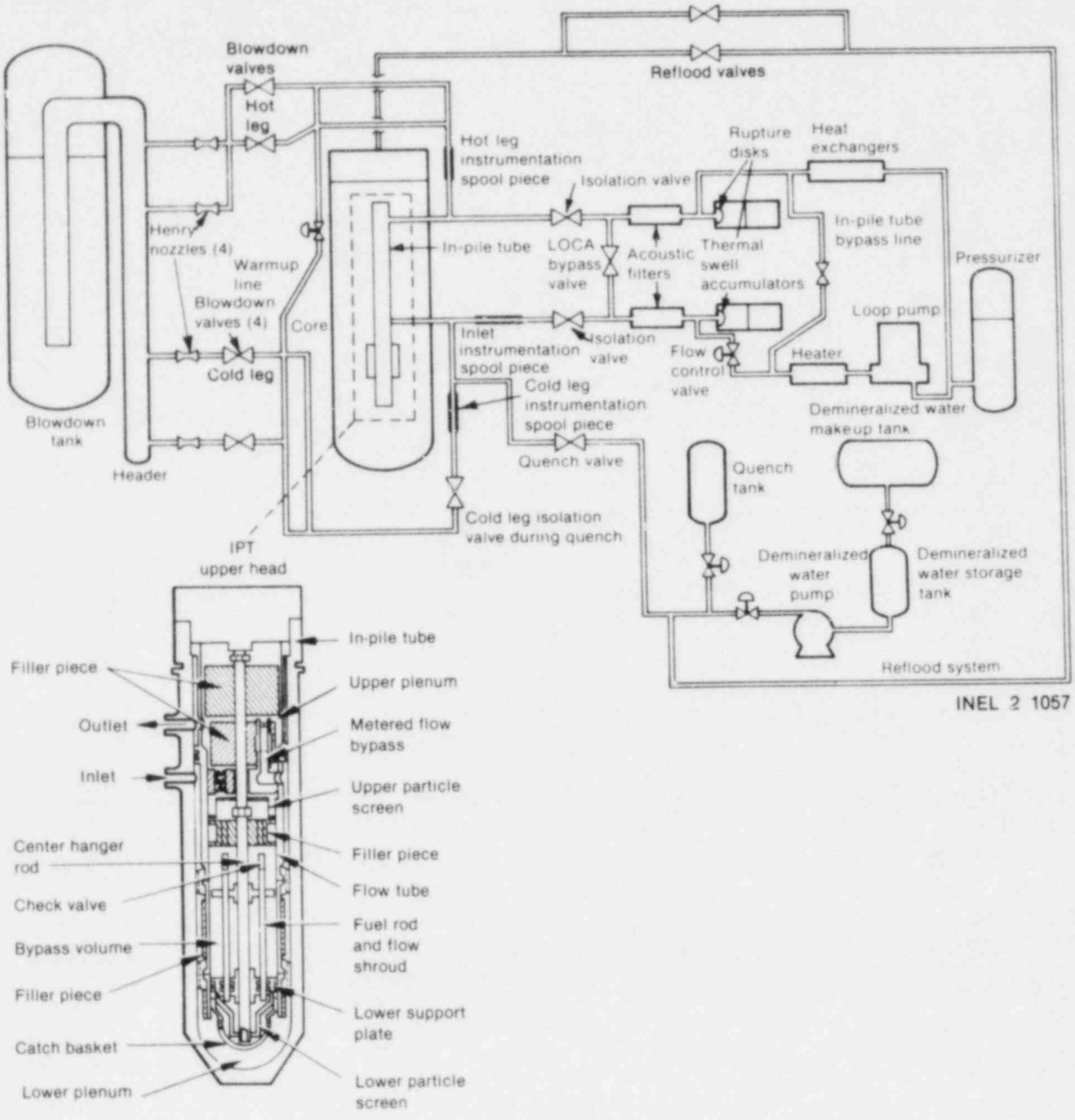

Figure 5. PBF loss-of-coolant accident test system illustration.

A new series of tests, TC-3, was designed to provide additional cladding surface temperature data by changing two of the fuel surface thermocouples in Rods 03 and 04 to welded internal cladding surface thermocouples. In addition, a lower quality slug flow was provided during Test Series TC-3 by injecting coolant into the PBF in- pile tube loop from the primary loop coolant system. The slug of coolant was injected into the in-pile tube loop by closing the cold leg blowdown valve and momentarily opening the cold leg loop isolation valve (shown in Figure 5). This provided a slug of initially subcooled, high pressure coolant (15.5 MPa pressure and 590 K temperature) that created a lower quality condition at the inlet to the test rod flow shrouds. Total isolation valve operation time (opening and closing) was only approximately 120 ms for Test TC-3A. Following injection of the coolant into the system, the slug duration was set at about 5.5 s by opening the small hot leg blowdown valve at 5.5 s into the blowdown, then closing it at 11.0 s and

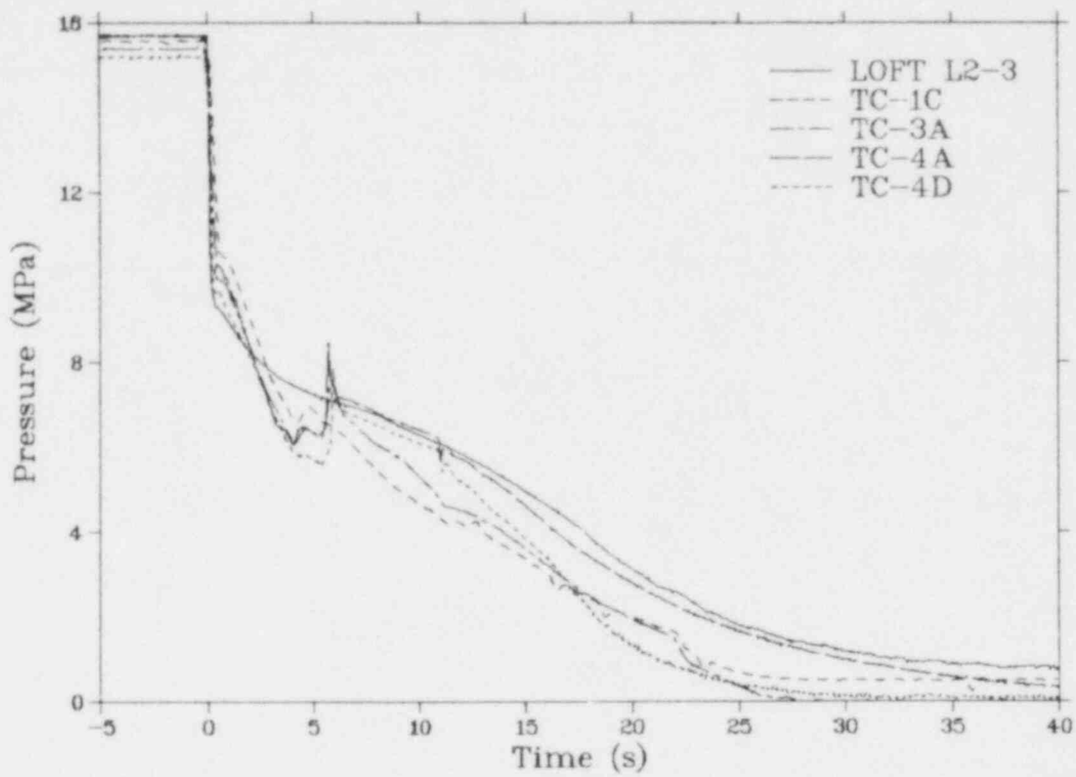

Figure 6. Comparison of the PBF TC Test Series system depressurization with the LOFT L2-3 test system depressurization.

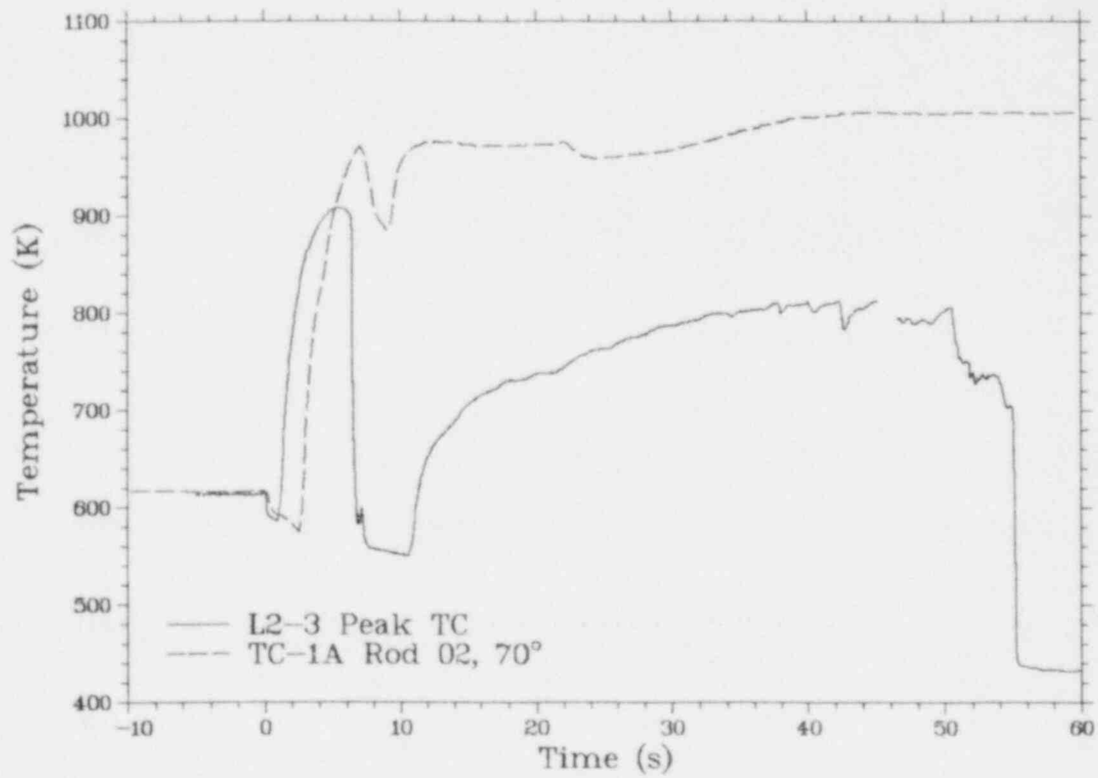

Figure 7. Comparison between measured cladding surface thermocouple responses for Test TC-1A (Rod 02) and the LOFT L2-3 test.

opening the small cold leg blowdown valve to continue system depressurization.

A comparison between a Test TC-3A cladding surface thermocouple response and a LOFT L2-3 cladding surface thermocouple response, shown in Figure 8, indicates that a momentary quench of the cladding surface thermocouples did occur, but that the quench duration (~0.5 s) was much shorter than the desired ~5.0 s observed during the LOFT L2-3 test. In addition, the measured coolant velocity of ~1.0 L/s during the slug period was significantly faster than the ~0.4 L/s noted during the LOFT L2-3 test.

Analysis of the data obtained from Test TC-3A indicated that the coolant velocity during the slug period could be decreased by reducing the hot leg blowdown nozzle size, and the slug quality could be further reduced by increasing the mass of coolant injected into the in-pile tube loop. Utilizing two of the test rods from Test TC-3A (Rods 01 and 03), and fabricating two new rods with embedded internal cladding thermocouples, Test Series TC-4 was designed to obtain additional information on the effects of surface thermocouples on LWR fuel rod thermal response during a LOCA, and to provide an in-pile evaluation of the embedded thermocouple concept. The two new rods were again designated Rods 02 and 04.

Test TC-4A was identical to Test TC-3A, with the exception that the flow area of one of the hot leg blowdown valves was reduced by a factor of two in an attempt to reduce the coolant velocity during the slug flow period. As shown in Table 1, the slug velocity during Test TC-4A was reduced to approximately 0.4 L/s, the value observed during the LOFT L2-3 test. However, comparison between the measured cladding surface thermocouple response during Test TC-4A and the surface thermocouple response during LOFT L2-3, shown in Figure 9, indicates that the fuel rods did not quench during the slug flow period of Test TC-4A. Apparently, an insufficient mass of coolant was injected into the system during the short (~120 ms) isolation valve operation time. To evaluate the repeatability of the system operation and fuel rod thermal response,

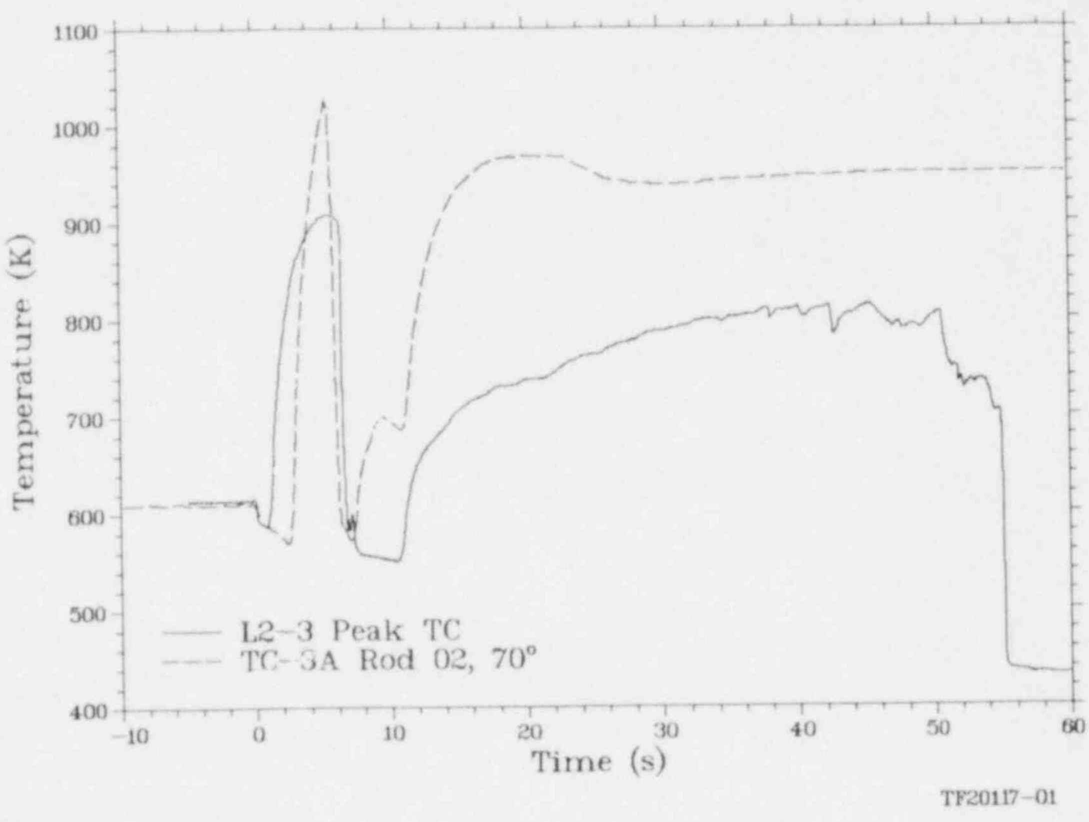

Figure 8. Comparison between measured cladding surface thermocouple responses for Test TC-3A (Rod 02) and the LOFT L2-3 test.

