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Author(s): E. L. Tolman
E. W. Coryell

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Responsible NRC Individual and NRC Office or Division:

G. D. McPherson, LOFT Research Branch
Division of Reactor Safety Research, USNRC

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EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

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LOFT TECHNICAL REPORT

Title Review of LOFT Cladding Temperatur[illegible] Response for L2-2 & L2-3: Recommendations for Improved LOFT Fuel Rod Measurements	LTR No. EGG-LOFT-5244
Author E. L. Tolman, E. W. Coryell *E. Tolman* *E. W. Coryell*	Released By LOFT CDCS
Performing Organization LOFT Instrumented Fuels Branch	Date October 17, 1980 *SH*
LOFT Review and Approval *D. J. Hanson* LMD Mgr.	Project System Engineer *M. K. Russell*

ABSTRACT

This report summarizes the measured cladding temperature response during the LOFT L2-2 and L2-3 tests with particular emphasis on both the early cladding quench which occurred during the first 6-10 seconds of the transients and the final fuel rod quench resulting from reflooding of the core with ECC water. Supporting analysis work is also presented to aid in understanding the data. A discussion of the measurement errors of the LOFT cladding thermocouples is presented with emphasis on recent separate effects tests. A knowledge of the thermocouple cooling effects based on these separate effects tests is used to estimate an upper bound temperature response for the L2-3 test, which indicates that an uninstrumented LOFT fuel rod may have experienced peak cladding temperatures nearly 100 K higher than indicated by the cladding temperature measurements. In addition, uninstrumented LOFT fuel rods may have experienced quench during the final reflooding of the core by as much as 25 seconds later than indicated by the cladding thermocouples. To resolve the uncertainty in the fuel rod response, additional experimental and analytical work is required to better quantify instrumentation perturbations, particularly the cooling influence of cladding surface thermocouples during rapid cooling transients. In addition, it is recommended that improved cladding temperature measurements be made for future LOFT tests.

DISTRIBUTION OF RECOMMENDATIONS

The additional experiment and analytical work is underway at INEL, West Germany, Switzerland, and Norway and the improved cladding temperature measurements (small zircaloy sheathed thermocouples embedded in the cladding inside surface and stainless steel sheathed thermocouples in the fuel pellet periphery) and other special features are being developed and incorporated into the F1 fuel bundle. This recommendation is expected to be finally resolved by evaluation of the data from the L2-5 test.

ABSTRACT

During the first two large-break loss-of-coolant-experiments conducted in the Loss-of-Flow-Test (LOFT) facility, cladding surface temperature quenches were observed at all measurement locations early in the transient, before the emergency core cooling (ECC) systems were activated. The test data suggests that during a large-break loss-of-coolant-accident, the hydraulic response of the primary system coolant effectively cools the fuel rods before any cladding damage would occur and significantly reduces the initial energy removal required of the ECC systems.

The characteristics of the cladding temperature response have been questioned because of hypothesized perturbation effects of the LOFT cladding thermocouples. This article summarizes the measured cladding temperature response during the tests with particular emphasis on both the early cladding quench which occurred during the first 6-10 seconds of the transients and the final fuel rod quench resulting from reflooding of the core with ECC water. Supporting analysis work is also presented to aid in understanding the data. A discussion of the measurement errors of the LOFT cladding thermocouples is presented with emphasis on recent separate effects tests. A knowledge of the thermocouple cooling effects based on these separate effects tests is used to estimate an upper bound temperature response for the L2-3 test, which indicates that an uninstrumented LOFT fuel rod may have experienced peak cladding temperatures nearly 100 K higher than indicated by the cladding temperature measurements. In addition, uninstrumented LOFT fuel rods may have experienced quench during the final reflooding of the core by as much as 25 seconds later than indicated by the cladding thermocouples. To resolve the uncertainty in the fuel rod response, additional experimental and analytical work is required to better quantify instrumentation perturbations, particularly the cooling influence of cladding surface thermocouples during rapid cooling transients. In addition, it is recommended that improved cladding temperature measurements be made for future LOFT tests.

SUMMARY

The LOFT large break loss-of-coolant experiments, L2-2 and L2-3, show a significant core cooling influence within 5-10 seconds after the simulated pipe rupture, well before the emergency core cooling systems were activated. The effectiveness of this cooling on the nuclear fuel rods has been questioned due to uncertainty in the influence of the cladding surface thermocouples during the LOFT nuclear tests. The thermocouples have been hypothesized to reduce the LOFT peak cladding temperature by (1) delaying the initial departure from nucleate boiling (DNB), (2) increasing the fuel rod heat transfer by effectively increasing the cladding surface area (fin effect), and (3) selective cooling of the entire fuel rod, and in particular the surface thermocouples, during cooling periods characterized by low quality, two-phase coolant flow.

Review of the measured fuel rod cladding temperatures is presented for both LOFT tests. Details of the steady state temperature characteristics and transient temperature responses are presented to show the consistency in the data and to establish the characteristics of the peak cladding temperature, the cladding quench which occurred between six and eight seconds, and the final reflood cooling characteristics. Fuel rod stored energy calculations based on the measured temperatures show the early quench period is effective in removing approximately 40 percent of the stored energy in the fuel rods.

The results of thermocouple separate effects tests enable one to estimate the cooling influences of the surface thermocouples during the LOFT tests. Transient tests on electric rod bundles with and without surface thermocouple simulators indicate the surface thermocouples do not affect time-to-DNB. However, recent loss-of-coolant experiments conducted in the Power Burst Facility utilizing nuclear rods show a delay in DNB of approximately one second. Simulated loss-of-coolant accident transients conducted in the Blowdown Facility located at the Idaho National Engineering Laboratory (INEL) utilizing electric heater rods, and tests

conducted in the Power Burst Facility on nuclear rods show that for uniform steam cooling, the cladding thermocouples accurately measure the cladding temperature. Recent tests in the Blowdown Facility and in the PBF indicate that under two-phase coolant conditions, the thermocouples provide additional cooling to the entire rod. For hydraulic conditions intended to simulate the core coolant behavior in LOFT during the initial rod quench, the Blowdown Facility data show the cladding thermocouples may be measuring coolant temperatures rather than cladding temperatures. Care must be taken in interpreting the data from these electric heater rod tests, but the similarity in the surface thermocouple response between the LOFT and quench tests, suggest that selective cooling of the surface thermocouples and the entire fuel rods may have occurred during the LOFT tests. The PBF TC-1 tests were scoping tests to study the cooling influence of surface thermocouples on nuclear rods. The test data show that during a simulated ECC reflood, fuel rod cooling rates are nearly the same for rods with and without surface thermocouples; however, rods with surface thermocouples quench 5 to 10 seconds earlier.

An upper bound cladding temperature response for the LOFT L2-3 test was estimated based on the thermocouple separate effects test data. LOFT fuel rods may have achieved peak cladding temperatures nearly 100 K higher than the measured values and the reflood cooling may have lasted 25 seconds longer than indicated by the thermocouple data.

Resolution of the actual LOFT cladding temperature will require additional experimentation, analysis work, and improvements in fuel rod measurements. Specific recommendations in these areas include:

1. Experimentation

Additional cladding quench tests are required to evaluate the rapid, high pressure quench characteristics of a nuclear rod during cooling conditions similar to those expected in LOFT. Tests are planned on nuclear rods in the PBF and on zircaloy clad electric rods with a simulated fuel-cladding gap in the INEL Blowdown Facility. These tests will provide the experimental basis of reducing the uncertainty in the cladding temperature response during the LOFT L2-2 and L2-3 test, and will provide well characterized thermal-hydraulic data for assessing improvements in analytical heat transfer models.

2. Analysis tasks

   a. <u>Heat Transfer and Cladding Thermocouple Perturbation</u>. Additional analysis work is required to (1) improve capability of modeling two-phase heat transfer for hydraulic conditions characteristic of those which resulted in the LOFT L2-2 and L2-3 quenches, and (2) adequately model the perturbation influence of the LOFT cladding surface thermocouples. Experiments are being designed to better characterize the heat transfer which occurred during the LOFT quenches. In addition, existing low flow, low quality heat transfer data is being evaluated to provide a basis for improving the heat transfer models. Improvements in the heat transfer models together with the quench experiments described above will provide the basis for modeling the cooling influence of cladding surface thermocouples during the LOFT tests.

b. <u>Fuel Centerline Temperature Measurement</u>. Analysis is required to evaluate the perturbation effects of fuel pellet thermocouples in measuring accurate fuel temperatures (both fuel centerline and peripheral fuel temperatures).

c. <u>Microwave Technique Development</u>. Continue conceptual analysis for measuring cladding temperatures via microwave radiometry methods.

3. Fuel Rod Measurement Improvements

a. Continue development and testing of small (.010 inch thick) cladding thermocouples to be embedded on the inside cladding surface.

b. Develop hardware requirements for measuring cladding temperature via radiometry methods and experimentally evaluate the method in the Blowdown Facility for possible utilization in LOFT and commercial nuclear power plants.

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1. INTRODUCTION

The purpose of the Loss-of-Flow-Test (LOFT) facility is to experimentally investigate the response of nuclear reactor systems, including the engineered safeguard features, to a variety of loss-of-coolant-accident (LOCA) conditions. The data will provide a better understanding of the conservative margin of both system thermal-hydraulic and fuel rod behavior and provide the basis for computer model development and verification.

The first two large-break loss-of-coolant-experiments (LOCE) have demonstrated the usefulness of integral nuclear systems tests. Both tests showed that high cladding temperatures which would result in fuel rod failure were not achieved primarily because of the system hydraulic response during the first few seconds of the experiment which provided a significant cooling influence on the fuel rods. References 1 through 4 present data from the tests and Reference 5 discusses the system thermal-hydraulic response, interpretation of the test results, and applicability of the test results to a commercial PWR system. The early, rapid cladding quench has been attributed, at least in part, to the selective cooling effect of the cladding surface thermocouples. The purpose of this paper is to present the details of the cladding temperature response during the tests and show the consistancy of the data, the extremely rapid nature of the early cladding quench, and to estimate the cooling effect of the LOFT thermocouples based on recent separate effects tests.

The LOFT core configuration and cladding temperature measurement locations are described in Section 2. The measured cladding temperature response for both tests is reviewed in Section 3 in which details of the early cladding temperature quench are presented. The cladding temperature response during reflood is also presented and shows the same general response as observed in many out-of-reactor reflood experiments using electric heater rods, except the cladding temperature was quenched more rapidly. In Section 4, analytical results are presented as an aid to evaluate fuel rod stored energy during the LOFT transients. Section 5 presents the results of recent separate effects tests to investigate the cooling influences of the cladding surface thermocouples. Section 6 presents the results of analysis to predict the unperturbed cladding temperature response for the L2-3 test based on the information presented in Sections 3, 4, and 5. This estimated upper bound cladding temperature together with the measured temperature, which represents a lower bound, provide an envelope representing the current uncertainty in the true cladding temperature response. Section 7 discusses ways to improve the fuel rod measurements to reduce the uncertainty in the fuel rod response and additional analysis work that will improve understanding of instrumentation effects and code capabilities to model important LOCA thermal-hyraulic phenomena. Specific recommendations for measurement improvements and an outline of required analysis tasks are presented.

2. LOFT CORE CONFIGURATION AND INSTRUMENTATION

The LOFT primary coolant system is shown in Figure 1 and consists of an intact loop containing active components to simulate three unbroken loops of a four-loop PWR, a reactor vessel containing a nuclear core, and a broken loop to simulate the single broken loop of a PWR. The broken loop contains passive steam generator and pump components (simulators) and has no appreciable flow prior to LOCE initiation. The broken loop terminates in two quick-opening blowdown valves, which simulate the pipe rupture. The broken pump loop and steam generator simulators contain orifice plates to simulate the pressure drops of their respective counterparts. The LOFT facility was scaled to generic PWRs, maintaining the system and component coolant volume-to-total power ratio whenever possible.

The 1.7 m long LOFT reactor core is about one-half the length of typical reactor cores (3.7 m long) in commercial plants. The core consists of 1300 fuel rods contained in nine fuel assemblies as shown in Figure 2. The fuel rods are nominal 15 x 15 PWR design except for length and fuel rod prepressurization. The low prepressurization (0.14 MPa) precludes fuel rod ballooning and failure and improves fuel utilization. The in-core instrumentation includes fuel rod cladding and guide tube thermocouples, core liquid level detectors, and neutron flux measurements. A total of 186 cladding thermocouples are attached to 76 fuel rods located throughout the core as shown in Figure 2.

The thermal response of the peak power rods are of most interest; these rods are contained in the center fuel module. Figure 3 shows the center module cross-section emphasizing the thermocouple locations on the instrumented fuel rods. Notice that three groups, or clusters, of five adjacent rods near the core center, are identically instrumented with thermocouples ranging in axial elevation from 2 to 64 inches. The center rod in each cluster represent the hottest rods in the core that are completely surrounded by other fuel rods. Notice also that four single