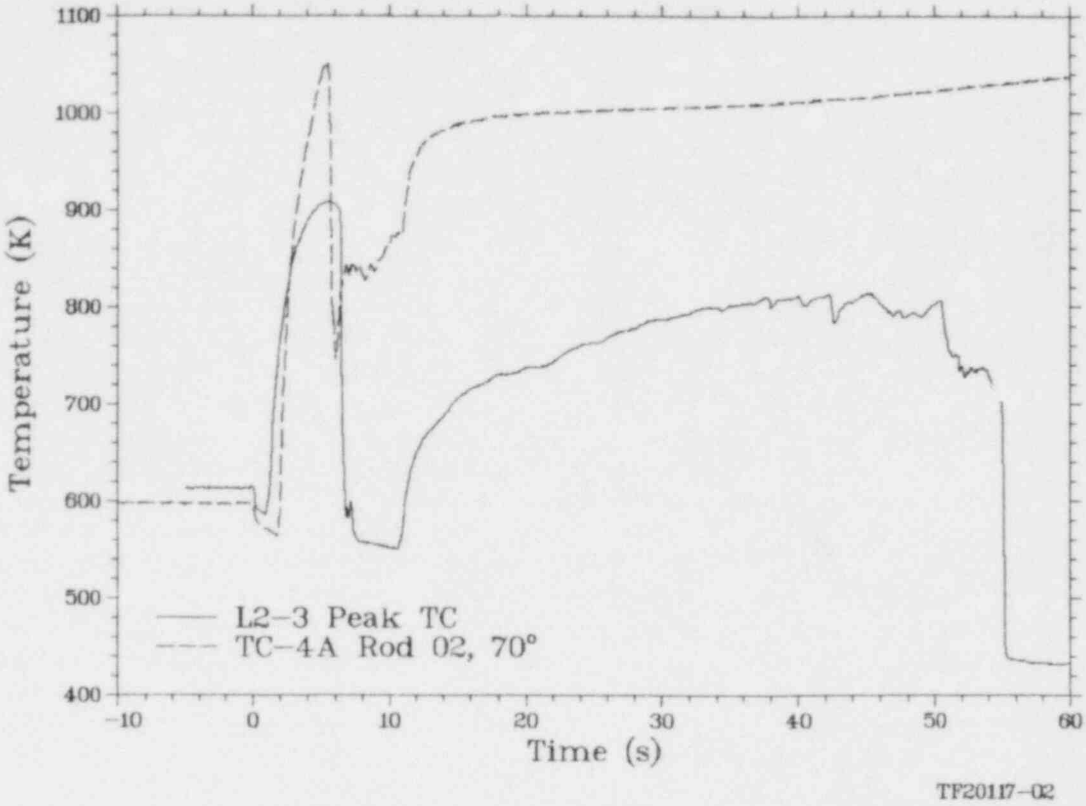

Figure 9. Comparison between measured cladding surface thermocouple responses for Test TC-4A (Rod 02) and the LOFT L2-3 test.

Test TC-4B was performed in a manner identical to Test TC-4A. The test results were identical in all respects.

Test TC-4C was then performed with a cold leg isolation valve operation time of 217 ms, which was calculated to essentially double the mass flows within the coolant shrouds. All other test parameters for Test TC-4C were the same as for Tests TC-4A and TC-4B. Posttest evaluation of the Test TC-4C data indicated that the slug mass flow did essentially double, but was still insufficient to quench the fuel rods in the desired manner.

Additional evaluation of the system hydraulics showed that approximately 75% of the slug flow was bypassing the test rod flow shrouds through the controlled bypass (shown in Figure 5), and a significant increase in the mass flow through the shrouds would require an unacceptably long isolation valve operation time. However, mass flow through the shrouds could be increased by reducing or blocking-off the bypass flow. With the controlled bypass flow blocked, there would be no connection between the upper and lower plenums of the test space, except through the test rod flow shrouds. Consequently, the upper plenum would not depressurize fast enough, unless a hot leg blowdown valve was also opened during the initial depressurization.

Test TC-4D was performed with the controlled bypass completely blocked. In addition, the large hot leg blowdown valve was opened at 0.1 s, the same time the cold leg valves were opened to initiate blowdown. To further reduce the magnitude of the pressure difference between the upper and lower plenums, the large cold leg nozzle was reduced to a diameter of 13.56 mm. the same as the large hot leg blowdown nozzle. At 4.0 s, the large hot leg valve was closed, the small hot leg valve was opened, and the large cold leg valve was closed. At 5.2 s, all blowdown valves were closed, and at 5.5 s, the cold leg isolation valve was opened for a duration of 106 ms to introduce coolant to the system for the slug flow. At 5.6 s, the small hot leg blowdown valve was opened to allow slug flow up through the test rod flow shrouds, and at 11.0 s, the hot leg valve was closed and the small cold leg valve was opened to terminate slug flow and continue system depressurization. The slug mass flow during Test TC-4D was increased by blocking the bypass, the slug flow velocity was increased, the slug quality was decreased, and slug flow did quench the test rod cladding surface thermocouples, but only for a period of approximately 2 to 3 s, rather than the desired 5 to 6 s. Apparently, the mass of coolant introduced into the system during the short (~106 ms) isolation valve operation time was again insufficient to provide the prolonged quench time that was noted during the LOFT L2-3 test.

Fuel rod cooling during the blowdown slug flow period is strongly dependent on the blowdown peak temperatures, which in turn depend on the stored energy in the rods at the time of blowdown initiation. The stored energy is dependent on the steady state power level prior to blowdown initiation. Test TC-4E was performed with the initial rod power reduced to 43 kW/m and the cold leg isolation valve operation time increased from the 106 ms of Test TC-4D to 228 ms, which increased the slug mass flow and reduced slug quality. The desired fuel rod quench duration was attained during the blowdown.

Test TC-4F was performed in the same manner as Test TC-4D, at an initial power of 50 kW/m, except the cold leg isolation valve operation time was increased to 230 ms. As expected, the increased slug mass flow and the reduced slug quality was sufficient to provide a surface thermocouple quench and a quench duration similar to the thermocouple response noted during the LOFT L2-3 test. Comparisons are shown in Figure 10.

Test TC-4G was performed in the same manner as Test TC-4F, except the initial rod power was reduced to 39 kW/m to further investigate the effect of initial rod power on the blowdown quench behavior. The cold leg isolation valve operation time during Test TC-4G was 229 ms, essentially the same as for Tests TC-4E and TC-4F. The Test TC-4G fuel rod thermal response results were quite similar to the results obtained for Test TC-4E.

The PBF core power was manually controlled during each test to establish cladding temperatures

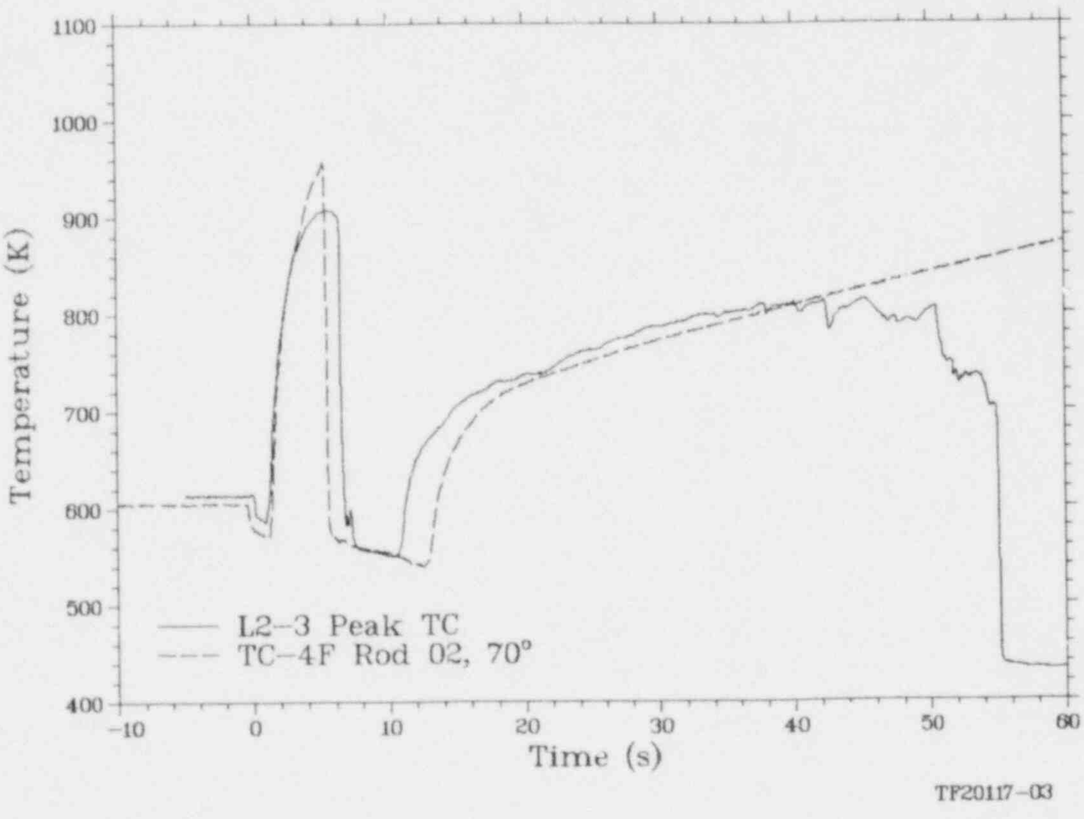

Figure 10. Comparison between measured cladding surface thermocouple responses for Test TC-4F (Rod 02) and the LOFT L2-3 test.

between 900 and 1100 K prior to reflood. Reflooding of the test train commenced 100 s after initiation of blowdown in each of the tests. The reflood was performed by injecting coolant at a temperature of 311 K into the in-pile tube upper head, down the center hanger rod and into the plenum volume beneath the lower particle screen. The lower plenum was filled within approximately 5 s, at a rate of 1.58 L/s. The flow shrouds were then reflooded at a rate of 0.95 L/s until termination of the reflood phase at 240 s.

The performance of the embedded internal cladding thermocouples was very good. Comparisons between the embedded and welded internal thermocouples consistently showed that the embedded thermocouples measured cladding temperatures more accurately and remained attached to the cladding, whereas some of the welded thermocouples showed evidence of temperature measurements more representative of pellet surface temperatures, possibly indicating detachment from the cladding inside surface. Two of the four embedded thermocouples used in the TC-4 Test Series performed extremely well during all seven tests, and the other two performed well during the first five tests and then failed due to an open junction.

TEST RESULTS

The PBF Thermocouple Effects Test Series was designed to answer the following questions:

1. Do cladding surface thermocouples accurately measure LWR fuel rod cladding temperatures during a large break LOCA transient?

2. What correction factor should be applied to cladding surface thermocouple measurements to obtain the correct peak cladding surface temperature of uninstrumented rods, and how is the correction factor influenced by fin cooling and by delay in the time to CHF?

3. What is the effect of surface thermocouples on LWR fuel rod thermal behavior during a large break LOCA blowdown quench, and how is that effect influenced by the quality of the slug and the initial rod power?

4. Do cladding surface thermocouples significantly influence LWR fuel rod thermal response during reflood?

The data presented in this section provide answers to these questions. Other data, although not presented, substantiate the trends and observations described herein. In each plot, time zero refers to time of blowdown initiation.

Accuracy of Cladding Surface Thermocouple Measurement During Large Break LOCAs

Figures 11 through 14 show representative comparisons between the thermal responses of internal cladding surface thermocouples and adjacent external cladding surface thermocouples during the first 30 s of blowdown for each test series. The measured cladding internal and surface

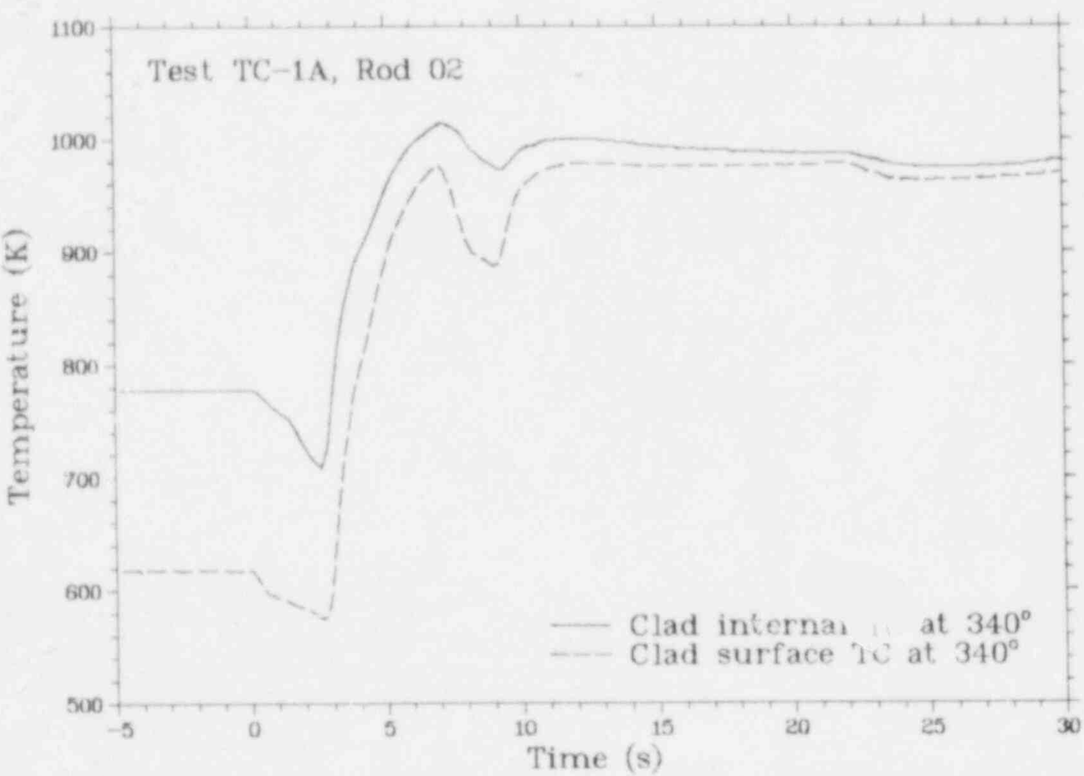

Figure 11. Comparison of Rod 02 embedded internal (340°) and surface (340°) cladding thermocouple responses during blowdown quench period of Test TC-1A.

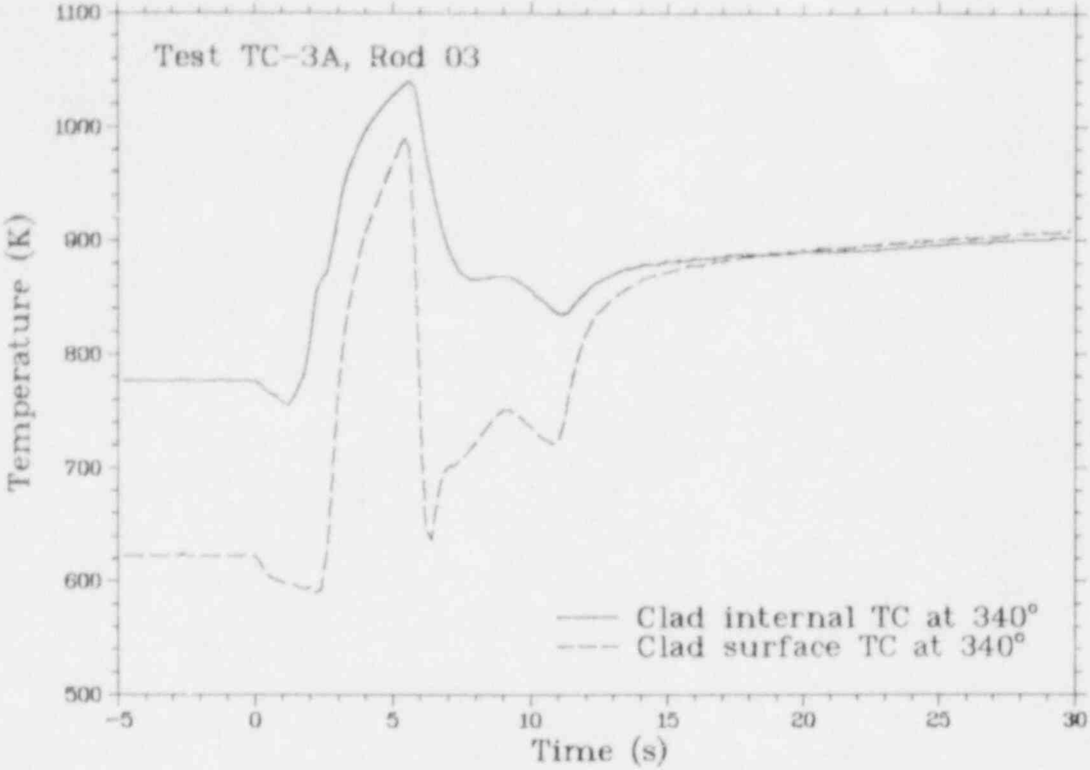

Figure 12. Comparison of Rod 03 internal (340°) and surface (340°) cladding thermocouple responses during blowdown quench period of Test TC-3A.

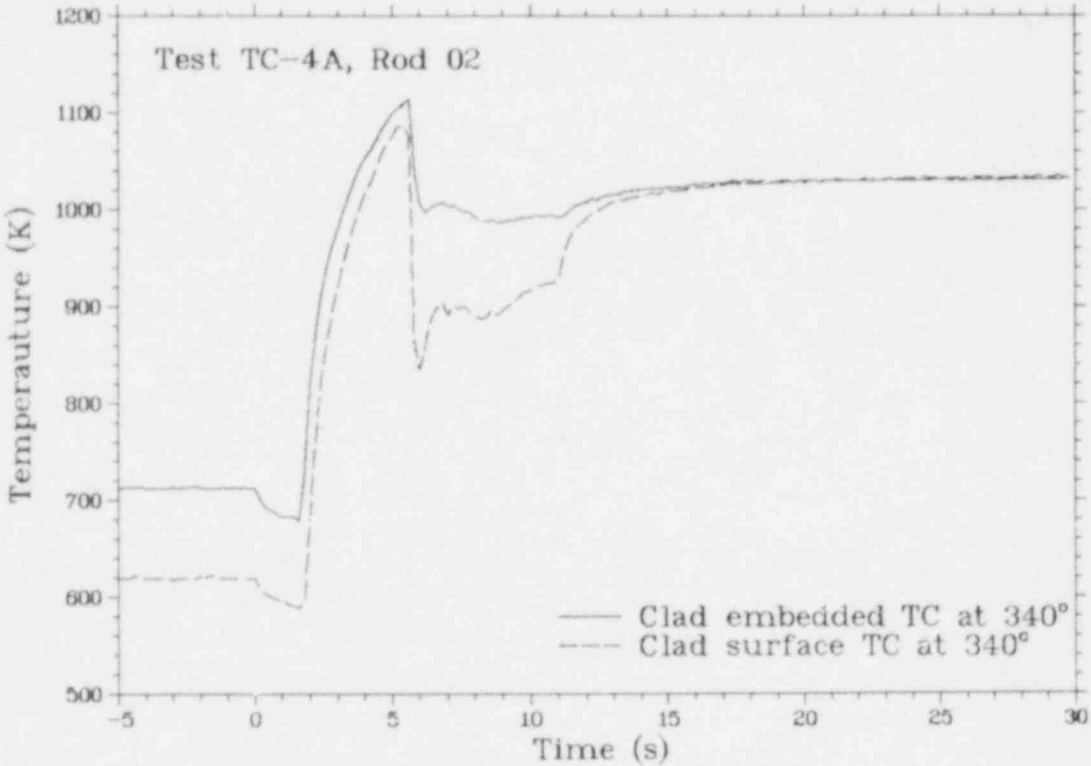

Figure 13. Comparison of Rod 02 embedded internal (340°) and surface (340°) cladding thermocouple responses during blowdown quench period of Test TC-4A.

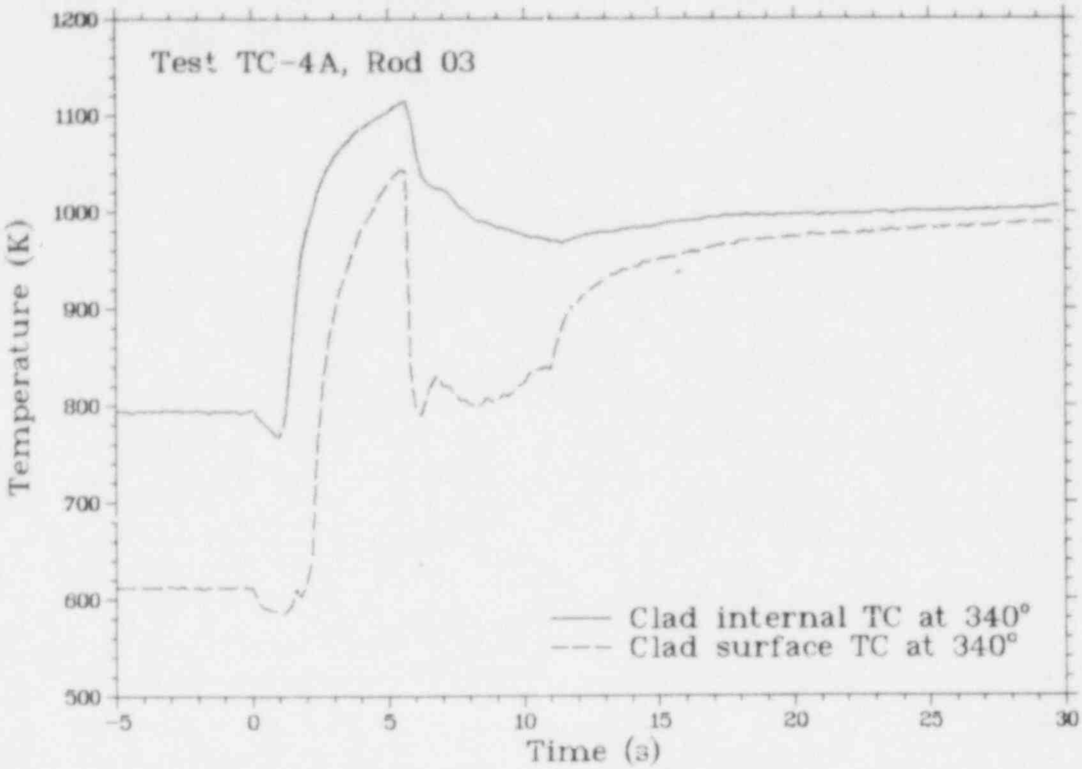

Figure 14. Comparison of Rod 03 internal (340°) and surface (340°) cladding thermocouple responses during blowdown quench period of Test TC-4A.

blowdown peak temperatures obtained from all of the tests in the TC Test Series are provided in Table 2[a] along with the corresponding differences. Only Rod 02 had both internal and external cladding surface thermocouples during Test Series TC-1, and the internal thermocouples were welded to the cladding surface. Both Rods 02 and 03 had internal and external cladding surface thermocouples during Test Series TC-3 and TC-4. The internal thermocouples were welded to the cladding surface during Test Series TC-3. The Rod 02 internal cladding thermocouples during Test Series TC-4 were of a new design and were embedded in the cladding surface.

The thermocouple responses in all the TC tests show the initial cooling of the fuel rods due to rapid expulsion of the coolant following initiation of blowdown, the occurrence of critical heat flux at between 1 and 3 s, rapid heating of the cladding due to the reduced heat transfer during film boiling, and the injection of slug flow at approximately 5.5 s, which terminates the temperature increase and provides subsequent cooling of the rods. The extent and duration of the rod cooling during the slug flow period were influenced by the slug flow characteristics and the initial rod powers listed. Following the slug flow period, the fuel rod temperatures rapidly increased, and then leveled off at an equilibrium value between 900 and 1100 K, as determined by manual control of the PBF core power.

On the basis of the comparisons shown in Figures 11 through 14, and the data provided in Table 2, the measured temperature drop across the cladding at the time of the blowdown peak temperature varies between 23 and 108 K over the three test series. Comparisons between test rods in which the internal thermocouples were welded to the cladding surface, at the same azimuthal

a. The Rod 02 internal cladding thermocouples indicated a time-to-CHF of greater than 3 s during Tests TC-1B, TC-1C, and TC-1D, which is significantly later than that indicated by the thermocouples on any of the other rods during any other tests. A cracked weld was found on the Rod 02 coolant flow shroud during the posttest evaluation. We believe that the cracked weld may have permitted bypass coolant to leak into the flow shroud and influence the thermal response of Rod 02. Consequently, the Rod 02 data for Tests TC-1B, TC-1C, and TC-1D were not included in the analyses described in this report.