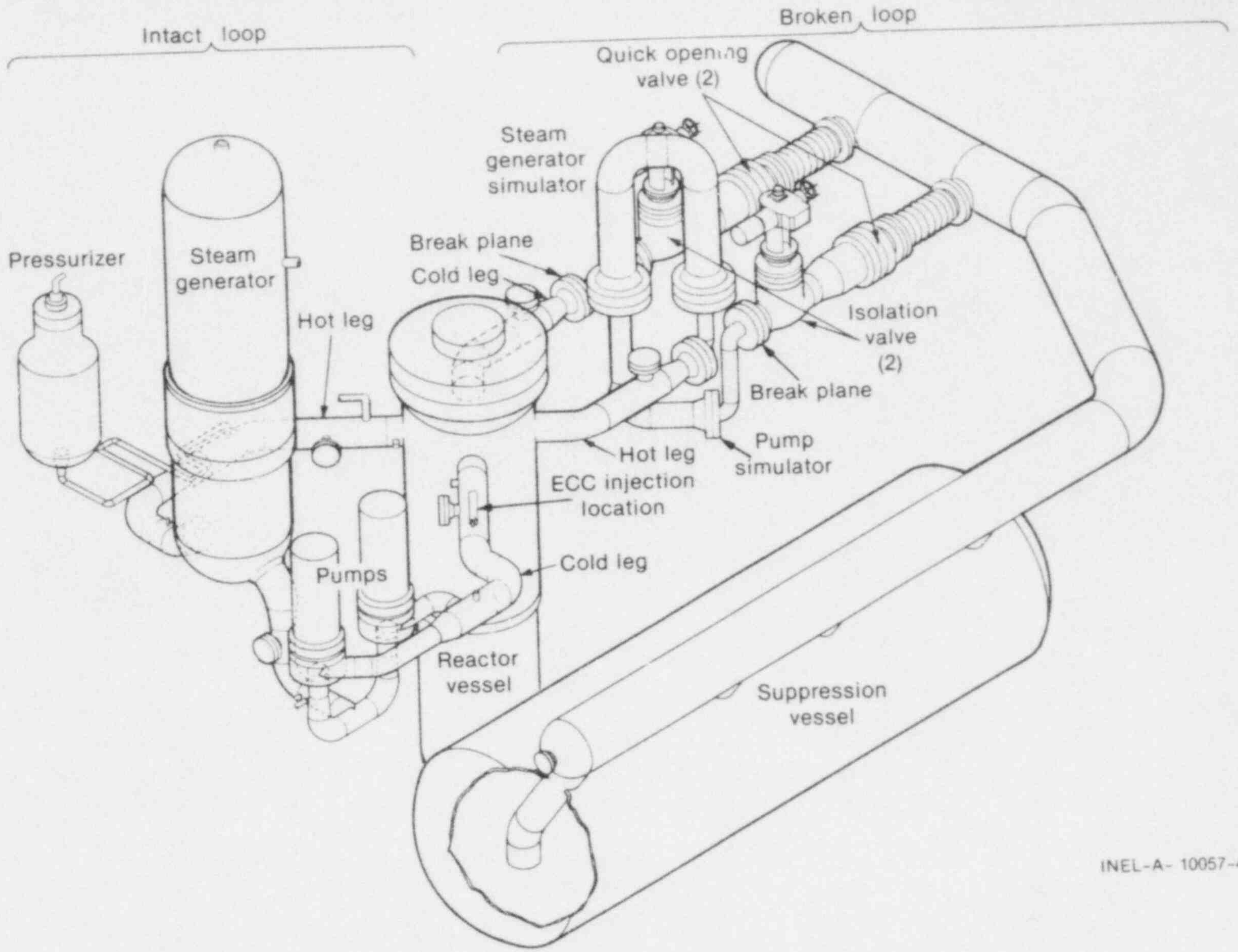

Figure 1. LOFT System Configuration

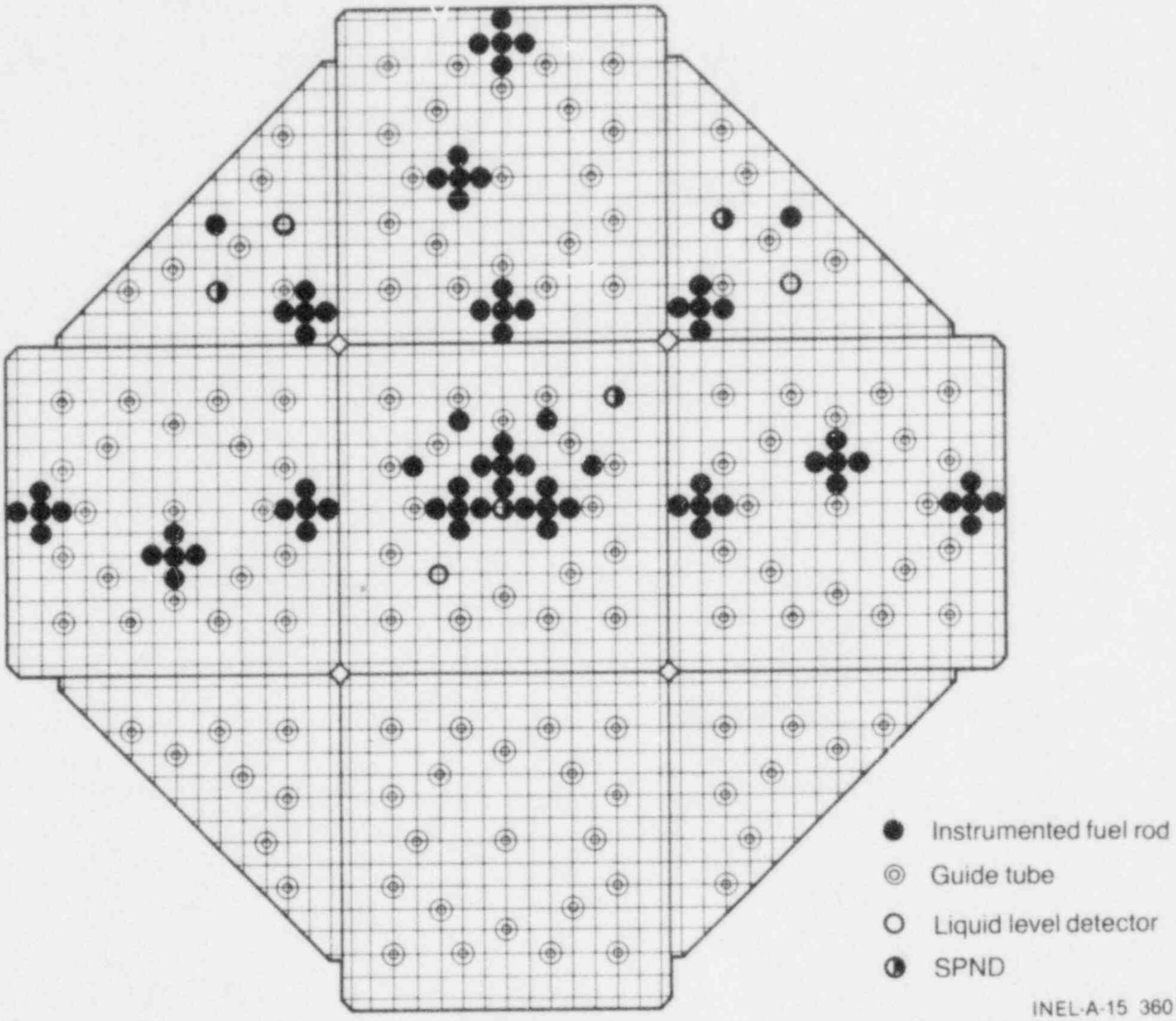

Figure 2. LOFT Core Configuration

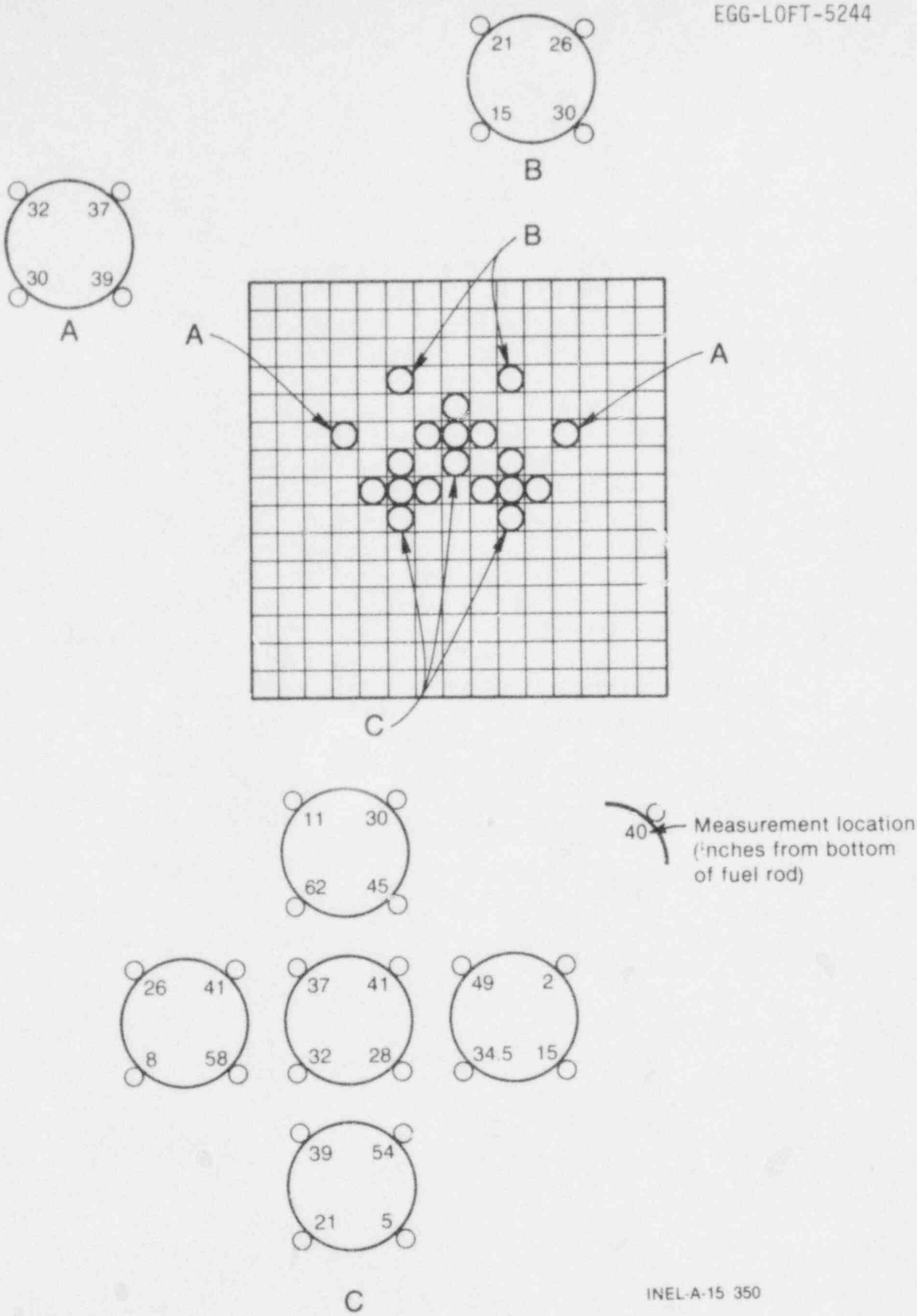

Figure 3. Center Fuel Module - Instrumented Rods

rods farther out from the core center each contain four thermocouples ranging axially from 15 to 39 inch. These four rods are the peak power rods in the core and have greater powers (two to seven percent) than rods in the five rod instrumented clusters.

The method of attaching the thermocouple to the cladding is shown schematically in Figure 4. The 1.17 mm OD titanium thermocouple sheath is laser welded to the cladding surface at approximately one inch intervals. To reduce axial rod bowing effects from non-symmetric thermal response, dummy thermocouple segments extend from upper level thermocouples to the lowest axial thermocouple position on each rod as indicated in Figure 4. The thermal junction is flattened to 0.67 mm and is shown schematically in Figure 5. Figure 6 shows a metallurgical cross-section of a LOFT thermocouple tip attached to the zircaloy cladding.