Table 2. Comparisons of internal and external cladding peak temperatures during blowdown, TC Test Series

	TC-1A	TC-3A	TC-4A	TC-4B	TC-4C	TC-4D	TC-4E	TC-4F	TC-4G
Rod 02									
Internal thermocouple at 340°	1014	—[a]	1114	1047	1054	1060	980	—[a]	—[a]
Surface thermocouple at 340°	978	1029	1086	1024	1021	1035	955	1004	903
Temperature differential	36	—	28	23	33	25	25	—	—
Internal thermocouple at 100° (115°, TC-4)[b]	1015	—[a]	1132	1021	1015	1034	983	1016	907
Surface thermocouple at 70°	976	1026	1046	978	954	971	906	953	854
Temperature differential	39	—	86	43	61	63	77	63	53
Rod 03									
Internal thermocouple at 340°	—	1040	1115	1090	1092	1130	1030	1100	995
Surface thermocouple at 340°	—	991	1043	1036	1030	1060	958	1045	920
Temperature differential	—	49	72	54	62	70	72	55	75
Internal thermocouple at 100°	—	1037	1122	1073	1069	1112	1042	1111	955
Surface thermocouple at 70°	—	952	1014	1014	1025	1047	962	1053	916
Temperature differential	—	85	108	59	44	65	80	58	39

a. Thermocouples were not working properly through these tests.

b. One of the embedded internal cladding thermocouples was at the 115° orientation in Rod 02 for the TC-4 Test Series.

orientation as the surface thermocouples, and test rods in which the thermocouples were embedded in the cladding inner surface, at the same azimuthal orientation as the surface thermocouples, show that the measured temperature drop across the cladding was consistently higher for the welded thermocouples (36 to 75 K) than for the embedded thermocouples (23 to 33 K). The welded internal cladding thermocouples indicated higher temperatures than actually existed at the cladding inside surface because of their close proximity to the fuel pellets. In some cases, the thermocouples may have actually detached from the cladding surface and may have been in intimate contact with the fuel pellet surface, as indicated by the high initial internal cladding temperatures shown in Figures 11, 12, and 14. The embedded internal cladding thermocouples apparently measure the internal cladding temperatures significantly more accurately and consistently than the welded internal cladding thermocouples.

FRAP-T5[a] computer calculations indicate that the temperature drop across the cladding during a large break LOCA at the time of the peak temperatures should have been approximately 6 K. Thus, the surface-thermocouple-indicated temperatures were only 17 to 27 K too low when the surface thermocouple was located at the same azimuthal orientation as the embedded thermocouple. Therefore, we conclude that the surface thermocouples measure the actual cladding temperatures reasonably accurately.

Effects of Cladding Surface Thermocouples on LOCA Blowdown Peak Temperature

The maximum cladding temperature attained during the blowdown transient is influenced by the stored energy in the rods, the system depressurization, the thermal-hydraulic characteristics of the coolant slug, the time of the occurrence of CHF, and fin cooling effects of the cladding surface thermocouples. Comparisons have been made to evaluate the effects of external surface thermocouples on fuel rod thermal response during the initial part of a large break LOCA blowdown. Figures 15 through 18 present typical comparisons between the thermal responses of internal cladding thermocouples in rods with external surface thermocouples (instrumented rods) and in rods without external surface thermocouples (bare rods). As is shown in each of the comparisons, the initial effect of the surface thermocouples is to delay the time of occurrence of CHF on the instrumented rods (Rods 02 and 03) with respect to the time-to-CHF on the bare rods (Rods 01 and 04). Because of the delayed time-to-CHF, the instrumented fuel rods experience a longer period of high cladding surface heat transfer, which in turn reduces the stored energy in the fuel rods at the time-of-CHF. In addition to the effect of delaying the time-to-CHF, the cladding surface thermocouples increase the surface heat transfer area of the fuel rods and further influence the fuel rod thermal response through a "fin cooling" effect.

The total reduction in cladding peak temperature during blowdown varied from approximately 85 K, shown in Figure 18 for Rods 01 and 03 during Test TC-4F, to as much as 185 K, shown in Figure 15 for Rods 01 and 02 during Test TC-1A. An attempt was made to separate the relative contributions to the surface thermocouple effect due to fin cooling and due to the delay in time-to-CHF. To do this, the cladding peak temperatures during blowdown, measured by the internal cladding thermocouples, were plotted versus time-to-CHF. The object was to identify the effect of delay in time-to-CHF on the measured peak temperature in the form of so many kelvin per second of delay in time-to-CHF.

Not all data from the entire TC Test Series could be used in this evaluation for a variety of reasons. As was explained earlier, we believe that the cracked weld in the flow shroud of Rod 02 during Tests TC-1B, TC-1C, and TC-1D may have permitted bypass coolant to leak into the flow shroud and influence the thermal response of the rod. Consequently, the Rod 02 data for Tests TC-1B, TC-1C, and TC-1D were deleted. In addition, comparisons of initial internal cladding temperatures prior to initiation of blowdown for all the tests series show large differences, in most cases, between initial temperatures indicated by the welded internal thermocouples as compared to the embedded internal thermocouples. For example, Figure 15 shows variations in initial internal cladding temperatures from 738 to 855 K for Rods 01 and 02, Test TC-1A, whereas the

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a. FRAP-T, MOD005. Idaho National Engineering Laboratory Configuration Control Number H01323IB.

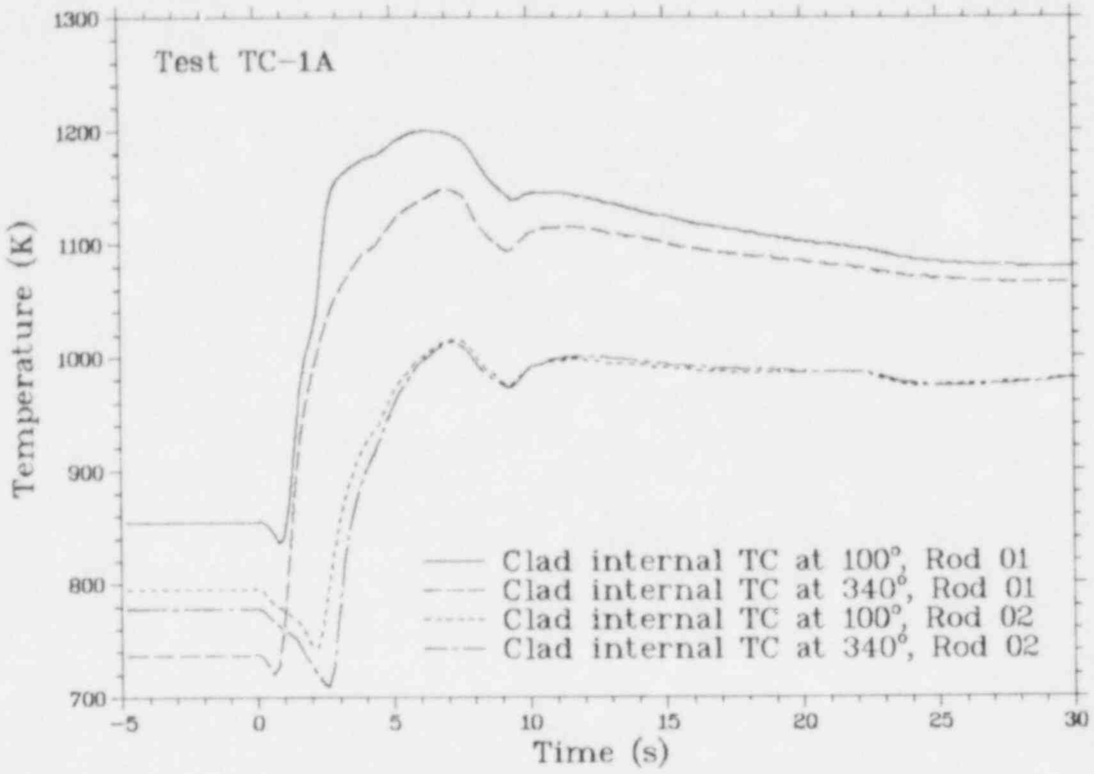

Figure 15. Comparison between internal cladding thermocouple responses in Rod 01 (bare) and Rod 02 (instrumented) during blowdown quench period of Test TC-1A.

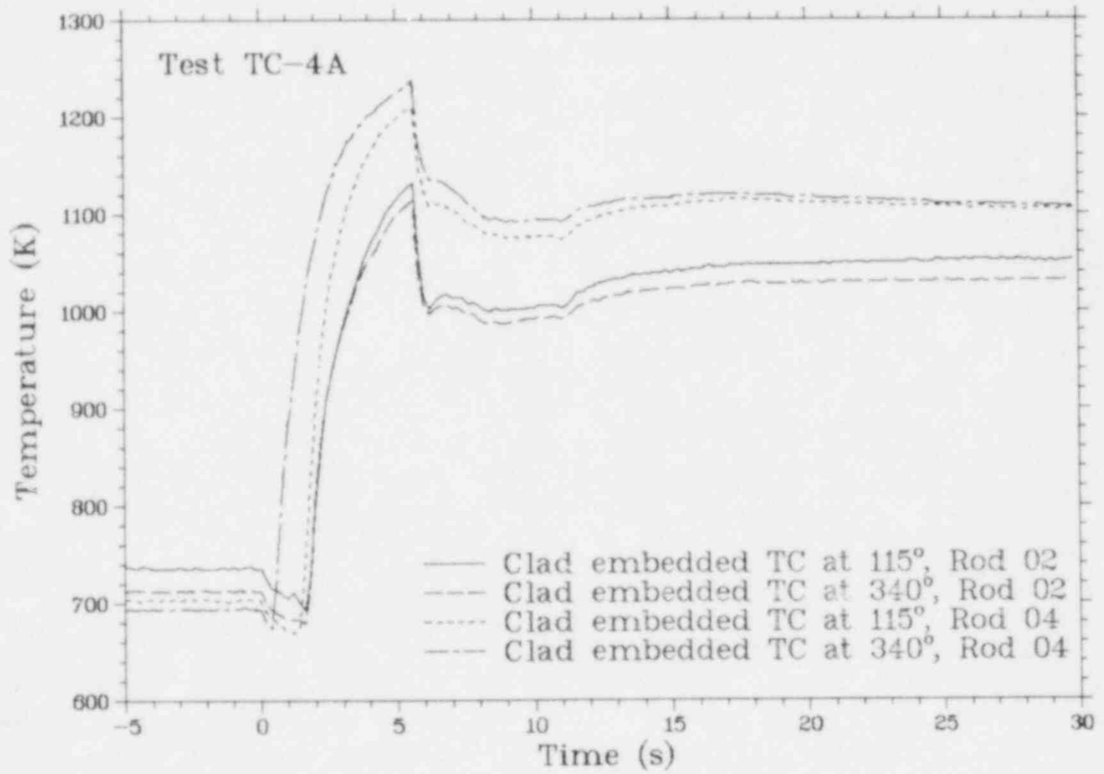

Figure 16. Comparison between embedded internal cladding thermocouple responses in Rod 04 (bare) and Rod 02 (instrumented) during blowdown quench period of Test TC-4A.

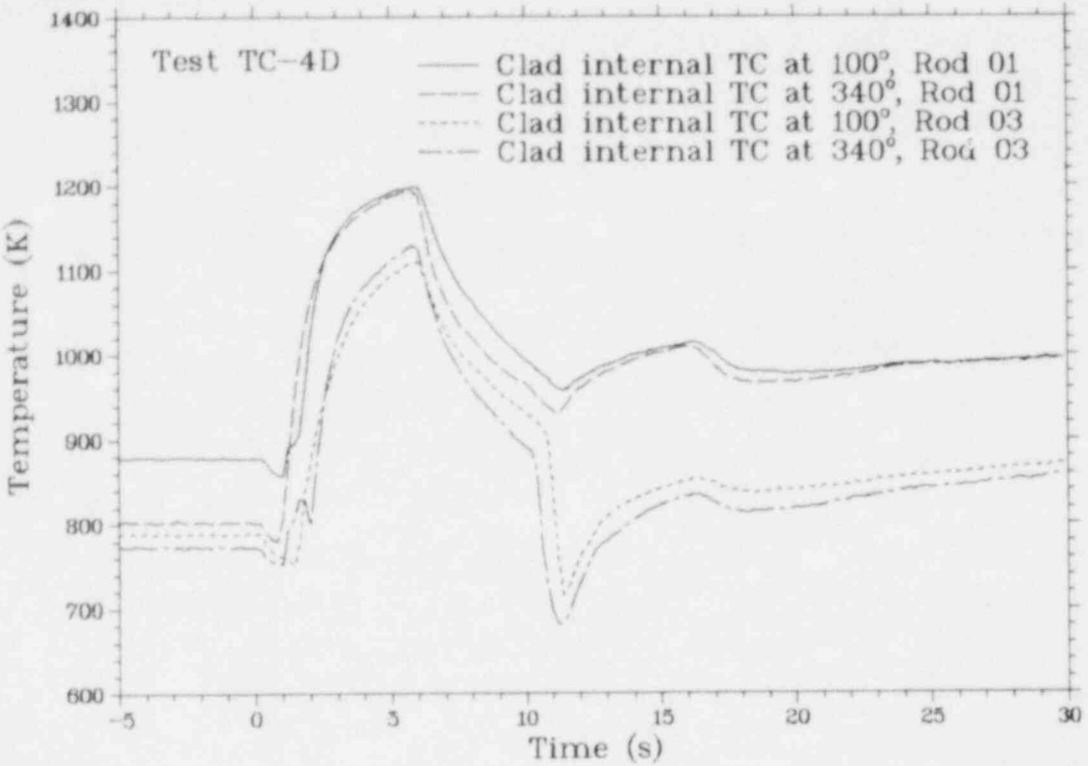

Figure 17. Comparison between internal cladding thermocouple responses in Rod 01 (bare) and Rod 03 (instrumented) during blowdown quench period of Test TC-4D.

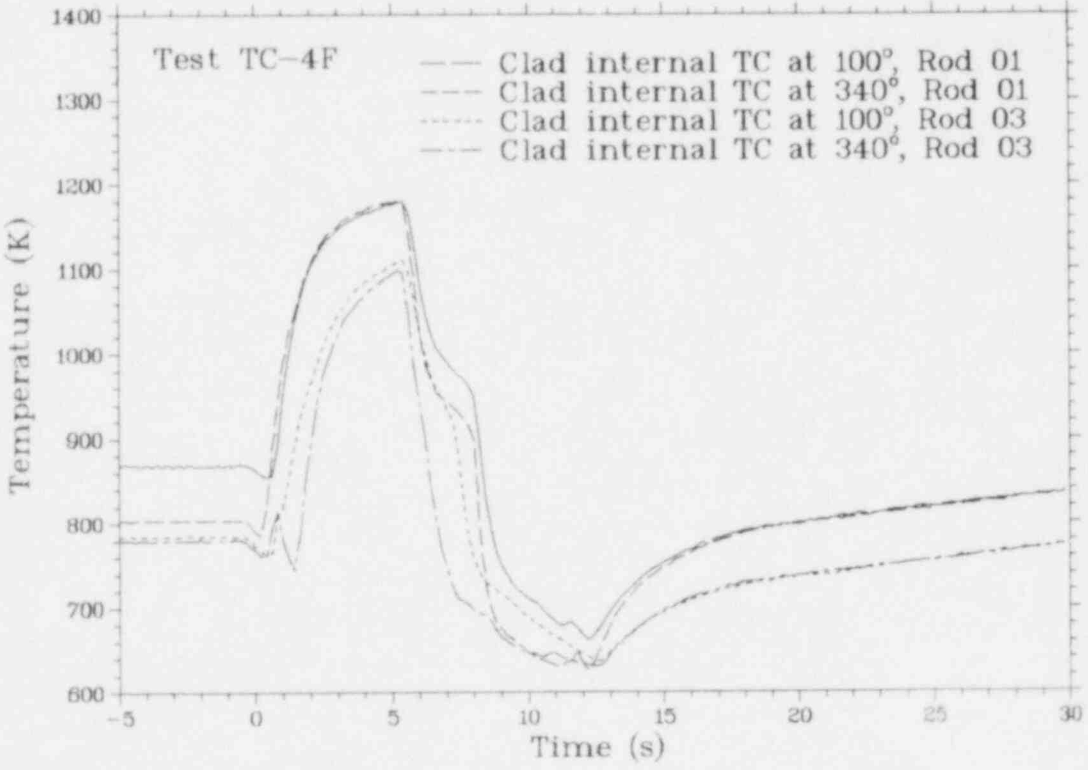

Figure 18. Comparison between internal cladding thermocouple responses in Rod 01 (bare) and Rod 03 (instrumented) during blowdown quench period of Test TC-4F.

difference in initial internal cladding temperatures between Rods 02 and 04 during Test TC-4A is 40 K (Figure 16). Apparently, the welded internal cladding thermocouples are strongly influenced by their close proximity to the fuel pellets, and the temperatures indicated by these thermocouples may not be representative of the true cladding temperature response during the blowdown transient. Therefore, the data from all of the internal thermocouples that indicated excessively high (arbitrarily chosen as greater than 750 K) initial cladding temperatures during all of the TC tests were eliminated. The data from Tests TC-4E and TC-4G, which were performed at lower initial rod powers, were also eliminated.

A plot of the measured cladding peak temperatures during blowdown as a function of time-to-CHF is shown in Figure 19. Although the data in Figure 19 do show a relatively large amount of scatter, a least squares fit to the data is plotted in the figure and is represented by the relationship, T(K) = 1.187 - 73.54 (time-to-CHF, s), which has a slope of -73.54 K/s.

In some cases, the data plotted in Figure 19 show a large variation in measured time-to-CHF between the two thermocouples in the same rod. However, by averaging the measured time-to-CHF for the two thermocouples and the two measured peak temperatures in Rod 02 and comparing with the same averages for Rod 04, the average delay in time-to-CHF for instrumented Rod 02 compared to bare Rod 04 ranges from 0.55 to 0.85 s. The average reduction in blowdown cladding peak temperature for the instrumented rod ranges from 101 to 115 K, as listed in Table 3. On the basis of the least squares fit to the data in Figure 19, for a delay in time-to-CHF of from 0.55 to 0.85 s, the predicted reduction in blowdown cladding peak temperature ranges from 40 to 62 K. Therefore, an estimate of the relative contribution to the surface thermocouple effect due to the delay in time-to-CHF ranges from about 35 to 58% of the total effect; the remaining 42 to 65% is due to fin cooling.

Effects of Cladding Surface Thermocouples on Large Break LOCA Blowdown Quench Behavior

Figure 20 shows a representative comparison between the responses of an embedded internal cladding thermocouple in Rod 04 (bare rod) and in Rod 02 (rod with surface thermocouples) during Test TC-4F. The initial cooling rates of the two embedded thermocouples during the

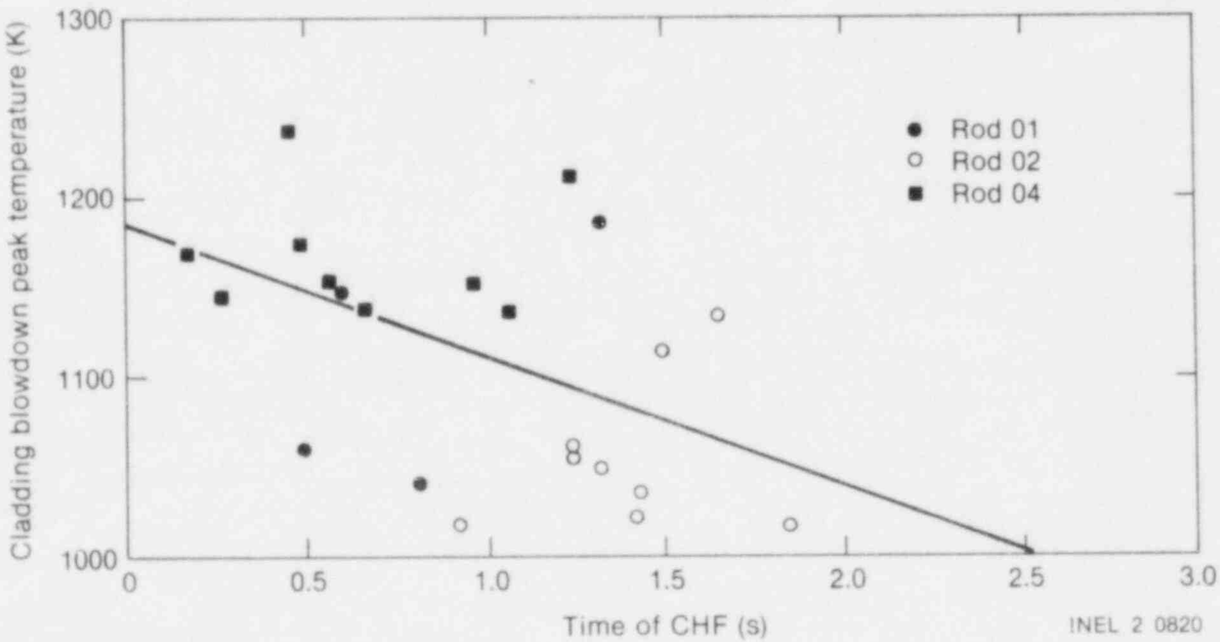

Figure 19. Comparison of internal cladding peak temperatures during blowdown with time-to-CHF for applicable TC tests.

Table 3. Average measured time-to-CHF and cladding peak temperature during blowdown, TC Test Series

	TC-4A	TC-4B	TC-4C	TC-4D
Rod 02 (instrumented)				
Average time-to-CHF (s)	1.6	1.3	1.55	1.3
Average peak temperature (K)	1123	1034	1034	1047
Rod 04 (bare)				
Average time-to-CHF (s)	0.85	0.5	0.85	0.75
Average peak temperature (K)	1124	1140	1143	1162
Rod 02 - Rod 04 [average time to CHF(s)]	0.75	0.85	0.7	0.55
Rod 04 - Rod 02 [average peak temperature (K)]	101	106	109	115
Predicted reduction in cladding peak temperature (K) during blowdown based on least squares fit of data in Figure 19	55	62	51	40
Relative contribution of delay in time-to-CHF to surface thermocouple effect (%)	54	58	47	35

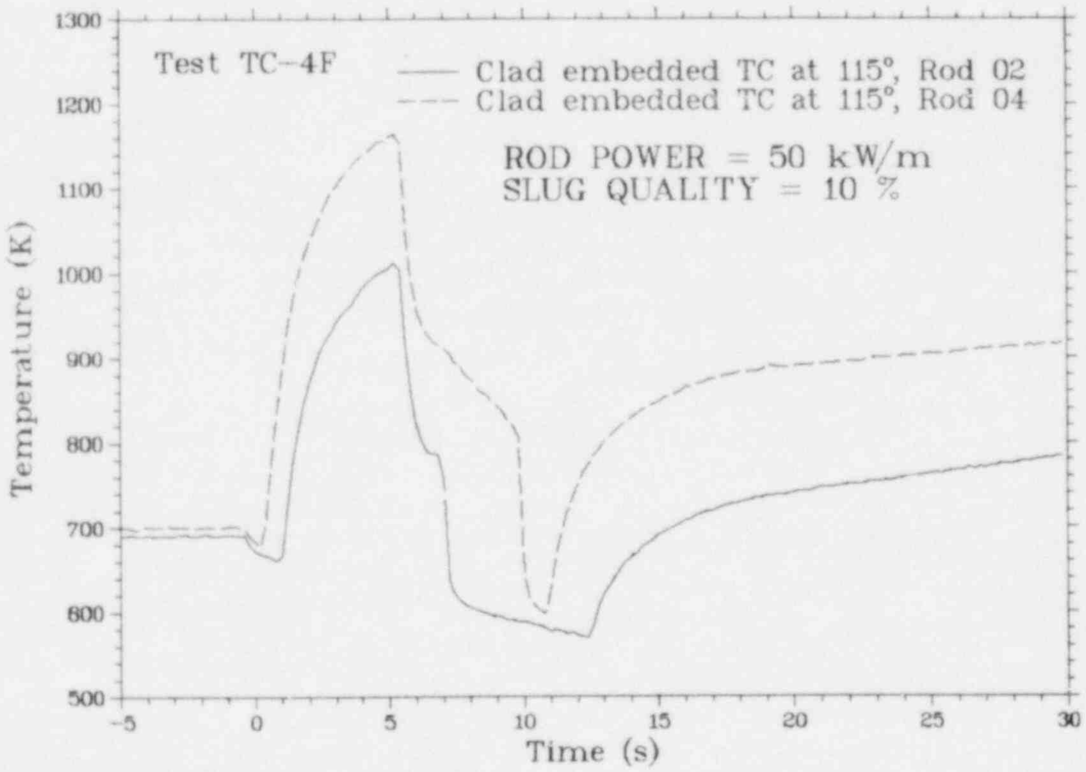

Figure 20. Comparison between embedded internal cladding thermocouple responses in Rod 04 (bare) and Rod 02 (instrumented) during blowdown quench period of Test TC-4F.

blowdown slug period were comparable, but the thermocouple in Rod 02 (instrumented rod) continued to cool at a high rate after approximately 6 s, whereas the cooling rate of the thermocouple in Rod 04 (bare rod) slowed down. The end result was that the Rod 02 thermocouple was quenched about 3 s earlier than the thermocouple in Rod 04, and remained quenched for approximately 5 s, whereas the Rod 04 thermocouple was quenched for only about 1 s. Part of the indicated differences in the thermal responses of the two fuel rods was probably due to a higher initial peak temperature in Rod 04 than in Rod 02, which was a result of the delay in time-to-CHF and fin cooling of Rod 02 early in the transient.

Figure 21 shows a comparison of an embedded thermocouple in Rod 02, during Test TC-4E, with an embedded thermocouple in Rod 04, during Test TC-4G, where the blowdown cladding peak temperatures of the two thermocouples are approximately the same (~30 K difference). The initial test rod powers were lower during Test TC-4G than during Test TC-4E, and the lower power of Rod 04 during Test TC-4G compensated for the initial delay in CHF and fin cooling of Rod 02 during Test TC-4E. The effect of the surface thermocouple on Rod 02 during the slug period is apparently small, and the Rod 02 and Rod 04 temperatures are similar in Figure 21. When cooling from the same temperature, both internal thermocouples quenched within about 2 s of each other and the quench durations were comparable.

On the basis of the comparisons shown in Figures 20 and 21, the majority of the influence of the surface thermocouples on fuel rod thermal response during blowdown quench is due to the differences in cladding peak temperature during blowdown, which are due to both the effects of delay in time-to-CHF and fin cooling of the rod with surface thermocouples early in the transient.

Influence of System Thermal-Hydraulic Conditions on Surface Thermocouple Effect During Blowdown Quench

The thermal-hydraulic conditions, such as volumetric flow rate and quality of the slug flow during the blowdown quench, would be expected to influence the thermal response of the fuel rods, as well as the effect the surface thermocouples have on fuel rod thermal response during the blowdown quench. Cladding surface heat transfer rates will be low and rod temperatures will decrease slowly when high quality coolant flow is present. Likewise, the fin effect of a surface thermocouple will be small in an essentially steam atmosphere. However, cladding surface heat transfer rates are high when low quality coolant flow is present and the increased heat transfer area added by the surface thermocouple may have a significant effect on the rod thermal response. On the other hand, coolant flow rate can also significantly affect cladding surface heat transfer. For example, high quality coolant at a high flow rate may result in higher surface heat transfer rates than a lower quality coolant at a much lower flow rate. Consequently, both quality and flow rate are important coolant parameters that must be considered in evaluating the influence of the coolant conditions on the effects of cladding surface thermocouples on fuel rod thermal response.

Fuel rod initial power (steady state rod power immediately prior to initiation of blowdown) would also be expected to influence test rod thermal response during a LOCA and, in particular, the effect of surface thermocouples during blowdown quench. High initial powers provide high stored energy and correspondingly high surface heat transfer rates. Because the effect of surface thermocouples on rod thermal response is greater for conditions of high heat transfer rates than for low heat transfer rates, it would be expected that the influence of rod initial power on the effect of the surface thermocouples would decrease as rod initial power decreases.