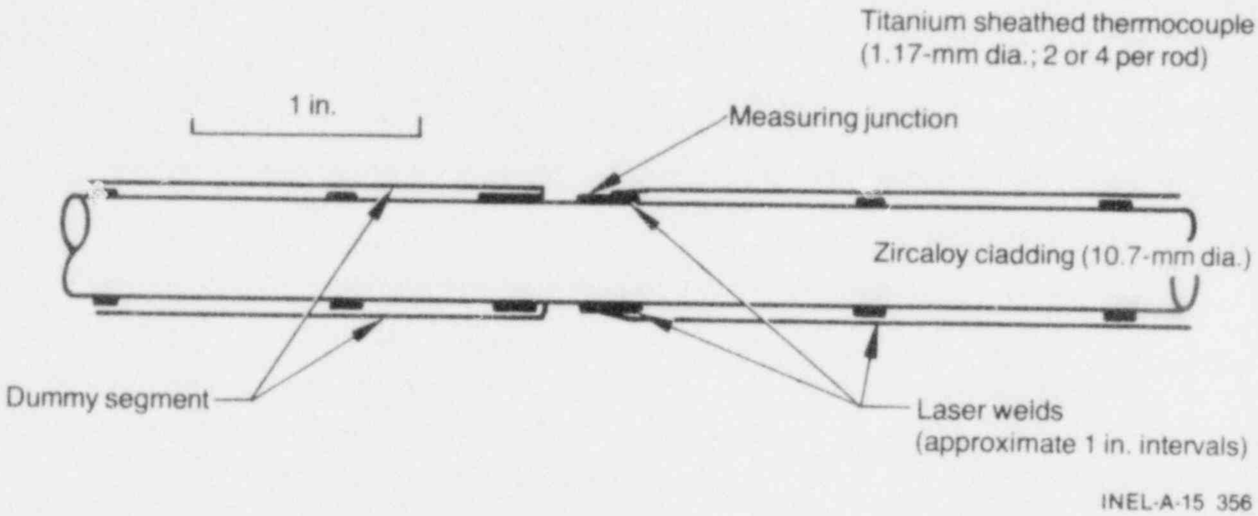

Figure 4. LOFT Cladding Thermocouple - Cladding Attachment

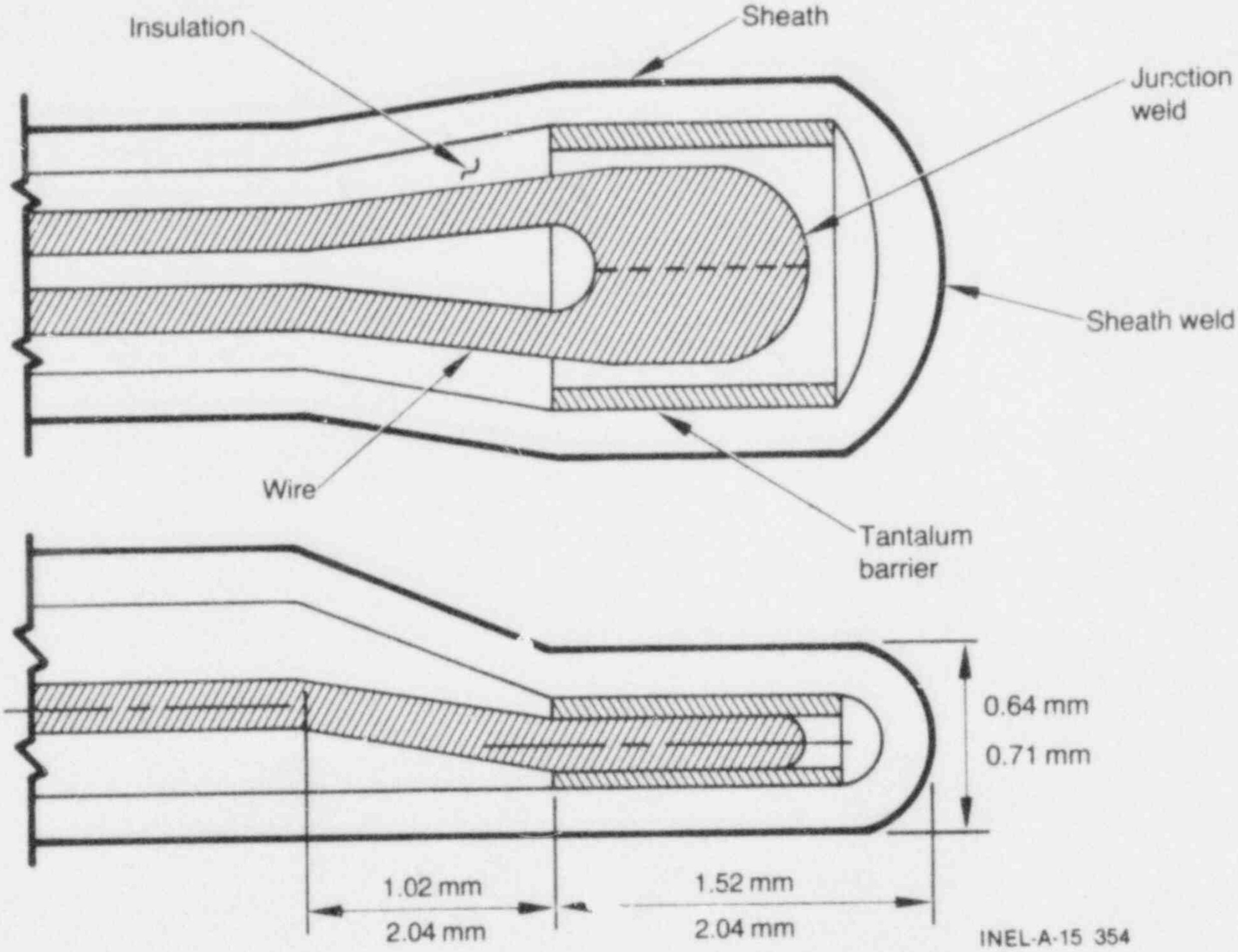

Figure 5. LOFT Cladding Thermocouple Tip Geometry

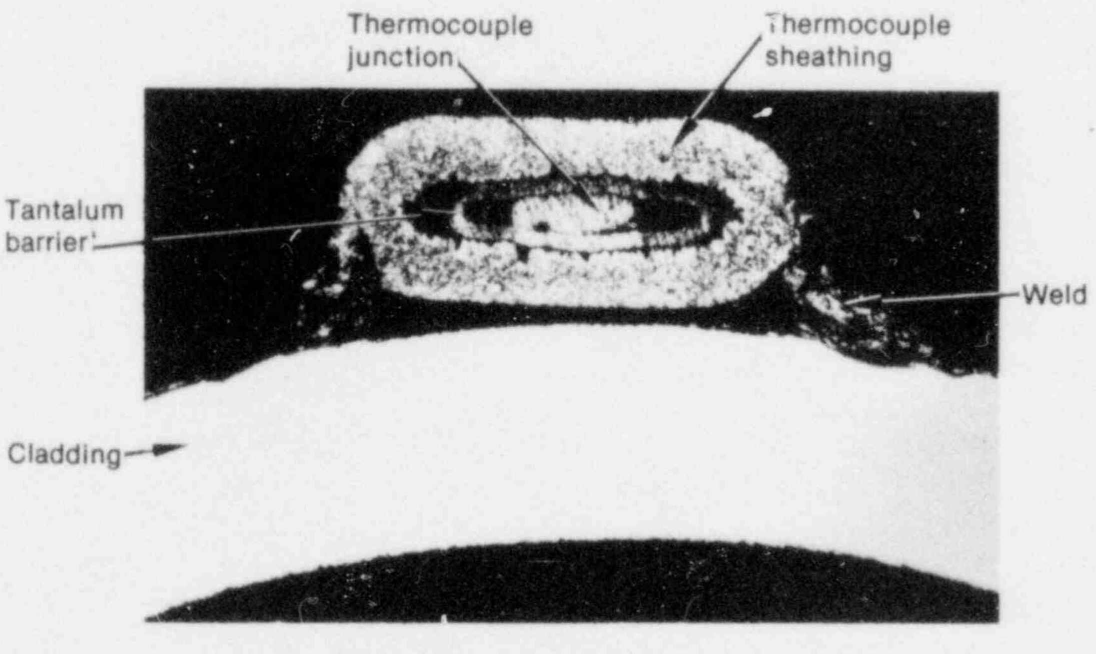

Figure 6. Metalographic Cross-section of LOFT Thermocouple Tip

3. LOFT CLADDING TEMPERATURE RESPONSE

Two large-break nuclear loss-of-coolant experiments (LOCEs) have been completed, designated L2-2 and L2-3, differing only in the linear fuel rod power generation. Table 1 summarizes the initial test conditions.

The measured transient cladding temperature response of the fuel rods, near the axial peak power zone for the two tests are compared in Figure 7. Initial DNB occurred between 1-2 seconds[a] and coincided with a general flow stagnation after which the measured cladding temperature rapidly increased for 1-2 seconds. At approximately 3 seconds, measured upward core flow was established which tended to cool the core and reduce the rate of cladding temperature increase. At about 4 seconds the flow in the reactor vessel was increased as a result of flow reduction out the cold leg break and resulted in increased flow through the reactor core at velocities estimated from 150-200 cm/s which resulted in the measured cladding quench from approximately 5.5 to 7.5 seconds. The cladding quench was maintained for several seconds, but eventually as the reactor vessel coolant was depleted, a second DNB or dryout occurred at about 10-12 seconds. After this time the cladding temperatures in the peak power location increase slowly until ECC water reflooded the core.

To evalute the consistancy in the measured cladding temperatures and to provide additional details of the temperature response, additional data is presented and discussed with particular emphasis on the following phenomena:

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a. Unless otherwise stated, all times are referenced to the blowdown valve opening, initiating the test.

TABLE 1. PLANT OPERATING CONDITIONS AT EXPERIMENT INITIATION

Parameter	LOCE L2-2	LOCE L2-3
Primary system:		
Pressure (MPa)	15.64	15.06
Temperature (K)	570	573
Mass flow (kg/s)	194.2	199.8
Boron (ppm)	838	697
ECC accumulator:		
Pressure (MPa)	4.11	4.18
Temperature (K)	300	307
Boron (ppm)	3301	3281
Injected volume(m^3)	1.05	0.96
Reactor core:		
Power MW(t)	24.9	36.7
Average linear heat generation rate (kW/m)	10.9	16.0
Maximum linear heat (kW/m) generation rate (kW/m)	26.37	39.4
Coolant temperature rise (K)	22.7	32.2

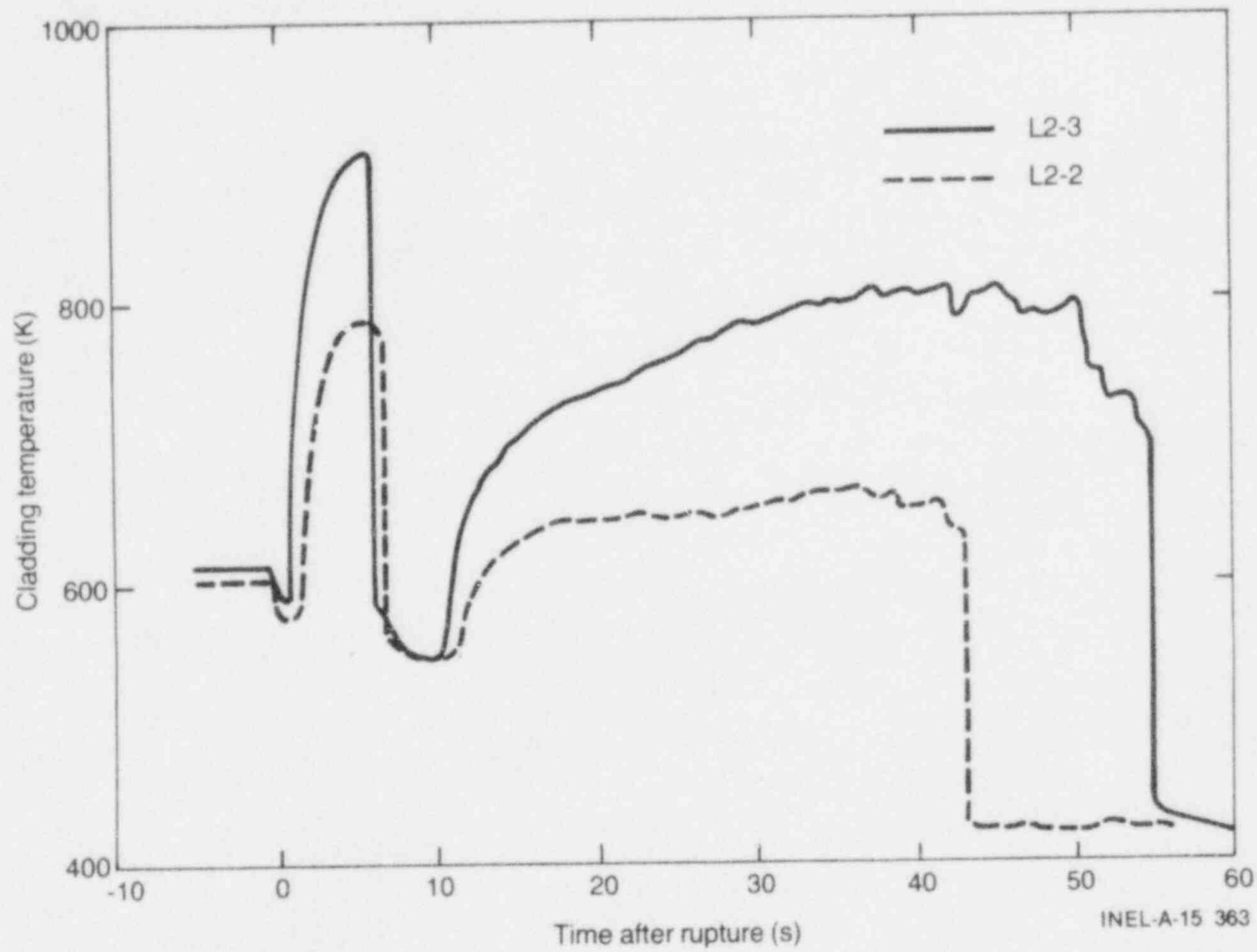

Figure 7. Peak Cladding Temperature for L2-2 and L2-3

1. Steady-state cladding temperatures

2. Initial time-to-DNB

3. Details of the peak cladding temperature and quench from 0-10 seconds.

4. Secondary dryout and characteristics of the reflood temperature quench.

3.1 Steady-State Cladding Temperatures

The steady-state cladding temperatures are a function of the local coolant temperature, heat convection at the cladding-coolant interface, and the steady-state power generated within the fuel rod. Thus, the measured steady-state cladding temperatures as a function of rod elevation reflect the axial fuel rod power as shown in Figure 8. The scatter in the measured steady-state temperatures shown in Figure 8 are due to the inherent accuracy limitation of the thermocouples, differences in rod power, and slight variation in the attachment geometry of individual instruments. Notice in Figure 8, the calculated steady state cladding temperatures do not agree well with the measured data as a function of axial distance along the rod. Analysis shows this difference to be due to the 'fin effect' (increase in surface heat transfer area) of the surface thermocouples. Section 5.2 presents separate effects test data which are utilized to estimate the fin effect of the surface thermocouples.

3.2 Initial Time-to-DNB

Since considerable heat is transferred from the fuel rod prior to the DNB, time-to-DNB is an important parameter influencing the large break LOCA peak cladding temperature. For example, a one second delay in the DNB initiation can result in 50-60 K reduction in peak cladding temperature for initial power levels near 16 kW/ft.

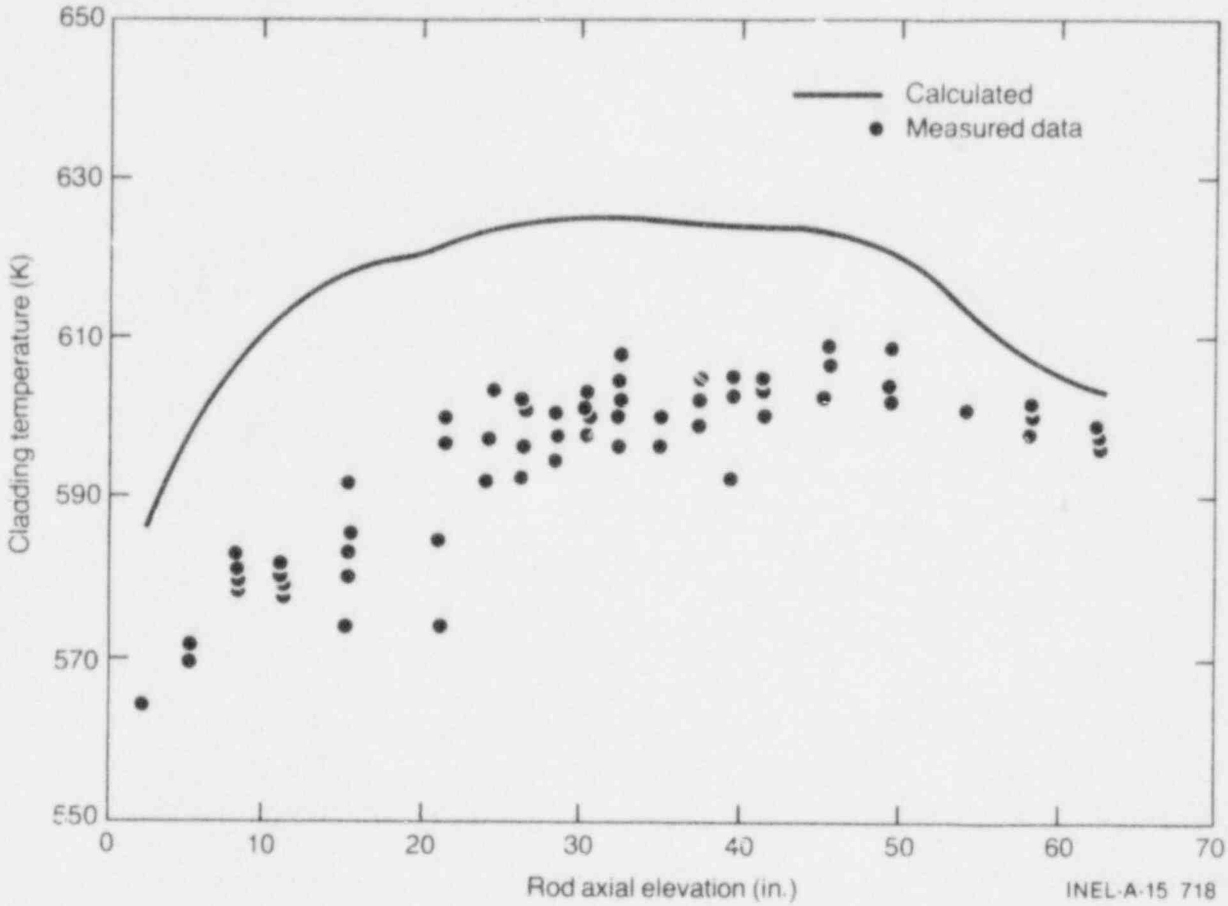

Figure 8. SteaJy State Measured and Calculated Cladding Temperatures vs Axial Position (L2-2)

For the LOFT tests, measured time-to-DNB was a function of rod axial elevation and generally occurred between 1-2 seconds of all locations for both tests. Figures 9 and 10 show the time-to-DNB as a function of fuel rod axial position for L2-2 and L2-3 respectively. From these figures, the effect of increasing test rod power reduces time-to-DNB in the peak power regions (20-30 inches) by 0.2 to 0.4 seconds. For the higher power test, lower axial positions of the rod experience DNB at nearly the same time as the peak power locations. Notice that during either test, the statistical spread between clustered and single instrumented rod data are not significant, even though the single rods are adjacent to a control rod guide tube.

The surface thermocouples which provide additional cooling can be hypothized to affect time-to-DNB. Separate effects tests have been conducted on bundles of electric heater rods and on nuclear rods to evaluate the cooling effects of LOFT surface thermocouples on time-to-DNB during transient blowdown conditions. These tests are summarized and compared to LOFT data in Section 5.

3.3 Peak Cladding Temperature and Initial Temperature Quench

In both L2-2 and L2-3, the peak cladding temperatures were achieved during the first six seconds, just prior to the measured cladding quench. The cladding temperatures measured in the center fuel module were consistant at identical axial locations and varied axially as a result of the power distribution and axially changing coolant conditions. For example the measured cladding temperatures vs time at the 8 inch axial elevation during the first 10 s of the L2-3 test are shown in Figure 11. Notice the uniformity in response from the three separate rods, the very sharp initiation of the cooling transient at about 5.5 s, and the rapid drop to the saturation temperature.

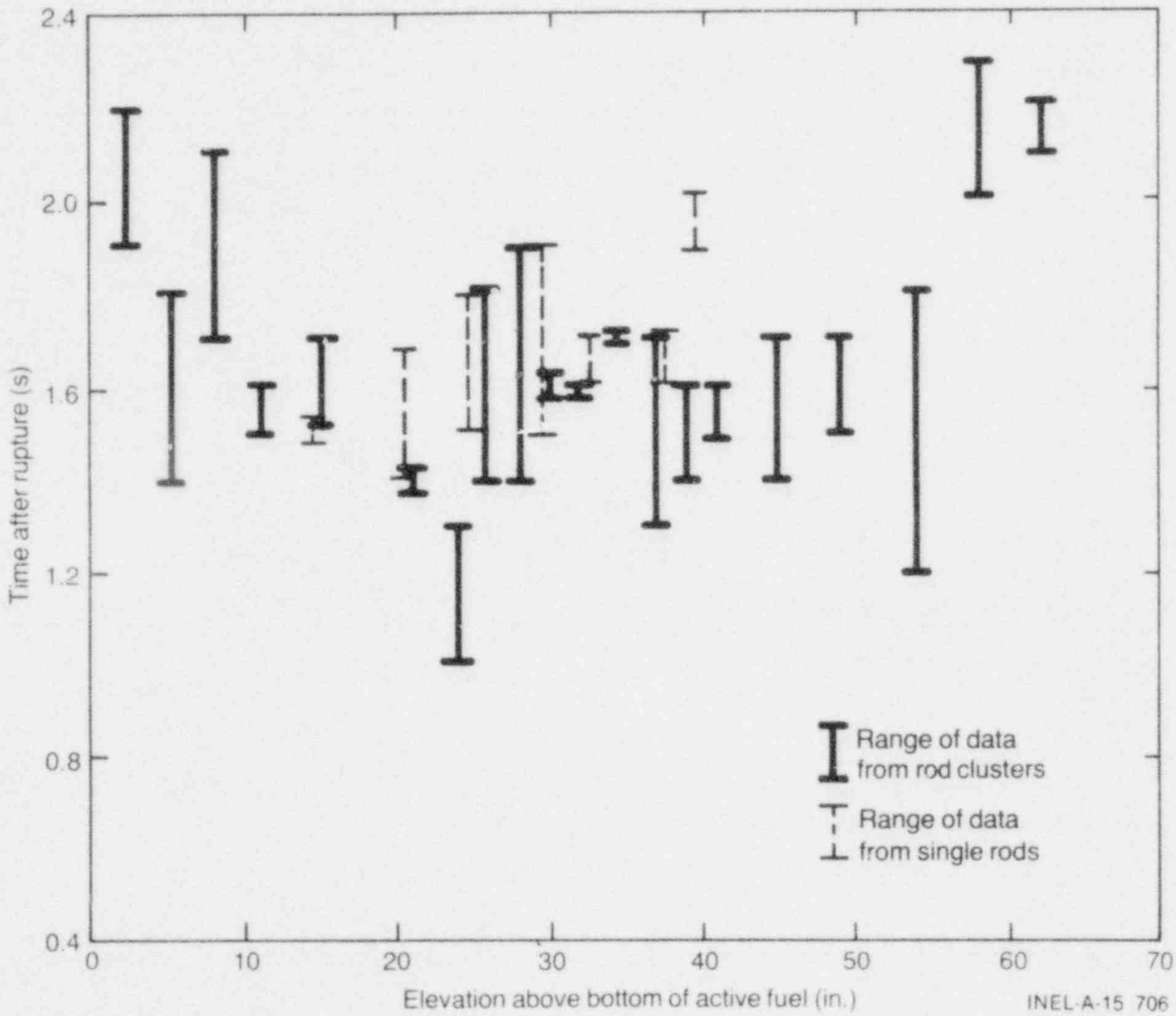

Figure 9. Time-to-DNB vs Axial Rod Position for L2-2 (center fuel bundle data)

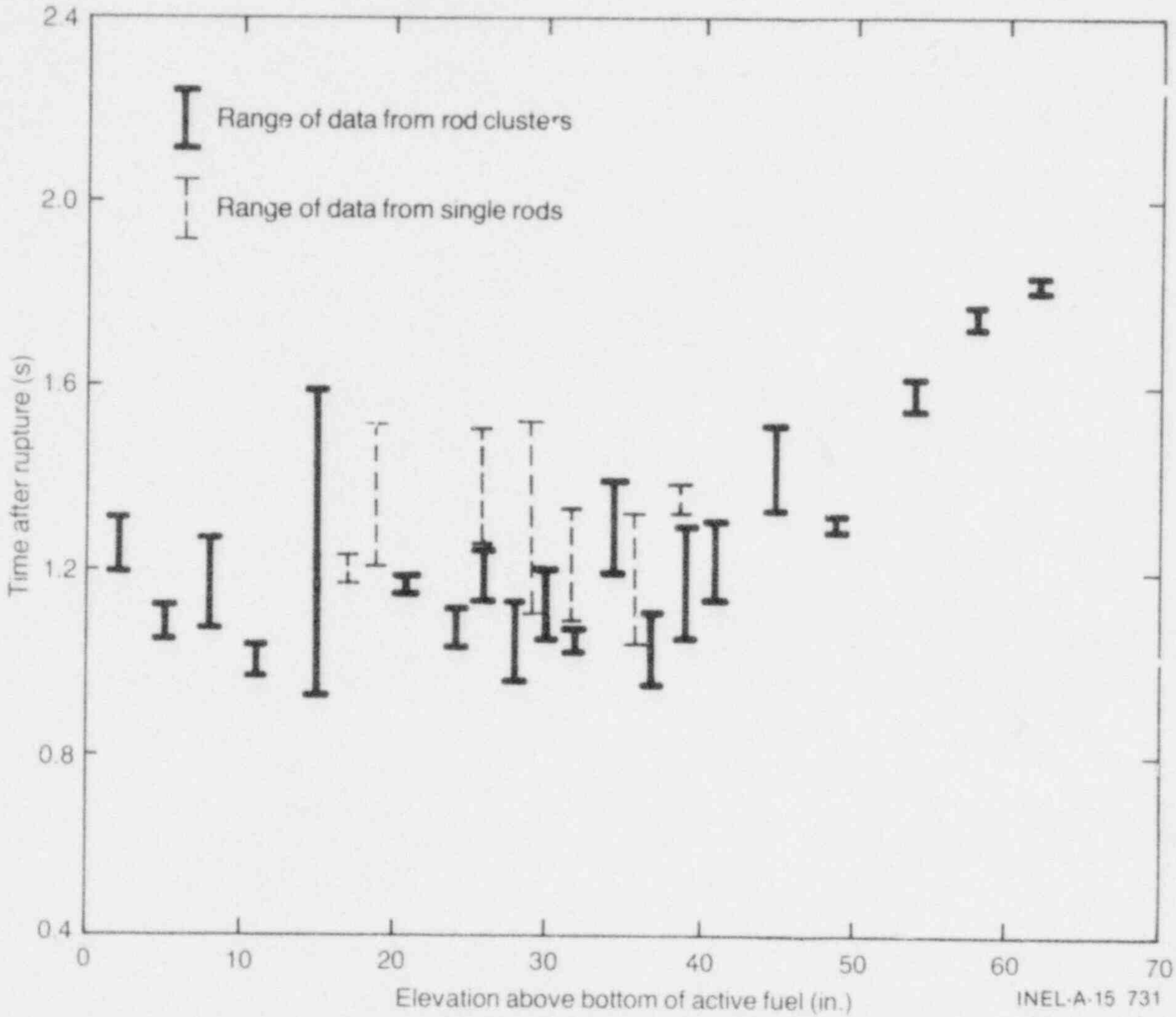

Figure 10. Time-to-DNB vs Axial Rod Position for L2-3 (center fuel bundle data)

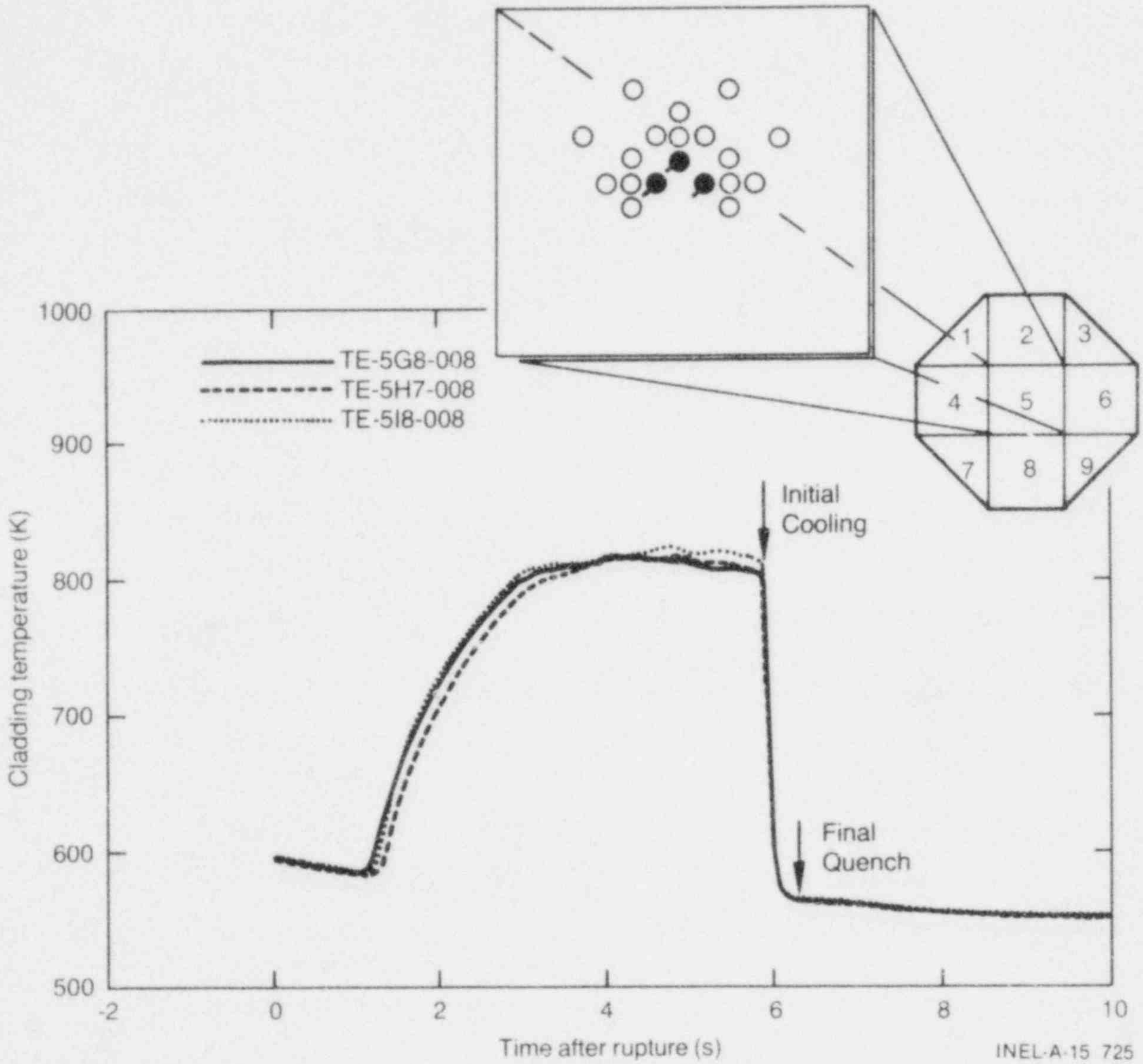

Figure 11. Center Module Cladding Temperature Response - 8.0 inch Axial Elevation (L2-3)

Figure 12 shows the temperature response (L2-3) at the 15 inch axial elevation. The initial time-to-DNB varies by approximately 0.75 s but the post-DNB temperature response is very similar for all measurements. The peak cladding temperatures correspond as expected to the time-to-DNB. The initiation of the quench cooling is well defined, occurring at about 6.0 s on all rods at the 15 in. axial elevation. The cladding quench at this axial location occurs rapidly, for most thermocouples in less than 0.3 s; however, two of the five thermocouples measured small temperatures oscillation for approximately one second just before reaching the coolant saturation temperature. The final quench is defined as the point at which the thermocouples indicate stable coolant saturation conditions as shown in Figure 12.

Figure 13 shows the measured cladding temperature at the peak power axial position (26 inches). Again the response is similar to the lower axial elevation response up to the time of the cladding quench. The quench initiation as measured by all five thermocouples is identical; however, the measured cooldown to the coolant saturation differs, ranging from 0.8-1.4 seconds.

Figure 14 shows the measured thermocouple response at the 32 in. axial elevation and is very similar to the 26 in. response. However, notice that even longer times ($\sim$ 1.0 - 2.5 s) are to required to cool the cladding during the cladding quench. Figure 15 shows the same general response, particularly an unstable cooling period, at a higher axial elevation (45 in.) even though the local power at this location is a factor of two lower than the peak rod power. This response indicates the importance of the thermal-hydraulic interaction during the cladding quench and the variation in rod cooling with axial position.