Figure 22 presents the calculated coolant qualities at the axial midplane of the test space as a function of time during the slug period of Tests TC-1A, TC-3A, TC-4A, TC-4D, and TC-4F. Following blowdown initiation, but prior to the slug flow period, the coolant in the flow shrouds of all the tests vaporized and the quality reached a value of approximately 100%. Upon initiation of slug flow, the low temperature liquid coolant below the test rods was drawn up into the flow shrouds and the calculated coolant quality was rapidly reduced. The slug flow period was from 7 to 9 s and the quality was reduced to approximately 35% by 7.5 s during Test TC-1A.

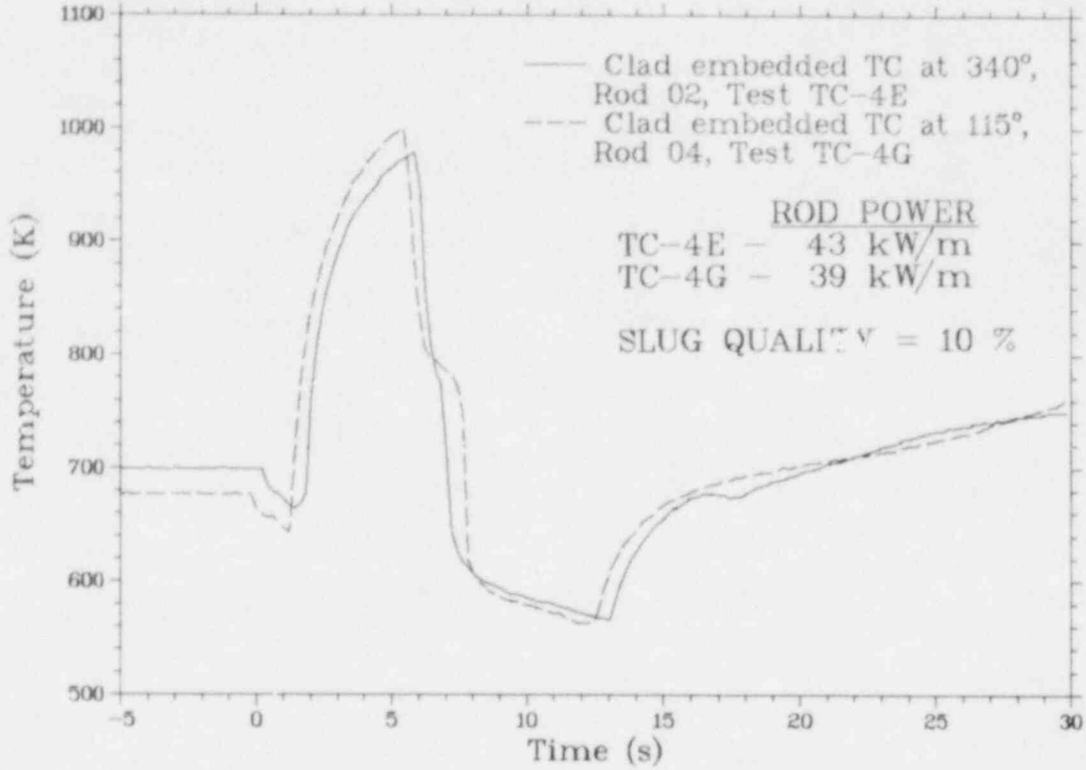

Figure 21. Comparison between thermal responses of an embedded internal cladding thermocouple in Rod 02 (instrumented) and an embedded internal cladding thermocouple in Rod 04 (bare) during blowdown quench under conditions in which the cladding peak temperatures of the two rods during blowdown are similar (Tests TC-4E and TC-4G).

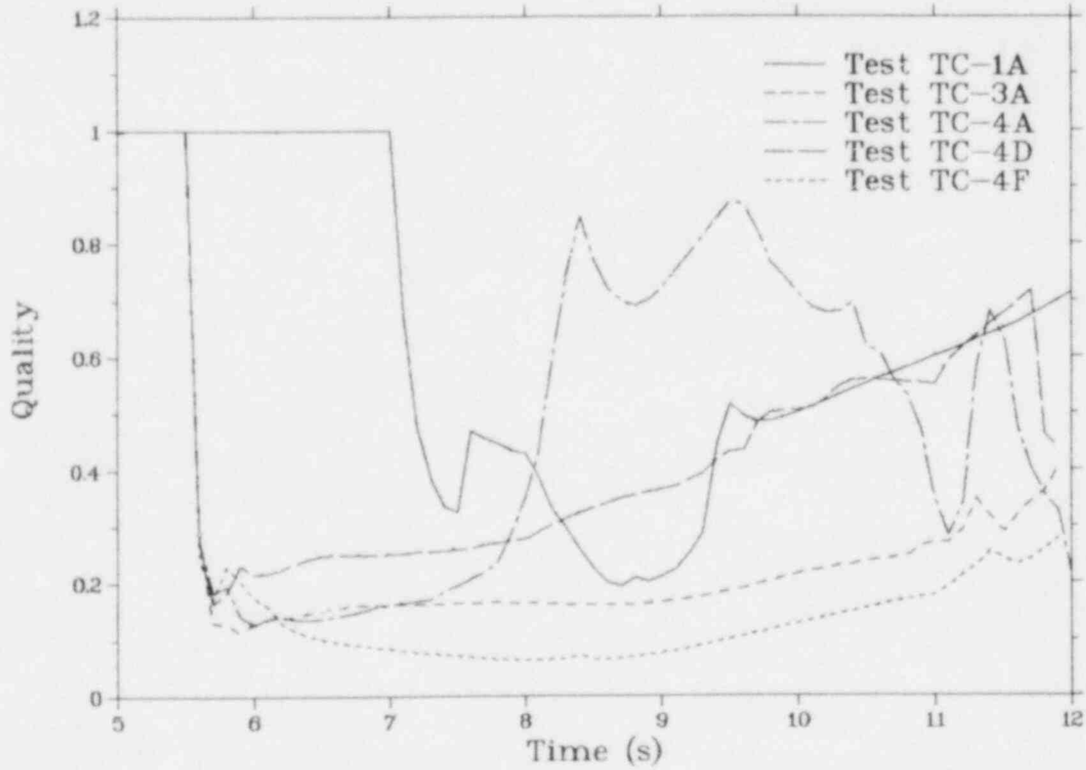

Figure 22. Calculated coolant qualities at the axial midplane of the test space as a function of time during the slug period of Tests TC-1A, TC-3A, TC-4A, TC-4D, and TC-4F.

The quality then increased rapidly to a value of approximately 49% at 7.6 s, then slowly decreased to a minimum of 22% at 8.8 s, and remained at this value until termination of slug flow at 9 s. The overall average quality during the slug flow period was approximately 35%, and the average slug volumetric flow rate was approximately 0.8 L/s.

The cold leg isolation valve was used to inject subcooled water into the system immediately prior to introducing slug flow, and the slug flow period was from 5.5 to 11 s during Test TC-3A, and all subsequent TC tests. The injected coolant reduced the initial coolant quality during the slug flow period to approximately 10 to 15% during Test TC-3A, and the quality remained at about 17% during most of the slug flow period, with an average volumetric flow rate of approximately 1.0 L/s.

The initial coolant quality during the Test TC-4A slug flow period was low, approximately 10%, and remained less than 20% until about 7.5 s, at which time it rapidly increased to 90% by 8.2 s, and remained high during the balance of the slug flow period. The hot leg blowdown nozzle area was reduced for Test TC-4A from the nozzle area used in Test TC-3A, and the slug flow volumetric flow rate was reduced to approximately 0.4 L/s. Detailed evaluation of the calculated coolant conditions during Test TC-4A indicated that due to the low slug flow coolant velocity, flow stagnation occurred at approximately the axial midsection of the flow shrouds, permitting countercurrent flow between the liquid and vapor phases of the coolant. The stagnant flow at the midplane quickly vaporized, leading to high coolant quality at the midplane. The calculated average coolant quality during the slug flow period of Test TC-4A was approximately 45%.

The volumetric flow rate through the shrouds increased to 1.2 L/s during Test TC-4D, because of the blocked bypass, but the short isolation valve operation time provided only a small mass of coolant. Consequently, the coolant quality quickly stabilized, but at the relatively high value of approximately 26%, and remained at this value until about 8 s, at which time it began increasing. By the end of the slug period, the quality was approximately 50%, resulting in an average quality during the slug period of approximately 35%.

The relatively long isolation valve operation time during Test TC-4F permitted a greater amount of subcooled liquid to enter the system than in Test TC-4D, consequently reducing the coolant quality to a minimum of approximately 6%, with an overall average during the slug period of approximately 10%.

The influence of these variations in coolant quality and volumetric flow rate on the effect of the cladding surface thermocouples on fuel rod thermal response is shown in Figures 23 and 24. Together, these figures show the relative thermal responses of the cladding internal surface thermocouples during the slug flow period for the bare rods (Figure 23) and for the rods instrumented with cladding surface thermocouples (Figure 24). On the basis of the comparisons shown in Figures 23 and 24, the decrease in slug quality from 45% for Test TC-4A, to 35% for Test TC-1A, and to 17% for Test TC-3A had a small influence on the relative thermal responses of the test rods with and without cladding surface thermocouples. None of these tests displayed the blowdown quench phenomenon observed during the LOFT L2 tests.

Although the coolant quality during Test TC-4D is calculated to be significantly higher than, for example, Test TC-3A, the measured cladding internal surface temperatures show a significant effect due to the high coolant flow rate. In particular, the instrumented Rod 02 temperature (Figure 24) is strongly influenced by the cladding surface thermocouple, and the rod is momentarily quenched near the end of the slug flow period. A similar quench behavior was not measured on the bare Rod 04 (Figure 23).

The increased coolant mass during Test TC-4F (identical to Test TC-4D, except for a longer isolation valve operation time, which provided a greater mass of subcooled coolant into the loop) significantly reduced the slug flow quality. The influence of the reduced quality and high coolant flows on the cladding surface thermocouple effect is shown in Figure 24, in which it is apparent that the cladding on the instrumented fuel rod experienced an early quench and a quench duration of approximately 5 s. On the other hand, the bare rod cladding inside surface temperature shown in Figure 23 indicated only a momentary quench near the end of the slug flow period. It appears, therefore, that the effect of surface

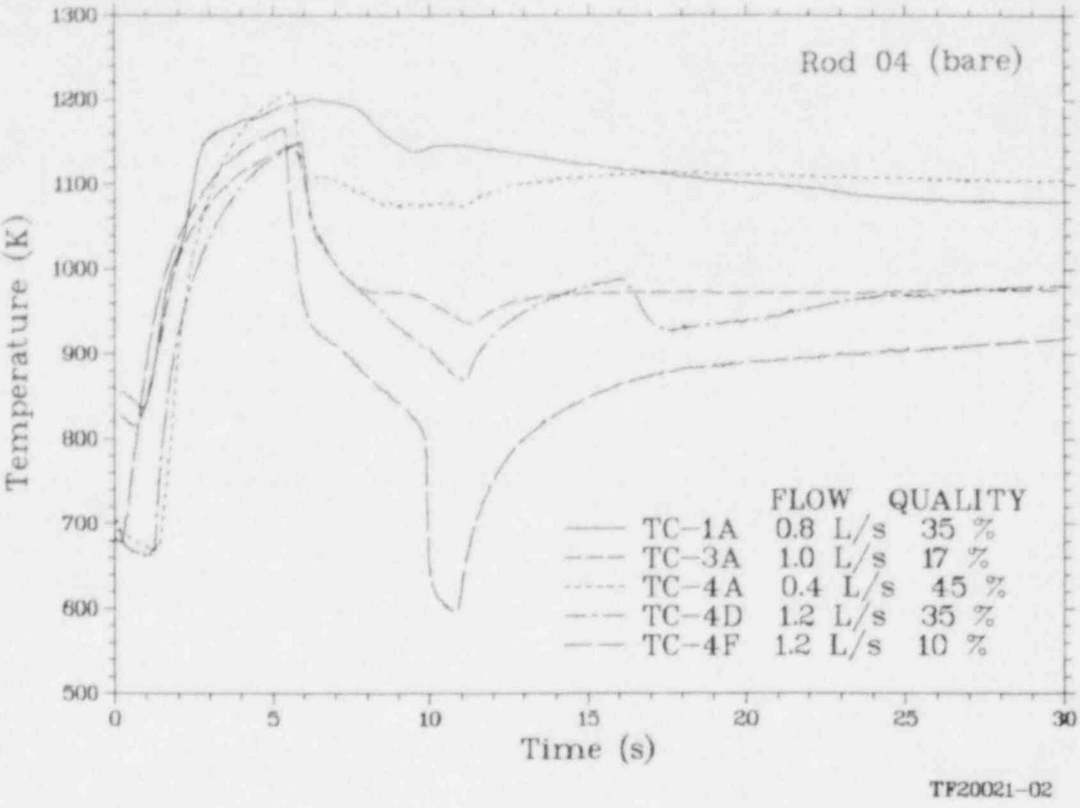

Figure 23. Internal cladding thermocouple responses, showing the influence of variations in coolant quality and flow rate on the thermal response of Rod 04 (bare) during the TC Test Series.