Figure 16 summarizes the measured cladding quench characteristic for the L2-3 test showing the behavior of the cooling iniation and final temperature quench as a function of axial position. Notice that the

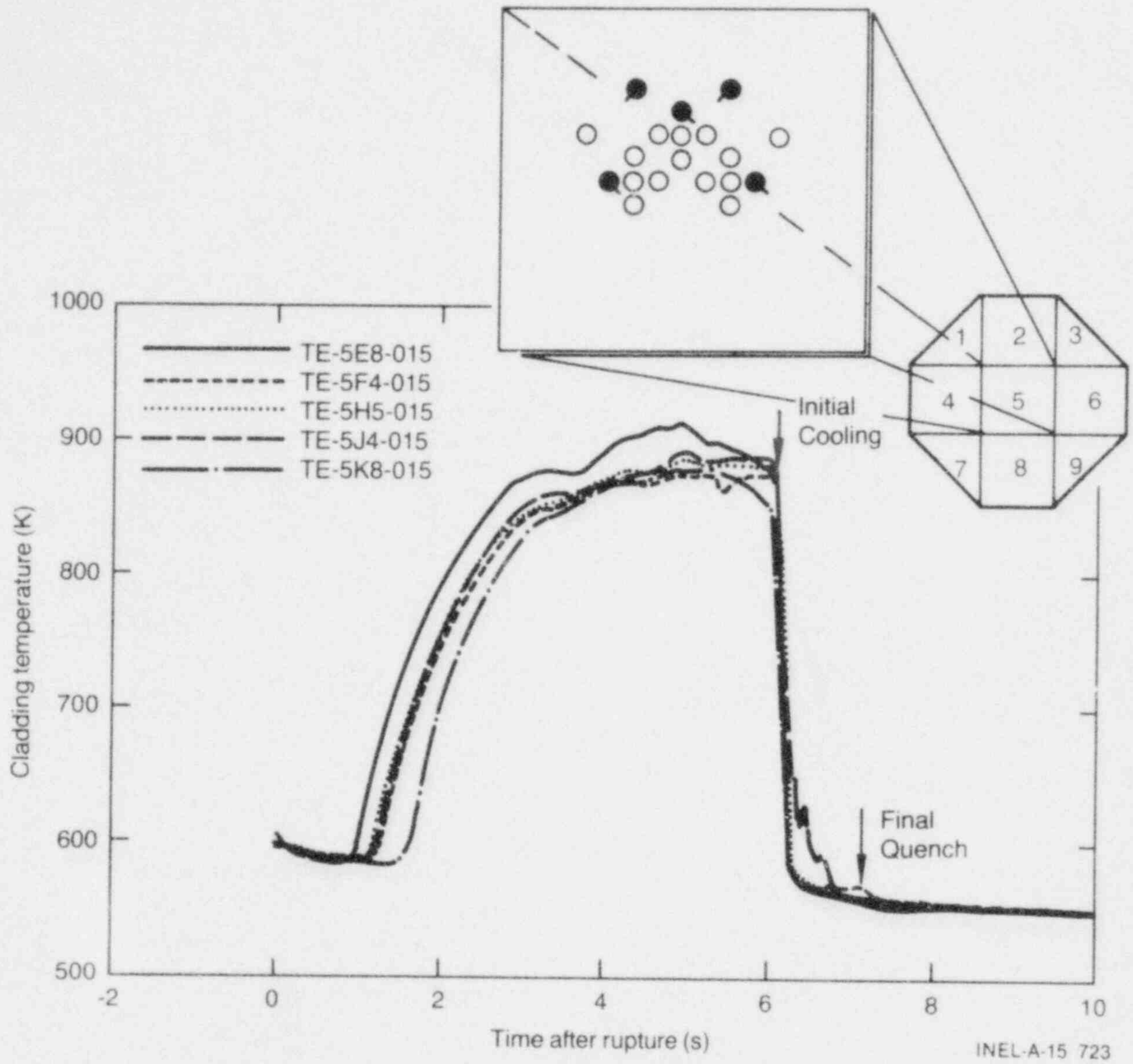

Figure 12. Center Module Cladding Temperature Response - 15.0 Inch Axial Elevations (L2-3)

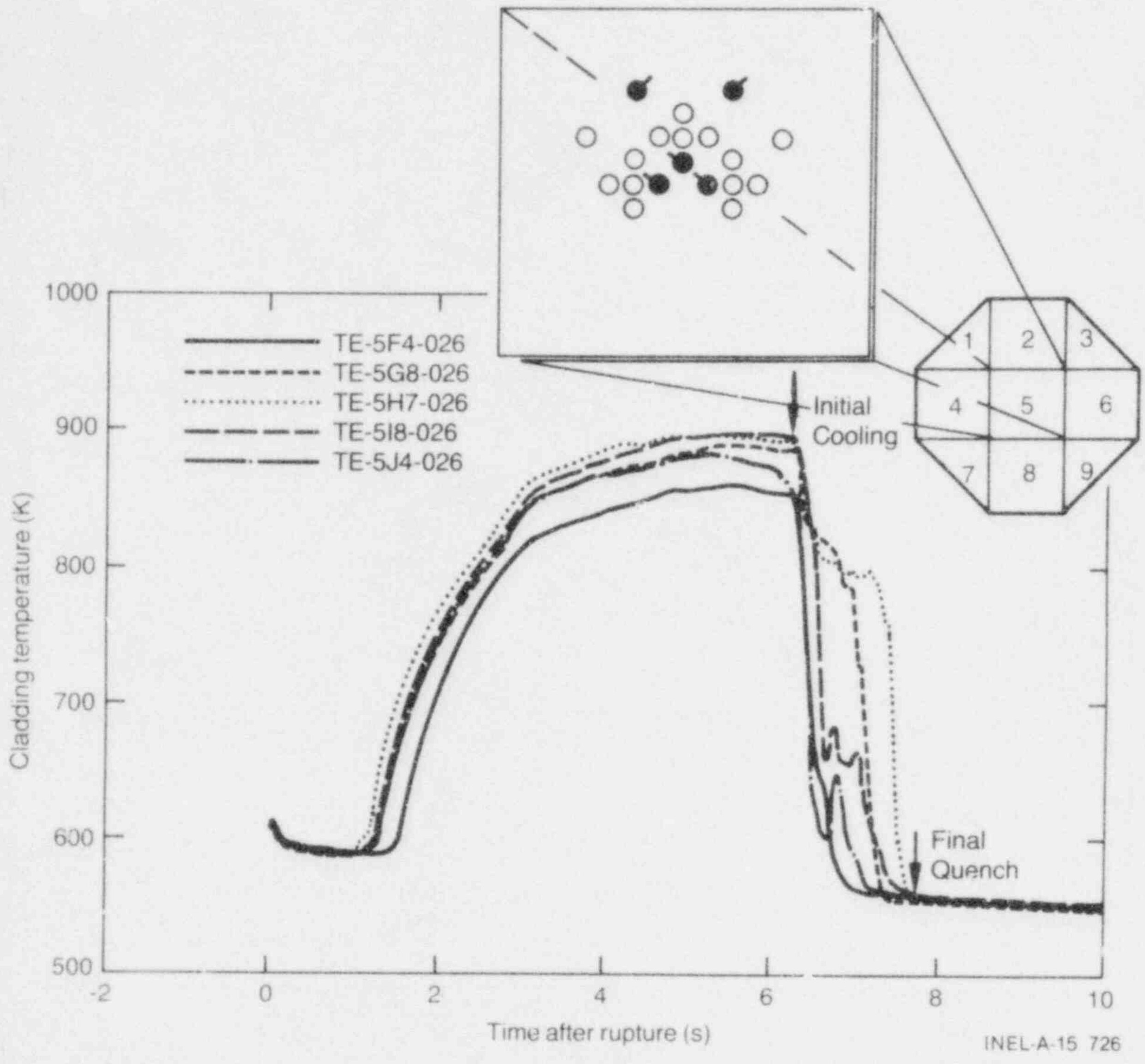

Figure 13. Center Module Cladding Temperature Response - 26.0 Inch Axial Elevations (L2-3)

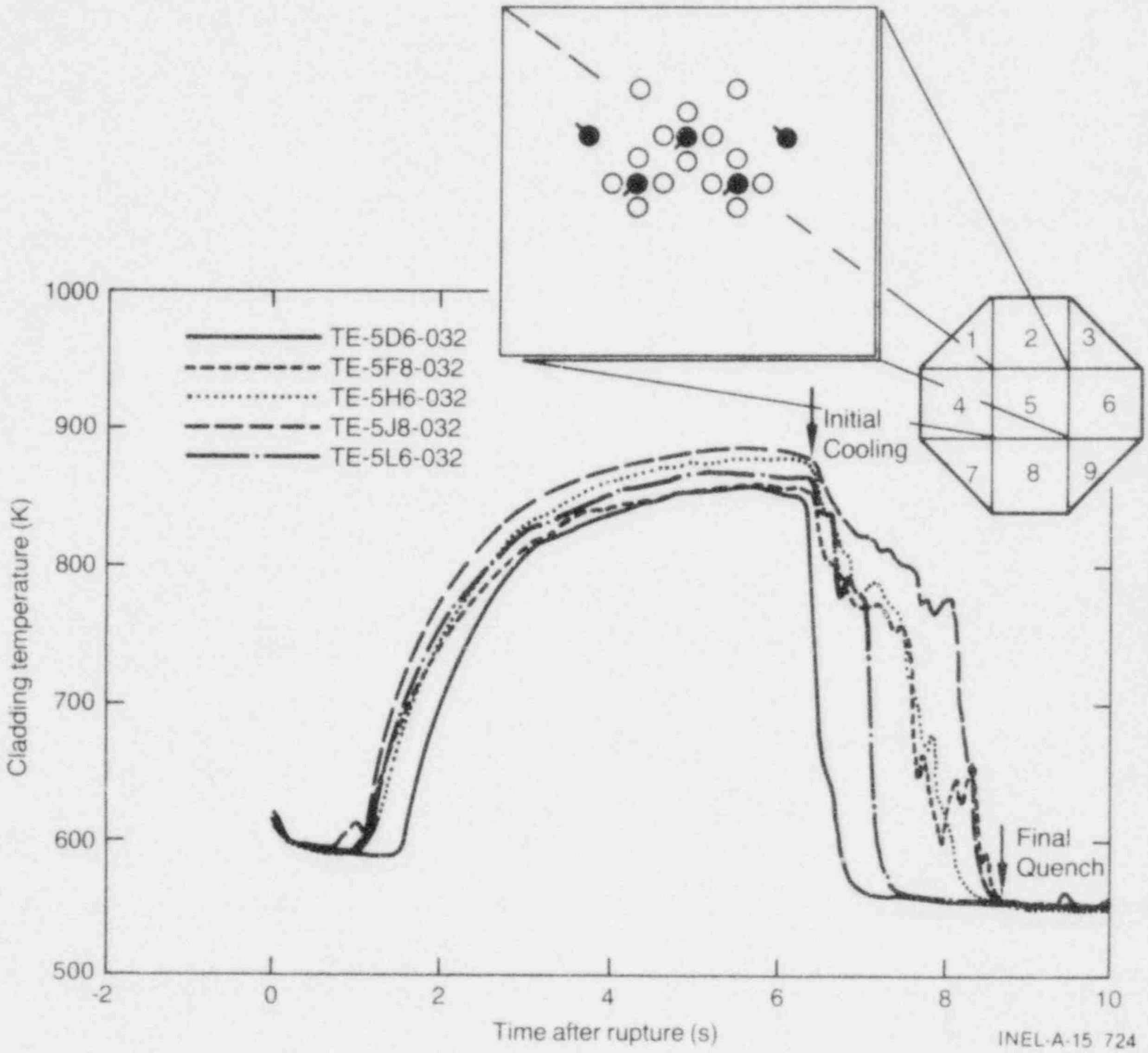

Figure 14. Center Module Cladding Temperature Response - 32.0 Inch Axial Elevations (L2-3)

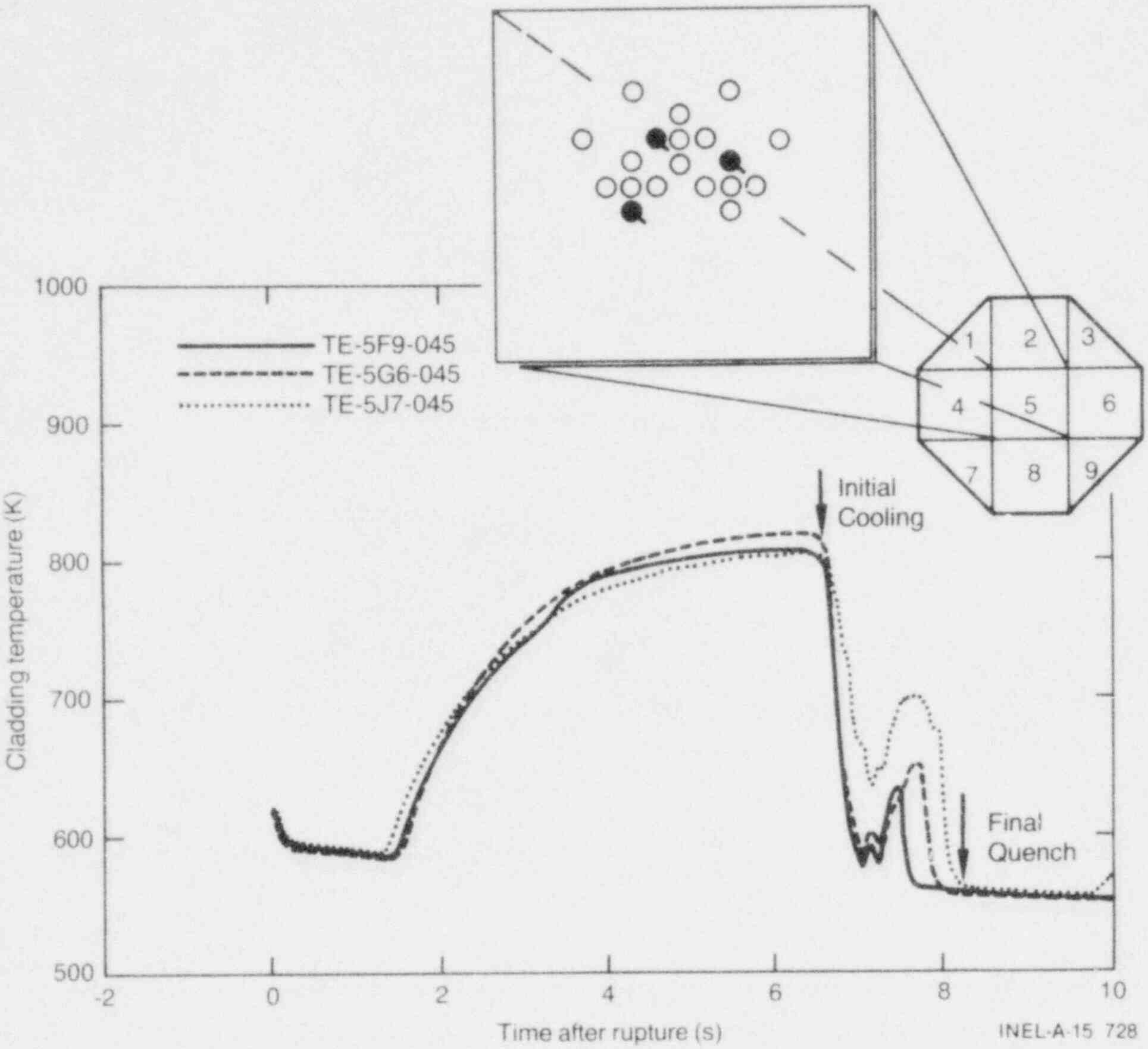

Figure 15. Center Module Cladding Temperature Response - 45.0 Inch Axial Elevations (L2-3)

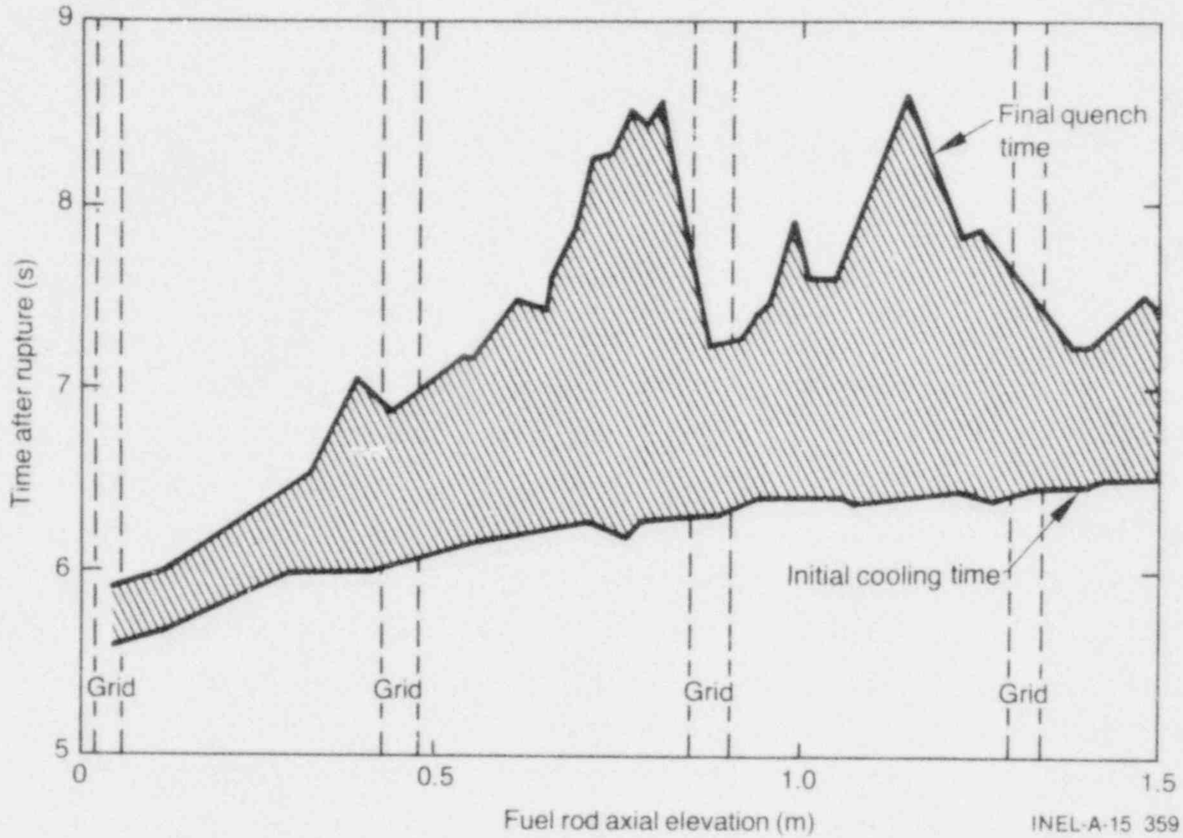

Figure 16. L2-3 Quench Characteristics vs Axial Elevation

initial cooling of the rod as a function of axial position is nearly linear with time. The final cladding quench is clearly a function of the axial power profile and is significantly influenced by the fuel rod grid spacers which suggests that changing coolant conditions along the rod affect the rod heat transfer and cladding quench characteristics.