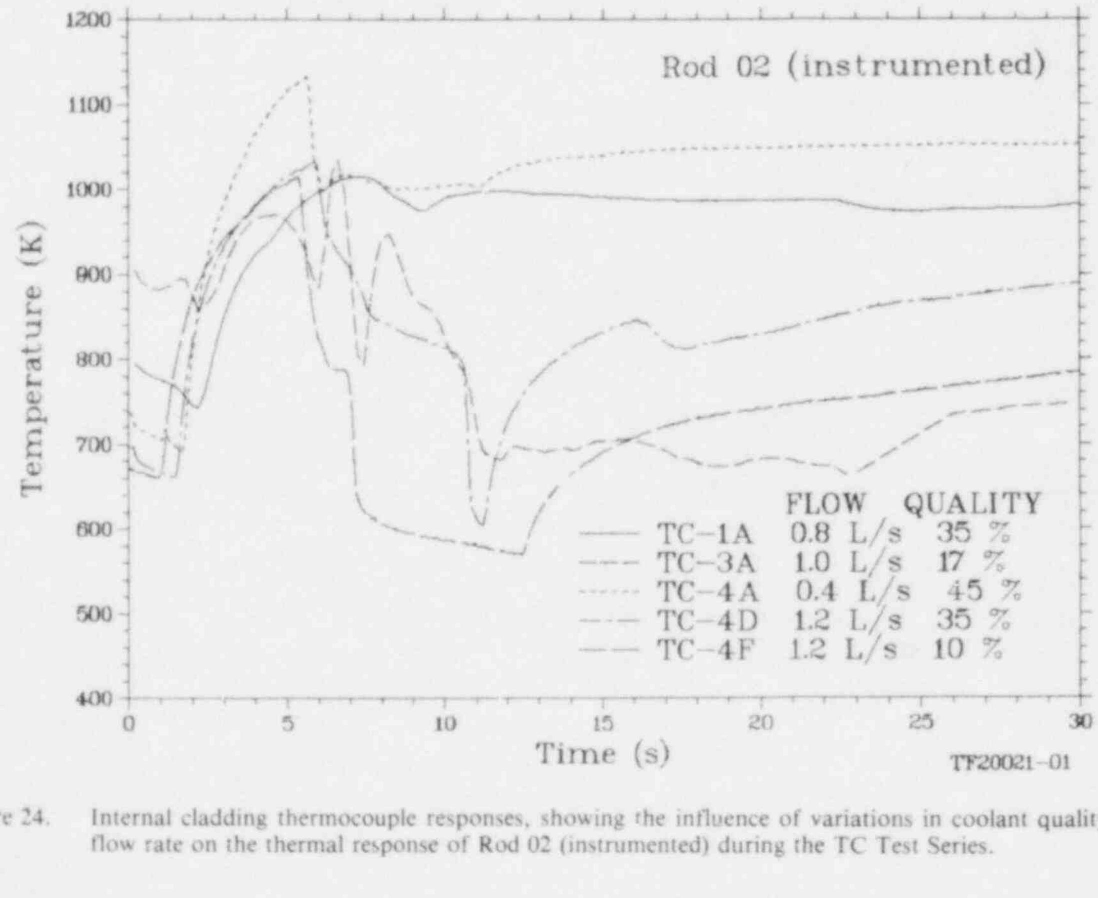

Figure 24. Internal cladding thermocouple responses, showing the influence of variations in coolant quality and flow rate on the thermal response of Rod 02 (instrumented) during the TC Test Series.

thermocouples on rod thermal response during blowdown quench increases as slug quality decreases, over the range of slug quality investigated, and that the effect is also influenced by the slug flow rate. However, it also appears that if slug quality were reduced further and the rods quenched extremely fast, the effect of the surface thermocouples would become small.

Figure 25 shows a comparison between the embedded cladding thermocouple responses for rods with and without surface thermocouples during three of the TC-4 tests during which all the test conditions were the same, except initial rod power (Test TC-4F, 50 kW/m; Test TC-4E, 43 kW/m; and Test TC-4G, 39 kW/m). The comparisons shown in Figure 25 indicate that at the highest initial rod power shown (50 kW/m), both the rods with and without external thermocouples initially cooled at equivalent rates, but that Rod 02, with surface thermocouples, continued to cool at a high rate, while the bare rod cooling rate slowed down. The cladding on Rod 02 quenched approximately 3 s earlier than the cladding on Rod 04 and remained quenched for about 5 s, while Rod 04 momentarily quenched (~1 s). At the intermediate power level (43 kW/m), the cladding on Rod 02 again quenched about 2 s earlier than the cladding on Rod 04, but both rods remained quenched for more than 3 s. The differences in thermal behavior between Rod 02 and Rod 04 at the lowest power level (39 kW/m) were further reduced. The Rod 02 cladding temperatures decreased to a quench temperature almost immediately and the cladding on Rod 04 followed within about 2 s, after which time both rods remained quenched for approximately 5 s. It appears, therefore, that the influence of initial rod power on the surface thermocouple effects decreases, as expected, as the initial rod power level decreases, and there is essentially no influence of surface thermocouples on the thermal behavior of LWR fuel rods during a large break LOCA at very low initial rod powers.

Effects of Surface Thermocouples on LWR Fuel Rod Thermal Response During a LOCA Reflood

Reflood was initiated at 100 s following initiation of blowdown during all of the tests in the Thermocouple Effects Test Series, and the reflood coolant conditions (temperature, flow rate, etc.) were essentially the same (~350 K, 0.2 L/s) during the TC-1 and TC-3 tests and Tests TC-4A, TC-4B, and TC-4C. The bypass flow was blocked during Tests TC-4D, TC-4E, TC-4F, and TC-4G, resulting in a considerably higher reflood rate (~1.2 L/s). Comparisons between the fuel and internal cladding thermocouple responses during reflood for each test rod, and comparisons between test rods, show a generally consistent behavior among all the rods, but also some small variations in rod thermal response under essentially identical conditions. Generally, the rods with cladding external surface thermocouples quenched slightly earlier than the bare rods, but not in every case. In some cases, the rod thermal response appeared to be influenced by rod temperature at the time of initiation of reflood, but not in other cases. Some representative thermal response comparisons during reflood are shown in Figures 26 through 30.

Figure 26 shows a comparison of the thermal responses of the internal (fuel) thermocouples in Rod 04 (bare) with the internal (fuel and two cladding) thermocouples in Rod 02 (with surface thermocouples) during the reflood portion of Test TC-1A. In the comparison, the rods with surface thermocouples quenched approximately 7 to 9 s earlier than the bare rods. However, Figure 27 shows a similar comparison for Test TC-4D, with essentially no differences in rod thermal responses between rods with surface thermocouples and bare rods.

Comparisons of the Rod 01 internal thermocouple responses during reflood for Tests TC-1A, TC-1B, TC-1C, and TC-1D are shown in Figure 28. Differences occurred in the time of quench of the same rod under essentially identical reflood conditions. Although the lower temperature at the time of initiation of the Test TC-1C reflood might account for the earlier rewet during that test, the initial temperature during Test TC-1D was also approximately 1000 K, but rewet was delayed (with respect to Test TC-1C) approximately 5 s. On the other hand, comparisons of the Rod 04 internal thermocouple responses during reflood for Tests TC-4A, TC-4B, and TC-4C, shown in Figure 29, indicate only slight variations in the quench times.

The controlled bypass was blocked to provide higher mass flow through the test space during the

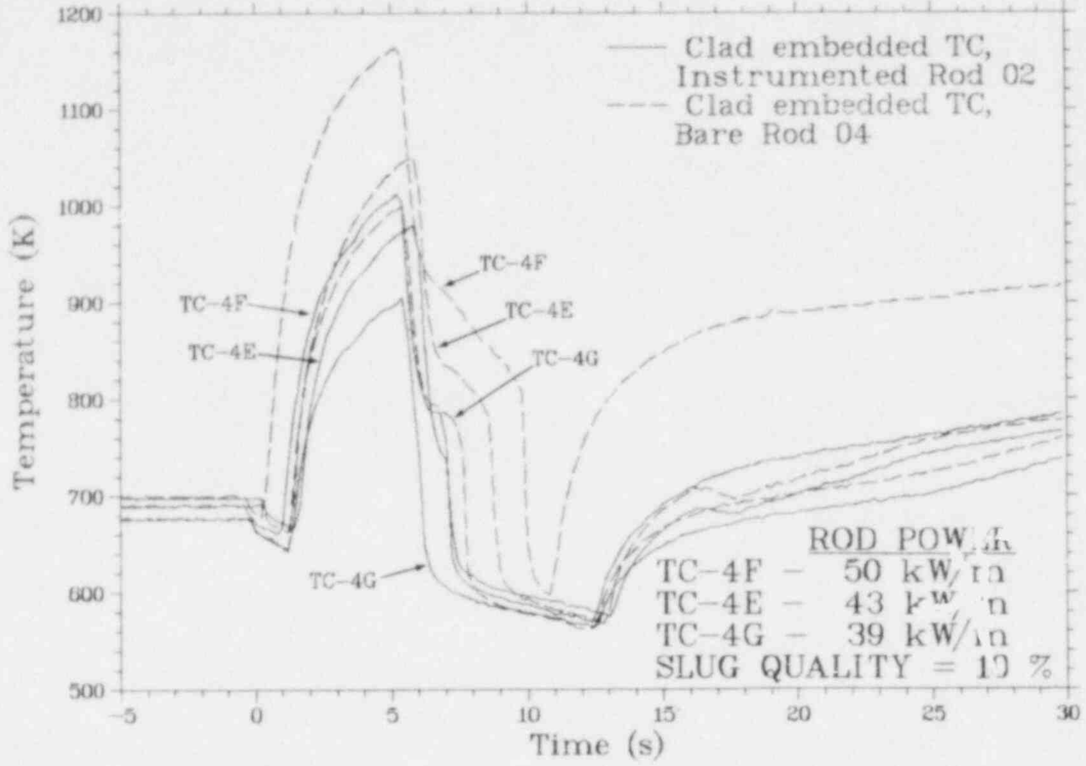

Figure 25. Comparison between embedded cladding thermocouple responses in bare (solid lines) and instrumented (dashed lines) rods during blowdown quench periods of Tests TC-4E, TC-4F, and TC-4G, illustrating the effect of initial rod power on the influence of surface thermocouples on rod thermal response.

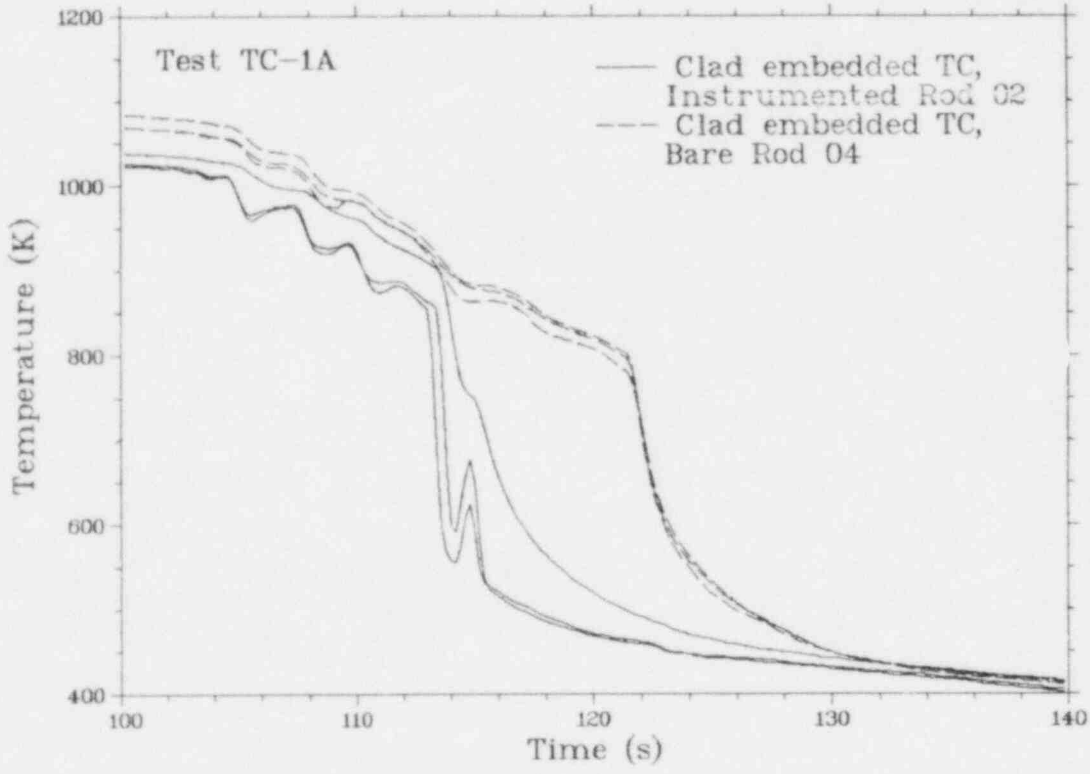

Figure 26. Comparison between embedded internal cladding thermocouple responses in Rod 04 (bare) and Rod 02 (instrumented) during reflood period of Test TC-1A.