The measured cladding quench characteristic during test L2-2 are shown in Figure 17 and are much the same as for L2-3, although, in general stable cladding is quenched in less time - 1.0-1.5 seconds compared to 2.0-2.5 seconds for L2-3. The differences in cladding quench characteristics between L2-2 and L2-3 (Figures 16 and 17) are largely due to differences in peak cladding cladding temperature and the initial fuel rod power.

Two additional measurements indicate a changing coolant flow through the core which is coincident with the cladding temperature quenches. The first is the self-powered neutron detector (SPND) located at the 24 inch axial position, which is sensitive to coolant quality changes. (Figure 2 shows radial core placement of SPNDs.) Figure 18 compares the response of the SPND and the 24 inch axial elevation cladding thermocouples. The rapid cooling of the thermocouples and the noticable decrease in the SPND response from 6.2 to 6.6 seconds indicates a low quality coolant influence during this period. The second indication of low quality flow upward through the core is obtained from the upper plenum thermocouples which measure coolant temperatures directly above the core. Figure 19 shows the measured coolant temperature and indicates from approximately 3-6 seconds, the coolant in the upper plenum nearest the core is superheated vapor. However, at approximately six seconds, the upper plenum coolant temperature is rapidly reduced to the saturation temperature. The time of coolant temperature reduction is consistant with the axial position vs time for initial cladding cooling as shown in Figure 20. The upper plenum coolant thermocouple quench occurs just after the highest elevation cladding thermocouples begin to quench. Assuming the initial, rapid cladding cooling vs axial position represents the coolant velocity through the core, flow velocities of 150-200 cm/s are achieved.

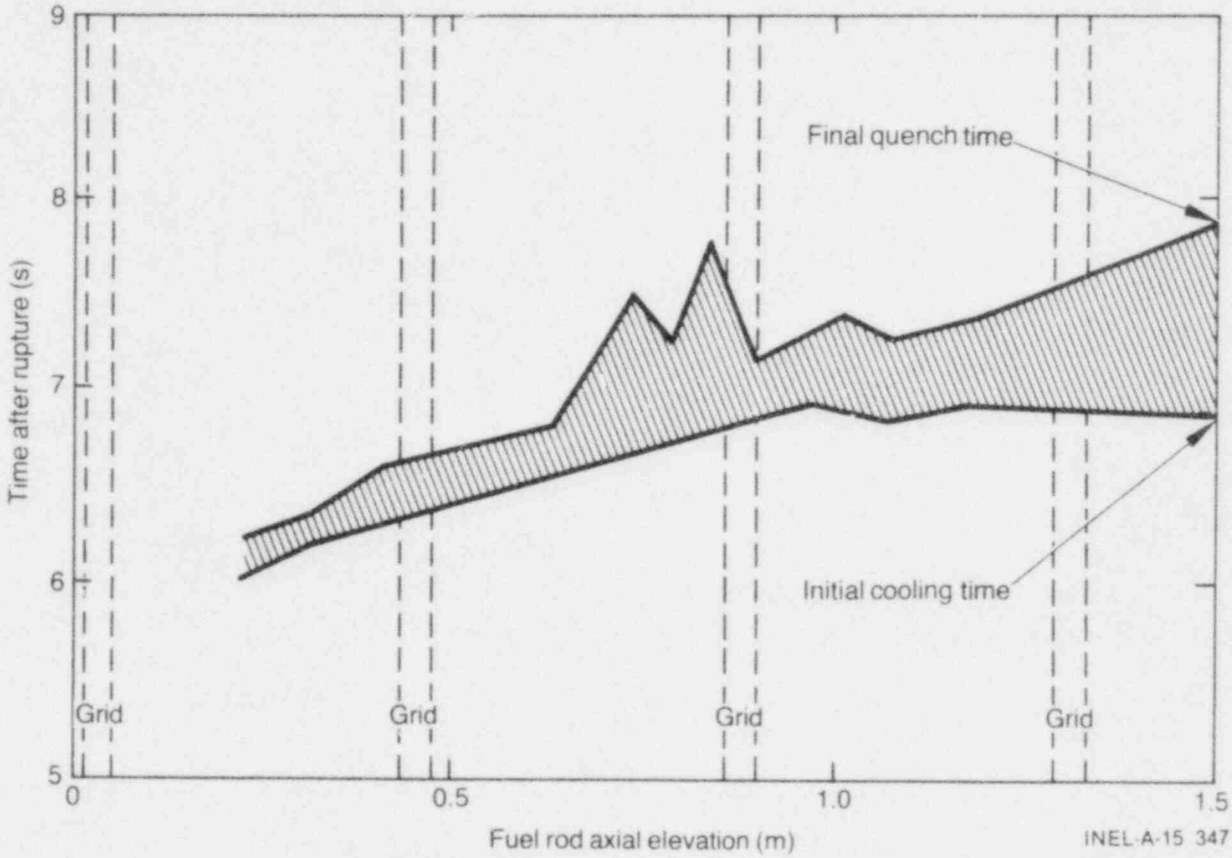

Figure 17. L2-2 Quench Characteristics vs Axial Elevation

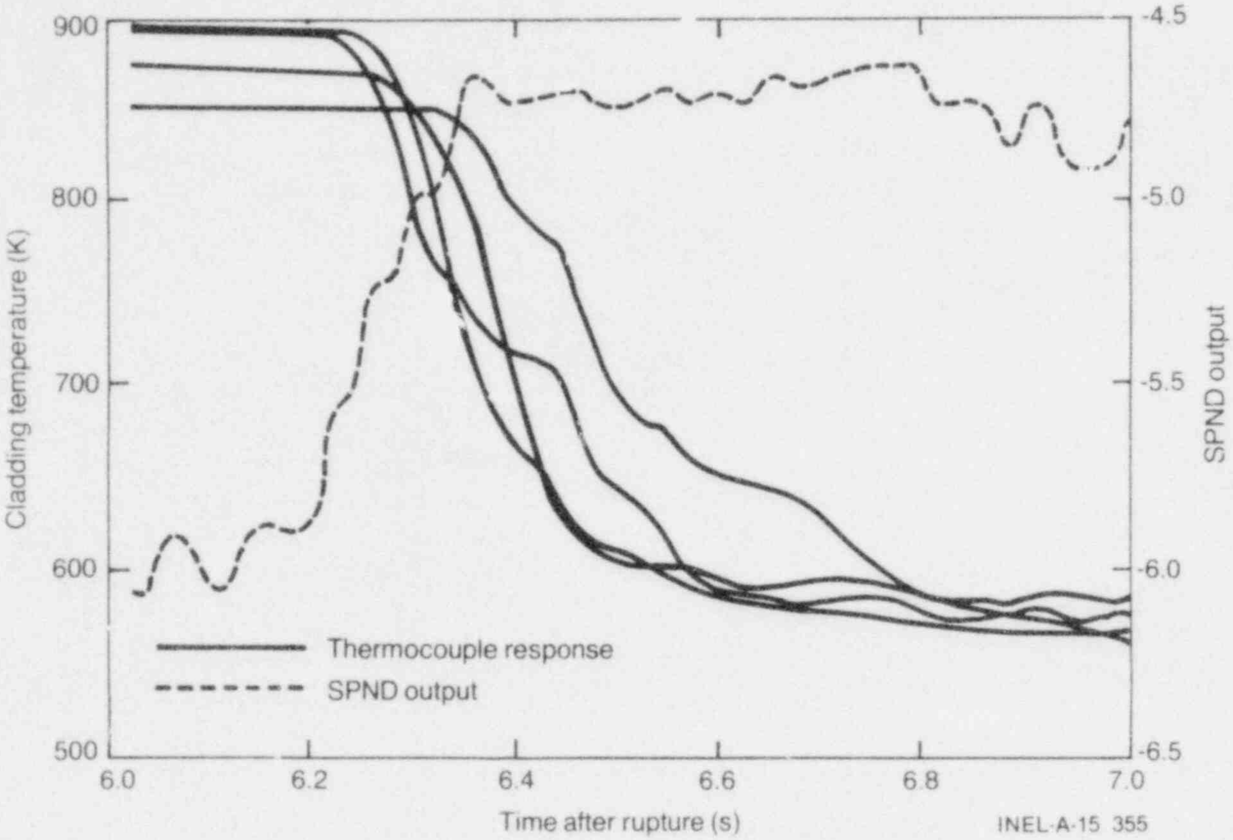

Figure 18. Cladding Temperature and SPND Response at the 24.0 Inch Axial Elevation (L2-3)

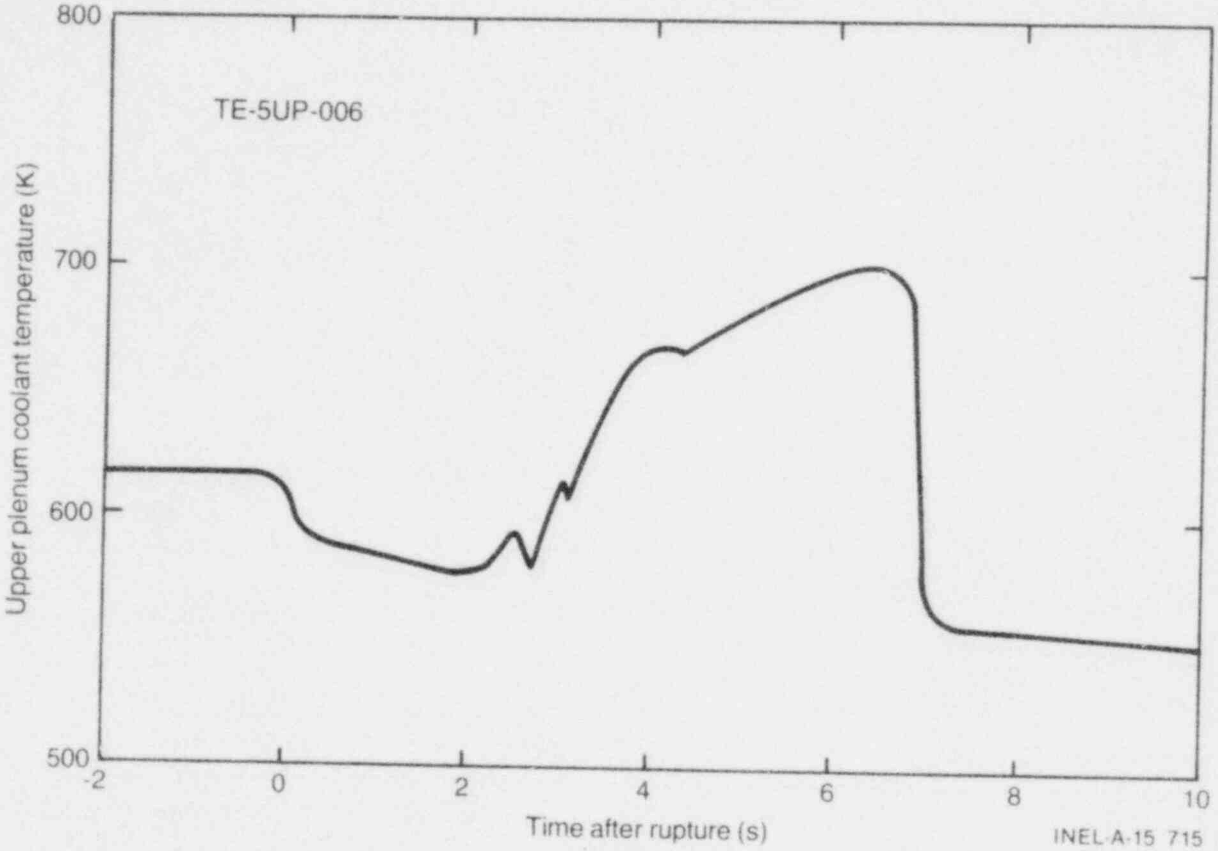

Figure 19. Core Upper Plenum Coolant Temperatures vs Time (L2-3)