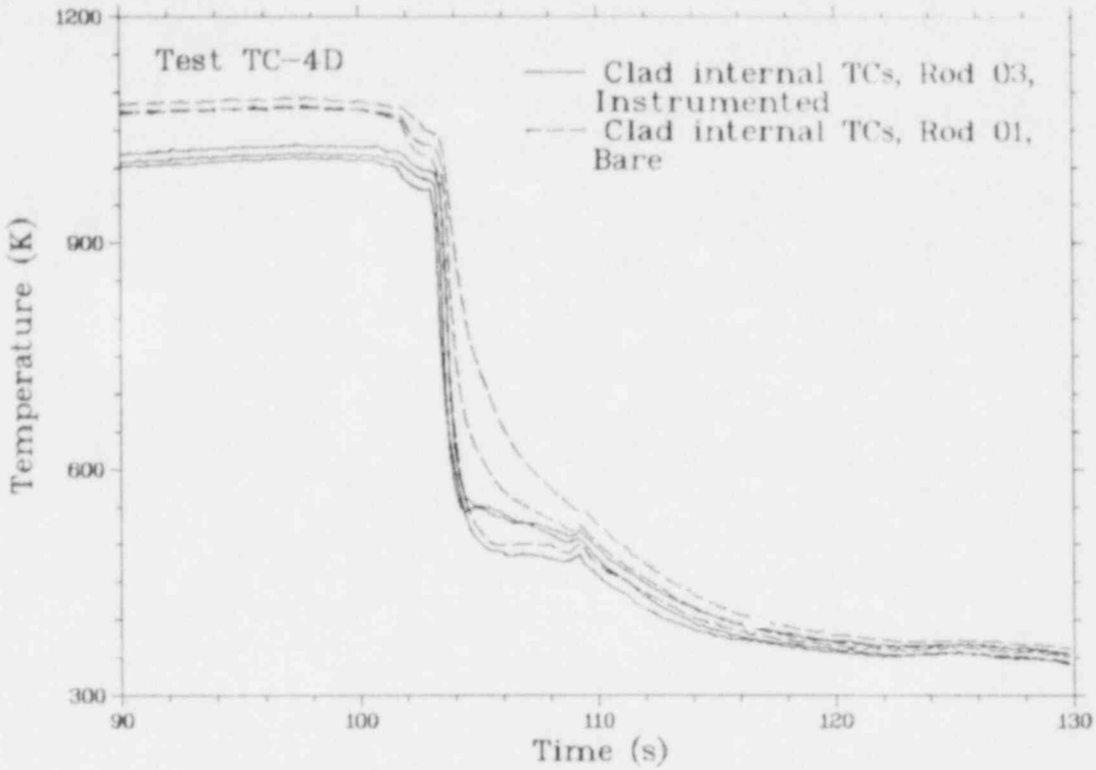

Figure 27. Comparison between internal cladding thermocouple responses in Rod 01 (bare) and Rod 03 (instrumented) during reflood period of Test TC-4D.

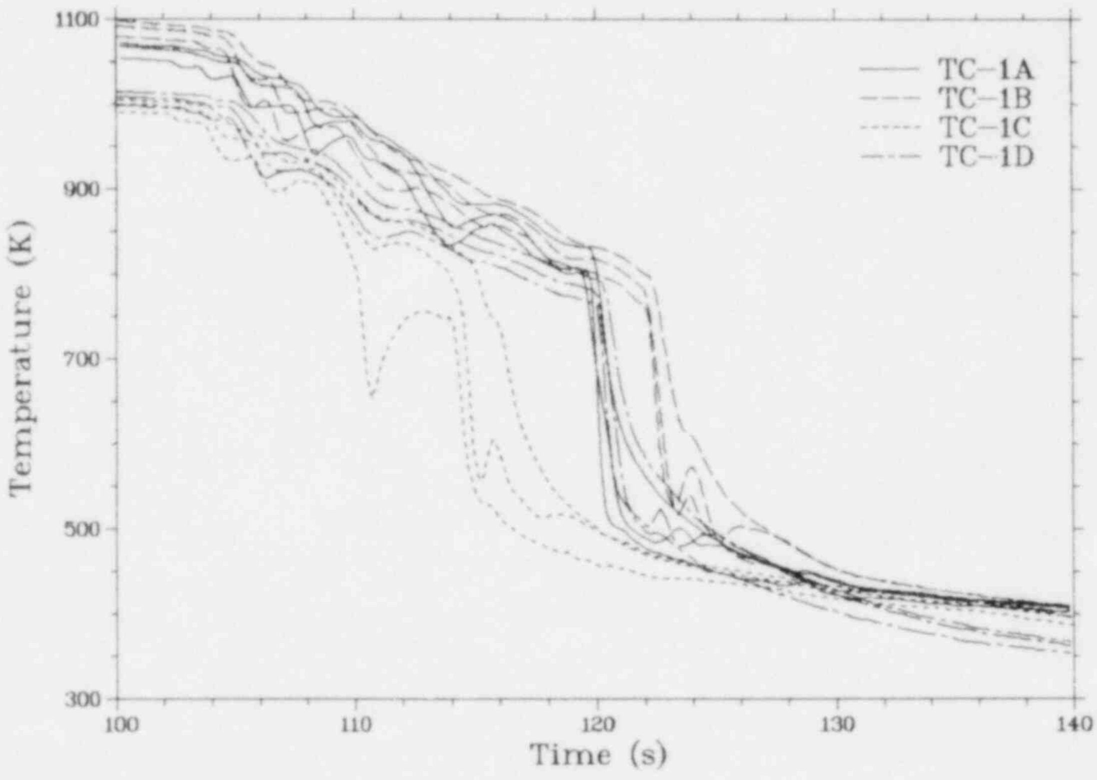

Figure 28. Comparison between internal cladding thermocouple responses in Rod 01 (bare) during reflood period of Tests TC-1A, TC-1B, TC-1C, and TC-1D.

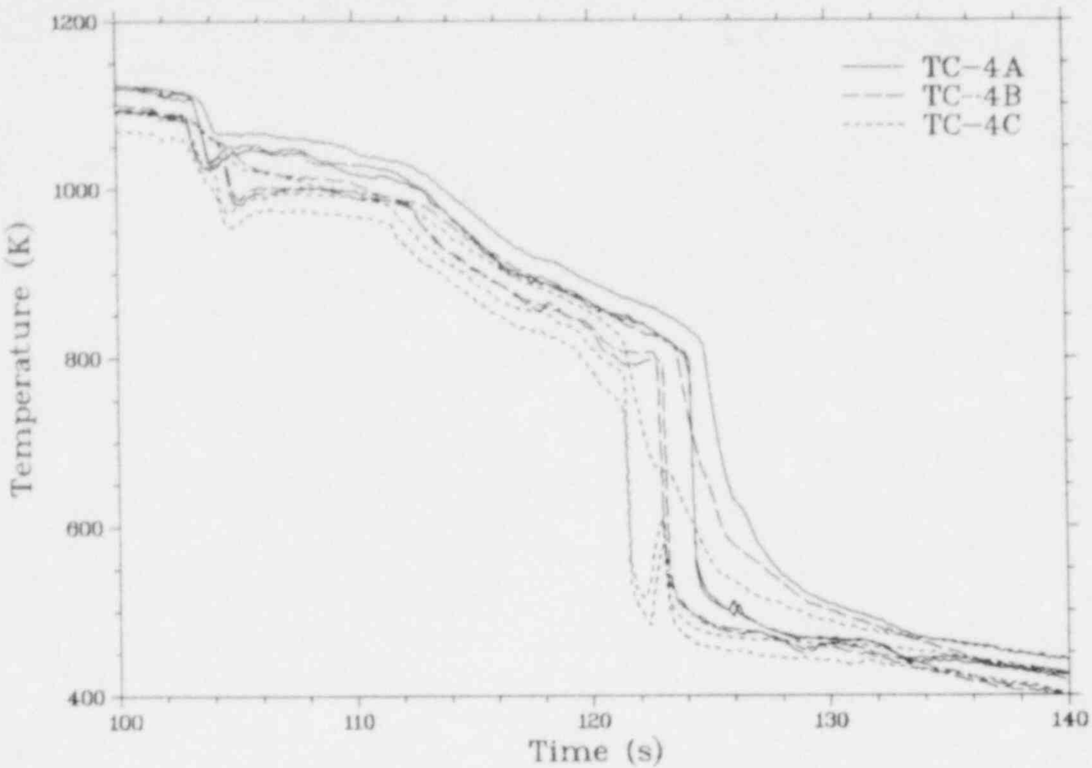

Figure 29. Comparison between embedded internal cladding thermocouple responses in Rod 04 (bare) during reflood period of Tests TC-4A, TC-4B, TC-4C.

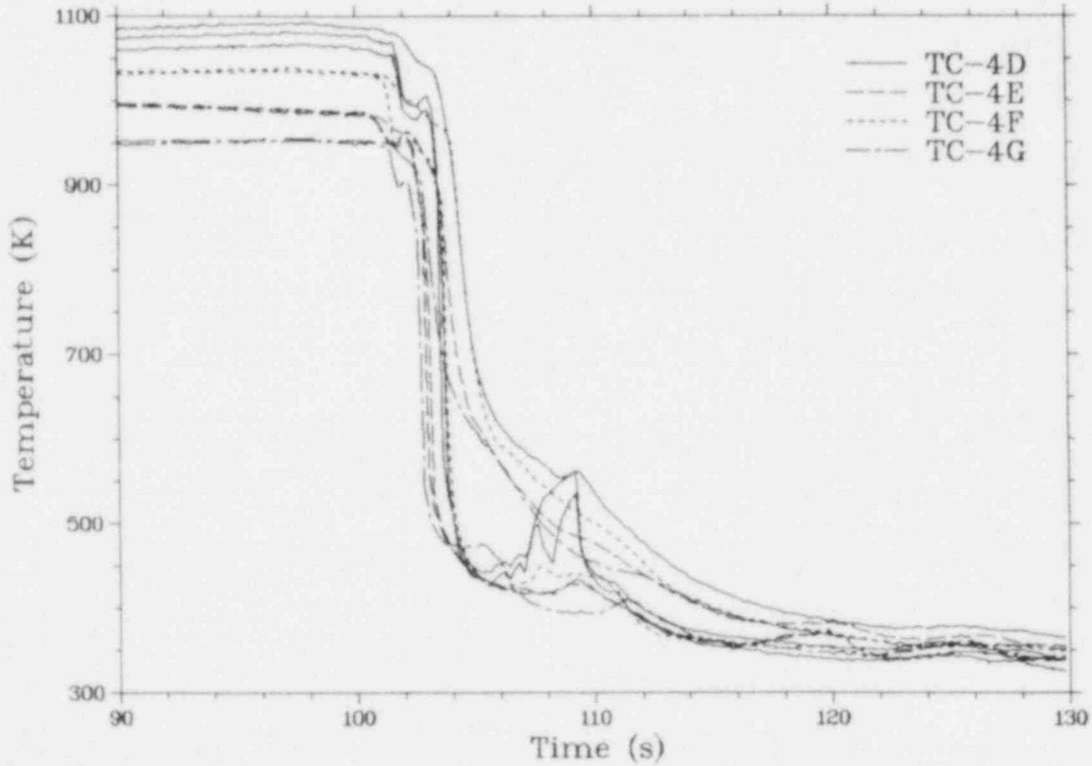

Figure 30. Comparison between embedded internal cladding thermocouple responses in Rod 04 (bare) during reflood period of Tests TC-4D, TC-4E, TC-4F, and TC-4G.

slug flow period of Tests TC-4D through TC-4G. The effect of closing the bypass during the reflood and quench portion of the tests was to also provide higher mass flow rates during quench, which resulted in an earlier quench during Tests TC-4D through TC-4G, as shown in Figure 30. However, in spite of wide variations in initial rod temperatures, the quench behavior was essentially identical during all four tests.

On the basis of the observations described above, it appears that if there is an effect of surface thermocouples on the reflood behavior of LWR fuel rods, it is small and of no importance.

CONCLUSIONS

The objectives of the PBF Thermocouple Effects tests were (a) to evaluate the ability of cladding surface thermocouples to accurately measure cladding temperature, (b) to investigate the effects of cladding surface thermocouples on the behavior of LWR fuel rods under large break LOCA conditions and to evaluate the influence of test variables on these effects, and (c) to evaluate the behavior and durability characteristics of embedded internal cladding thermocouples under in-pile LOCA conditions. On the basis of the results from the three TC test series, it is concluded that cladding surface thermocouples measure cladding peak temperatures during blowdown that are only slightly lower (17 to 27 K) than the actual cladding temperatures when the surface thermocouples were located at the same azimuthal orientation as the embedded thermocouples. External surface thermocouples do influence fuel rod thermal response during the blowdown phase of a LOCA by delaying the initial time-to-CHF of the cladding and by increasing the surface heat transfer (fin effect). Peak temperatures measured during blowdown were about 73.5 K lower for each second of delay in CHF, and the improved cladding heat transfer due to fin cooling reduced the peak temperatures an additional 50 K. The combined effects of the surface thermocouples reduced the cladding peak temperatures during the blowdown phase of the PBF tests by 101 to 115 K. The relative contribution to the surface thermocouple effect due to the delay in time-to-CHF ranged from about 35 to 58% of the total effect, on the basis of a least squares fit of the measured cladding peak temperatures during blowdown as a function of time-to-CHF. The remaining effect was due to fin cooling.

Cladding surface thermocouples also influence the fuel rod thermal response during a large break LOCA blowdown quench, directly due to fin effects during the rapid slug flow, and indirectly due to the reduced blowdown peak temperatures. Generally, during a given test, rods with surface thermocouples quenched earlier and remained quenched longer than bare rods. However, when the thermal behavior of fuel rods with and without thermocouples in different tests was compared, and the blowdown peak temperatures were artificially adjusted to the same value, the blowdown quench behavior of the two types of rods was indistinguishable. The major contributor to the surface thermocouple effect during blowdown quench appears to be the reduced blowdown peak temperature (due to the delay in time-to-CHF and initial fin cooling).

The effect of surface thermocouples on fuel rod thermal response during a LOCA blowdown quench (in any given test) was influenced by the slug quality, slug flow rate, and the initial (prior to blowdown) rod power. Although the influence is relatively small, the effect of surface thermocouples on rod thermal response during blowdown quench appears to increase as the slug quality decreases and as the flow rate increases. However, the data also indicate that the surface thermocouple effect may disappear at very low quality slug flows. In addition, the effect of surface thermocouples on LWR fuel rod thermal response during blowdown quench appears to decrease as the rod initial power decreases, and at low power the effect disappears.

The effects of surface thermocouples on fuel rod thermal response during the reflood portion of a LOCA transient were small and, in some cases, no effects were detected.

The experience with the recently developed embedded internal cladding thermocouples proved them to be a reliable and accurate cladding temperature measurement device that can be used in future experiments.

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