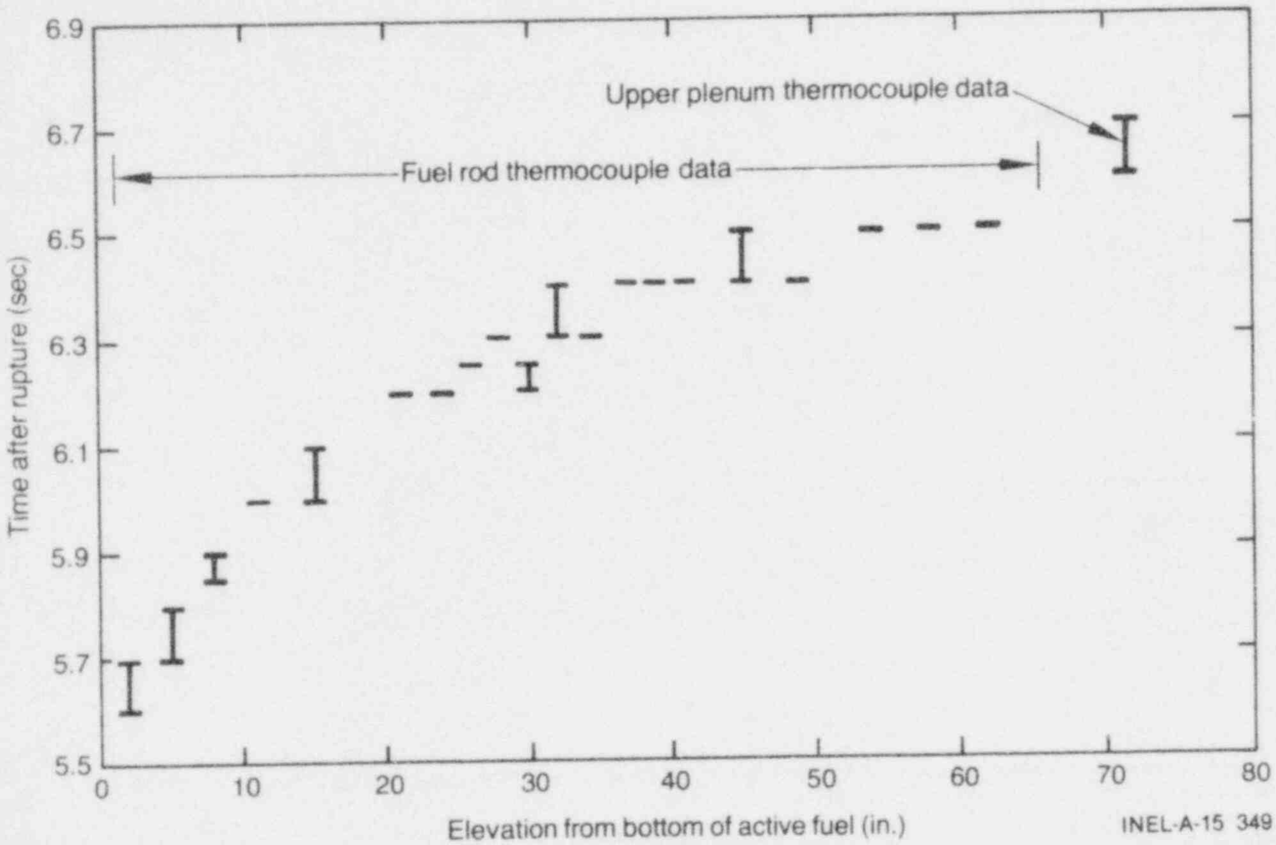

Figure 20. Initiation of Cladding and Upper Plenum Coolant Thermocouple Cooling vs Axial Position (L2-3)

Figure 21 shows the peak cladding temperatures for each of the axial cladding measurement locations compared to the fuel rod axial power profile. Notice the peak cladding temperatures do not reflect the axial power profile, being relatively greater at higher axial elevations. This behavior is consistant with the measured low upward core flow, for 1-2 seconds prior to quench, resulting in increased coolant quality and degraded rod cooling at higher elevations and the measured superheated vapor immediately above the core.

3.4 Secondary Dryout and Reflood Response

During the L2-3 test, from 10 to 15 seconds, a general coolant depletion occurred within the core region, causing the cladding temperature to increase, although at slower rates than occurred after the initial DNB. Secondary dryout times were not a strong function of axial position in either LOFT test as shown in Figure 22 and the cladding temperature at the core hot spot generally increased until the ECC water reflooded the core. For 5-10 seconds prior to reflood, the cladding temperatures were increasing at approximately 2.5 K/s which is very near the adiabatic heatup rate expected from nuclear decay power. Thus, just prior to final core reflood the cooling of the core was characterized by relative low steam flow.

Final reflooding of the LOFT core provides an important basis for assessing the capabilities of the emmergency core cooling systems (ECCS). The flow of ECC water through the core was inferred from the liquid level detectors which measure the coolant electrical conductivity between two metal probes. Nineteen probes were installed at different axial locations in a control rod guide tube in the center fuel module (see Figure 2 for location). Estimates of the reflood water level vs axial elevation are shown together with the measured cladding thermocouple quench times in Figures 23 and 24 for L2-2 and L2-3, respectively. From these figures, the estimated core flow velocity during reflood ranges from approximately 5 to

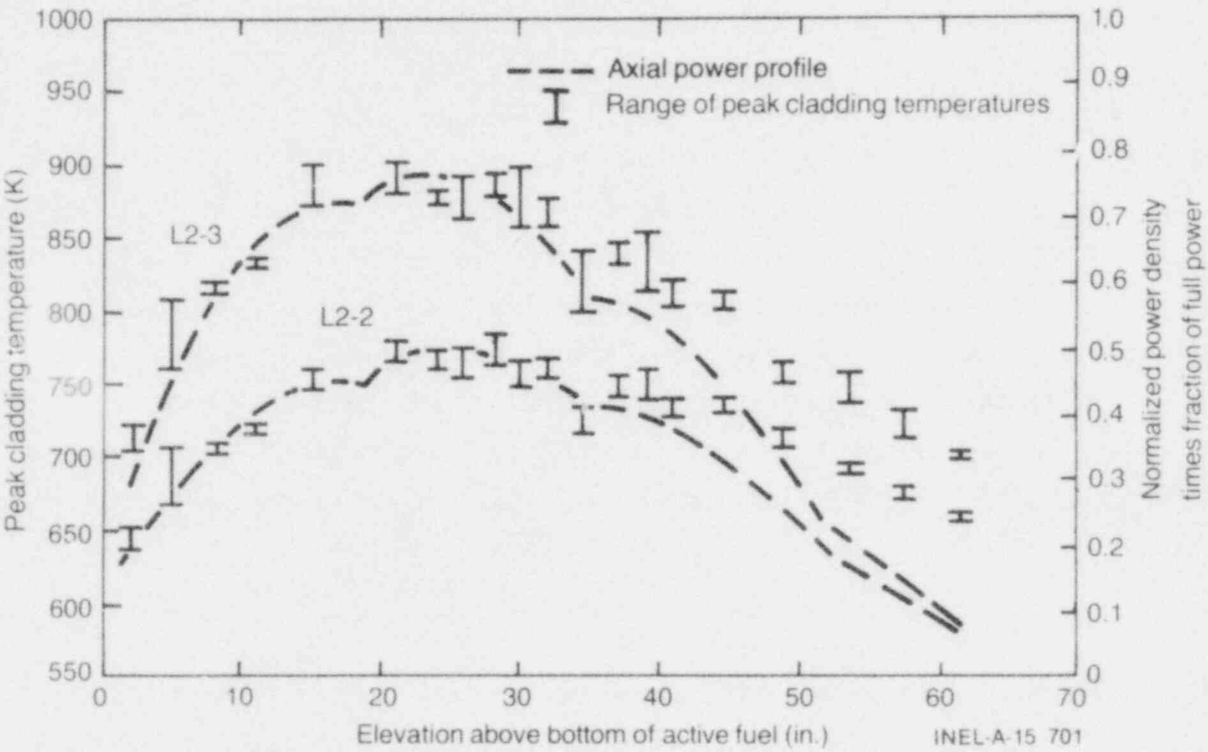

Figure 21. Peak Cladding Temperature vs Axial Position for L2-2 and L2-3

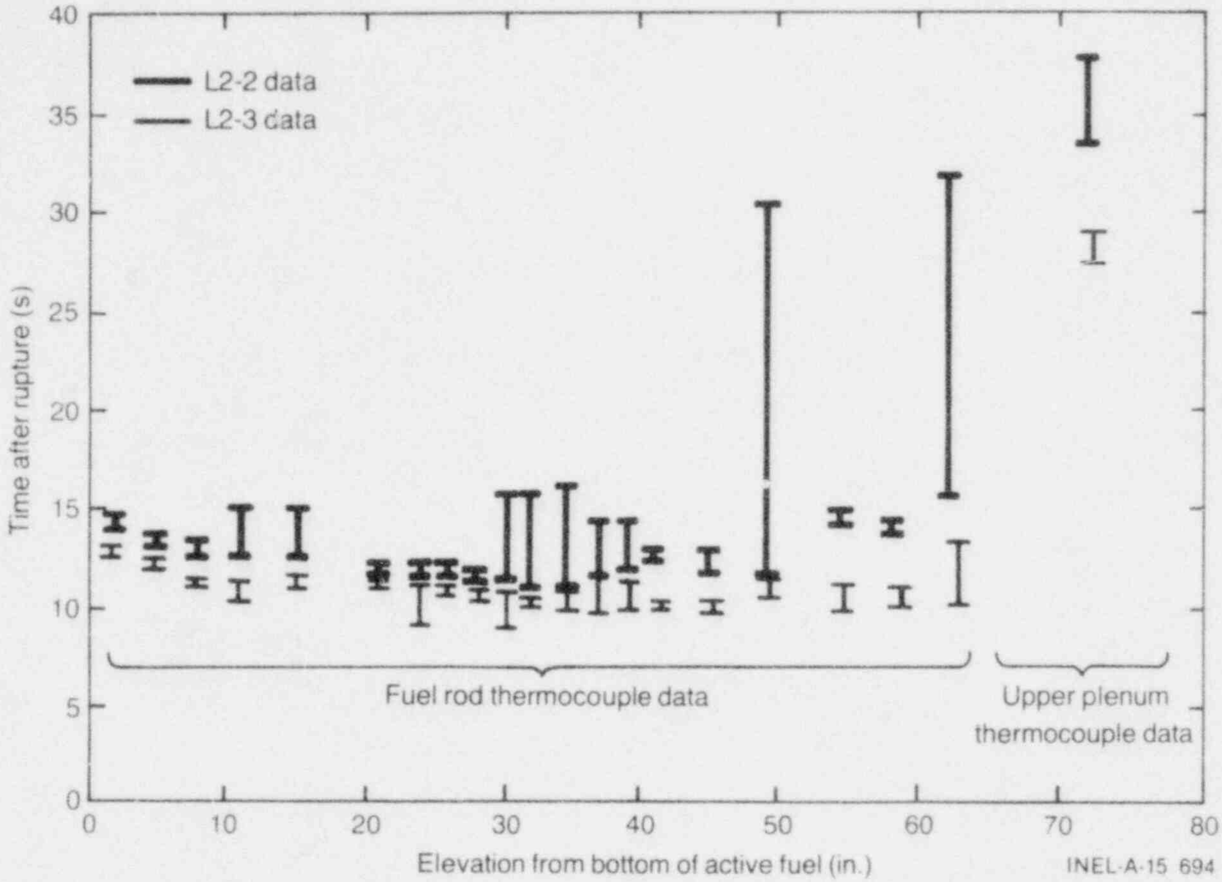

Figure 22. Time of Secondary Dryout vs Axial Position

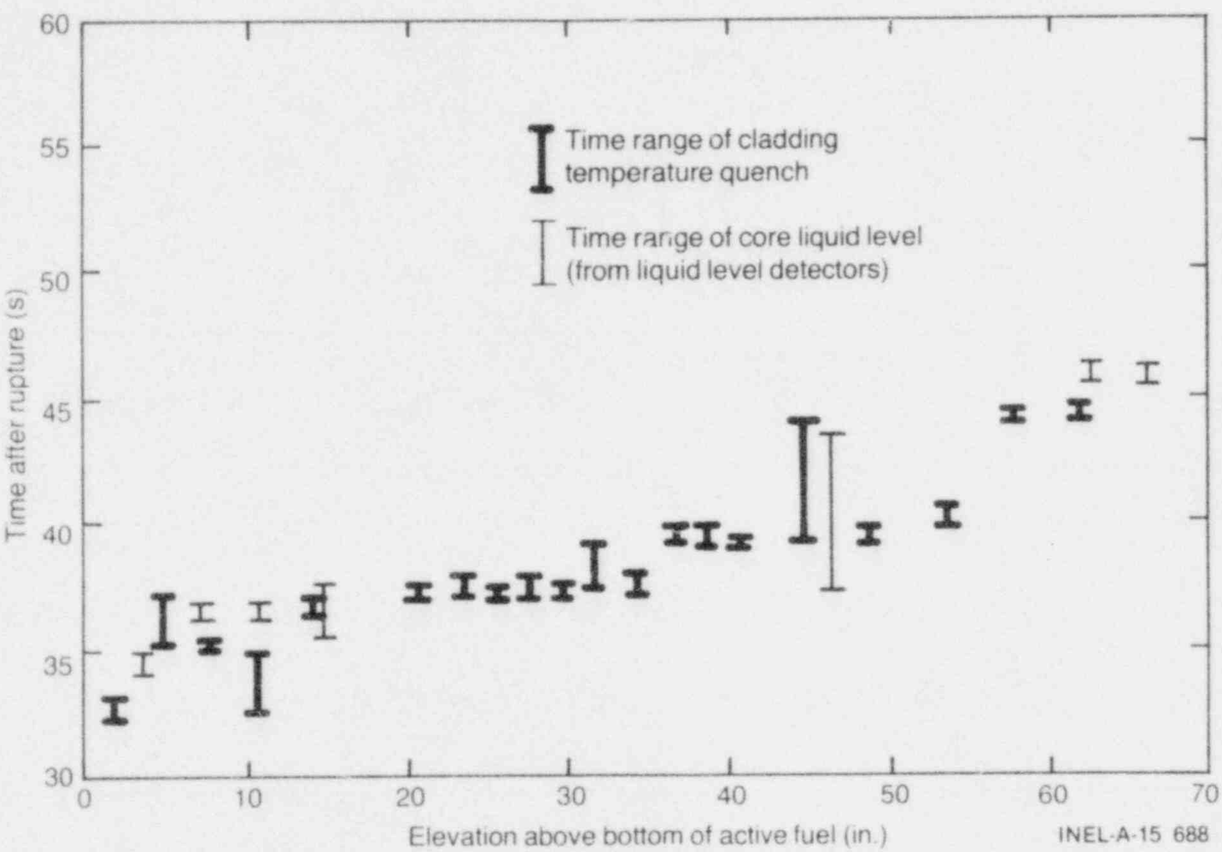

Figure 23. Liquid Level and Cladding Cooling Characteristics during Reflood (L2-2)

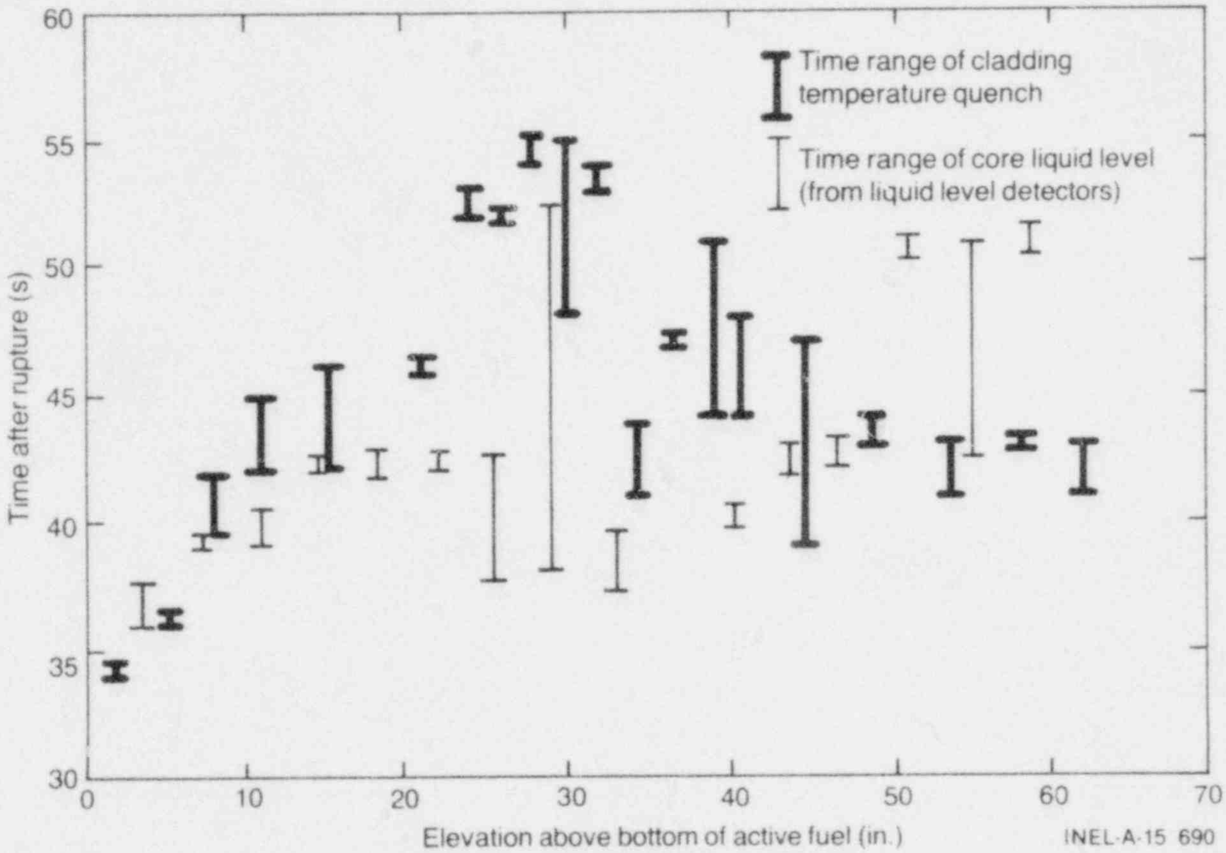

Figure 24. Liquid Level and Cladding Cooling Characteristics during Reflood (L2-3)

15 cm/s and the time required to cover the core (bottom to top) is estimated at 12 and 15 s for L2-2 and L2-3, respectively. During reflood, much longer times are required to quench the cladding temperature than was observed in the initial quench. The general cladding temperature response vs. axial position shown in Figures 23 and 24 is similar to most separate effects reflood tests, however the times to quench the LOFT cladding are much smaller. For example, Figure 25 compares the measured LOFT peak cladding temperature during the L2-3 reflood to Semiscale forced-feed reflood data.

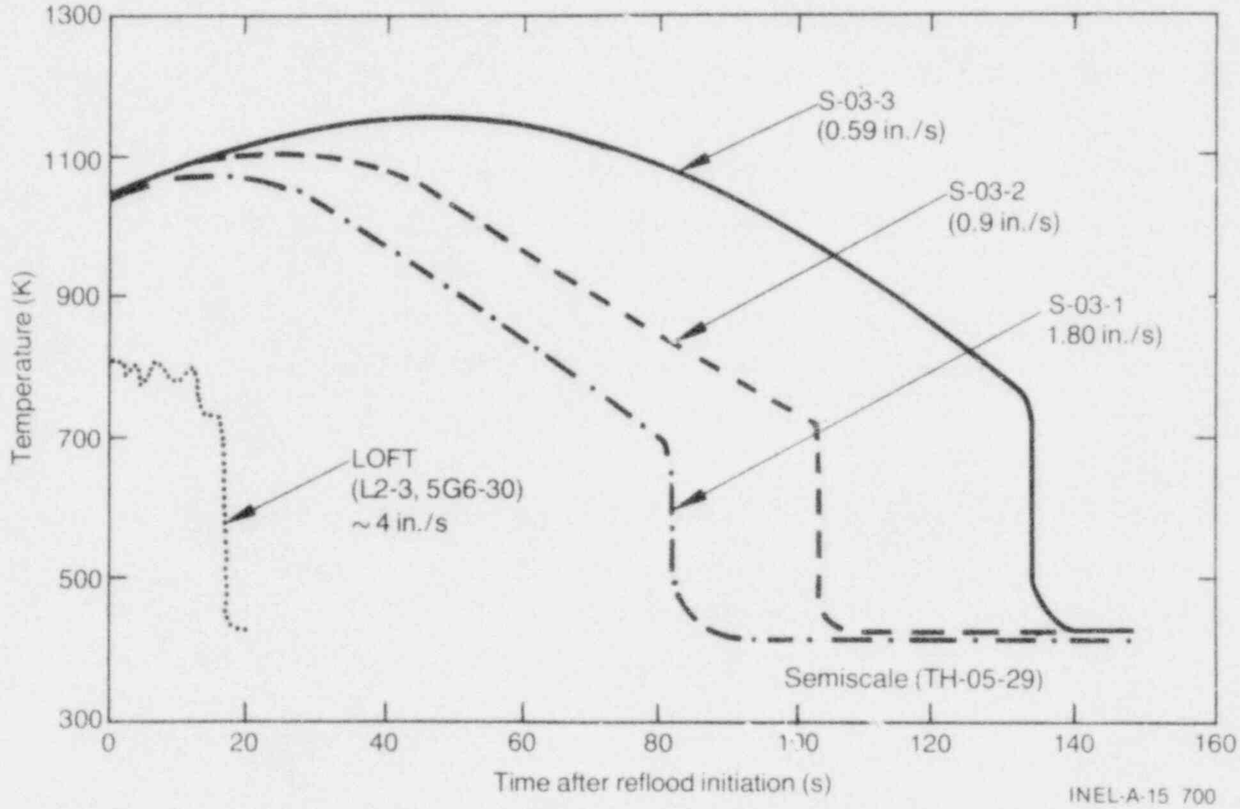

Figure 25. Comparison of LOFT Reflooding Cooling (L2-3) to Semiscale Forced Reflood Rod Cooling

4. FUEL ROD ENERGY DURING L2-2 and L2-3 BASED ON THERMOCOUPLE DATA

The fuel rod response during the tests were calculated with the FRAP-T5 fuel rod behavior code to estimate the influence of the cladding quench on the fuel rod energy. The initial, steady state fuel rod thermal conditions just prior to the LOCEs were obtained from FRAPCON-1 calculations and are shown in Figure 26. Table 2 summarizes the nominal values of the important thermal parameters as calculated by FRAPCON-1. Estimates of the initial, steady-state fuel rod stored energy can only be made from calculations, since no direct UO_2 pellet temperatures were measured during the LOFT tests.

The transient fuel rod power utilized in the FRAP-T5 calculations was obtained by RELAP4/MOD6 predictions which combines the core neutronics resulting from the rapidly changing coolant conditions with the standard ANS decay power generation. The measured transient cladding surface temperature was input to the code as a cladding temperature boundary condition.

The calculated fuel pellet energy vs time (volumetric average) is shown in Figure 27 and in general the response can be classified into three time periods - pre-quench, quench, and post-quench. During the pre-quench period (0-5.5 s), approximately 20-25 percent of the fuel rod energy is transferred from the rod. During the quench period (5.5-12 s) approximately 30-40 percent of the rod energy is lost. The post-quench period is characterized by very low heat transfer, and as shown in Figure 27, increasing cladding temperatures are measured as a result of continued energy equilibration and decay heat generation, for the L2-3 test. The calculated cladding surface heat transfer coefficients for both L2-2 and L2-3 are shown in Figure 28, based on the measured cladding temperature and coolant bulk temperature equal to the coolant saturation temperatures.

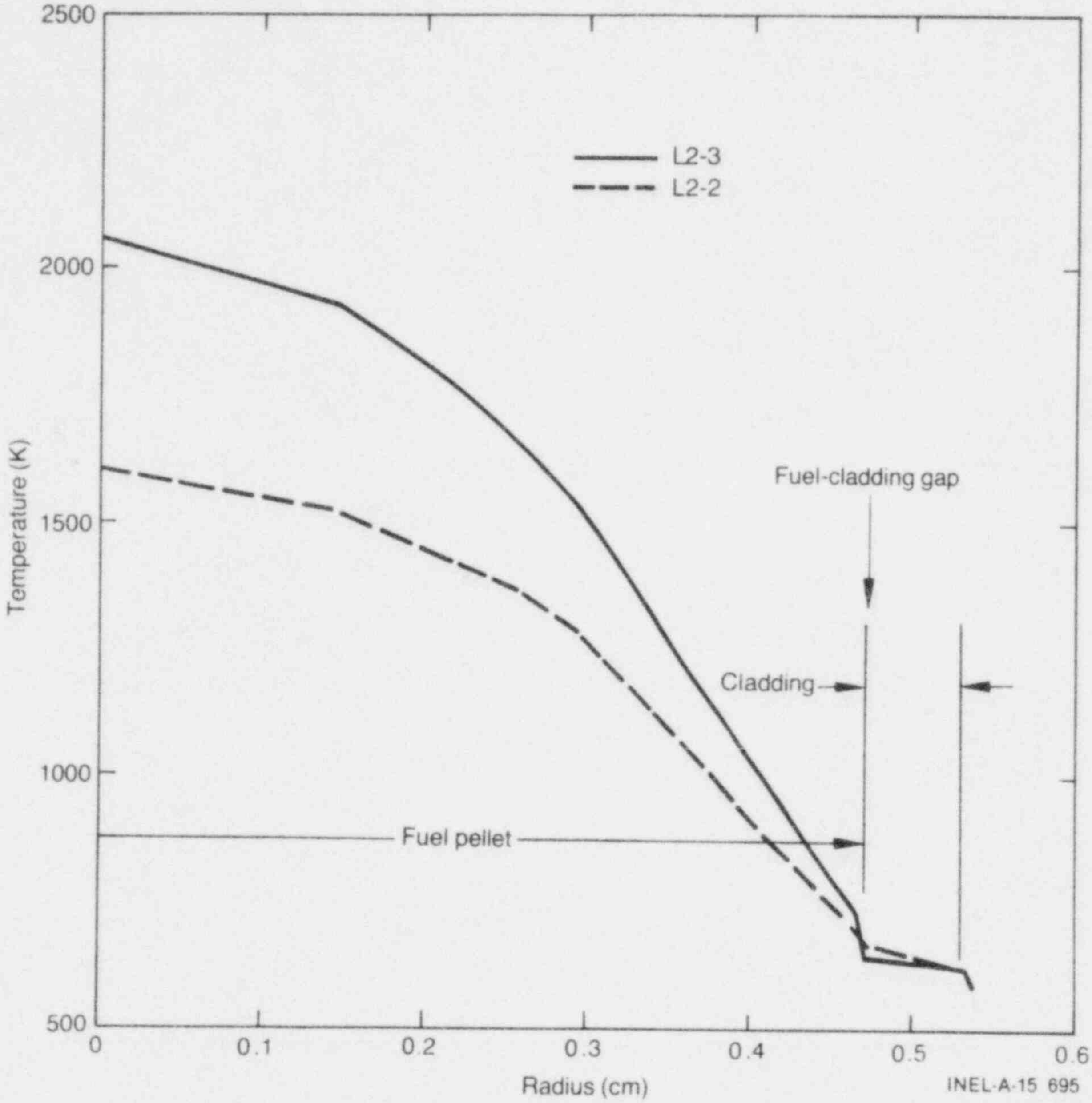

Figure 26. Fuel Rod Radial Temperature Profiles for Steady State Conditions Prior to L2-2 and L2-3 (peak power location)

TABLE 2. STEADY STATE FUEL ROD THERMAL DATA FOR THE LOFT L2-2 and L2-3 TESTS (FRAPCON-1)

Parameter	L2-2	L2-3
Peak Core Power, Kw/m	26.25	39.38
Peak Core Burnup, MWD/MTU	834.3	996.6
Fuel Centerline Temperature, K	1590.7	2041.1
Fuel Pellet ΔT, K	915.2	1341.3
Pellet-Cladding Gap ΔT, K	24.9	33.8
Gap Conductance, Kw/m^2 - K	36.7	40.06
Cladding ΔT, K	30.3	45.1
Fuel Stored Energy (Enthalpy) J/g	240.4	317.0

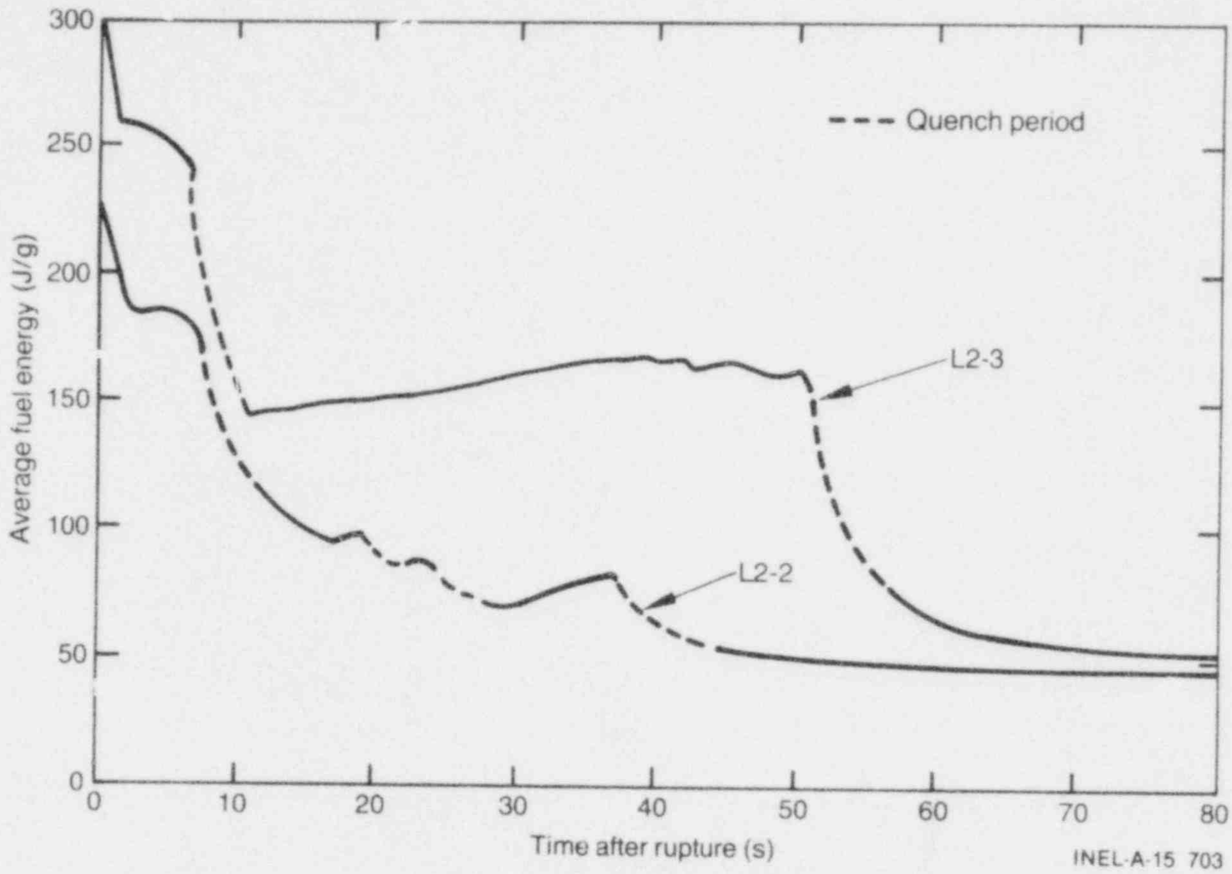

Figure 27. Calculated Fuel Rod Energy vs Time for L2-2 and L2-3

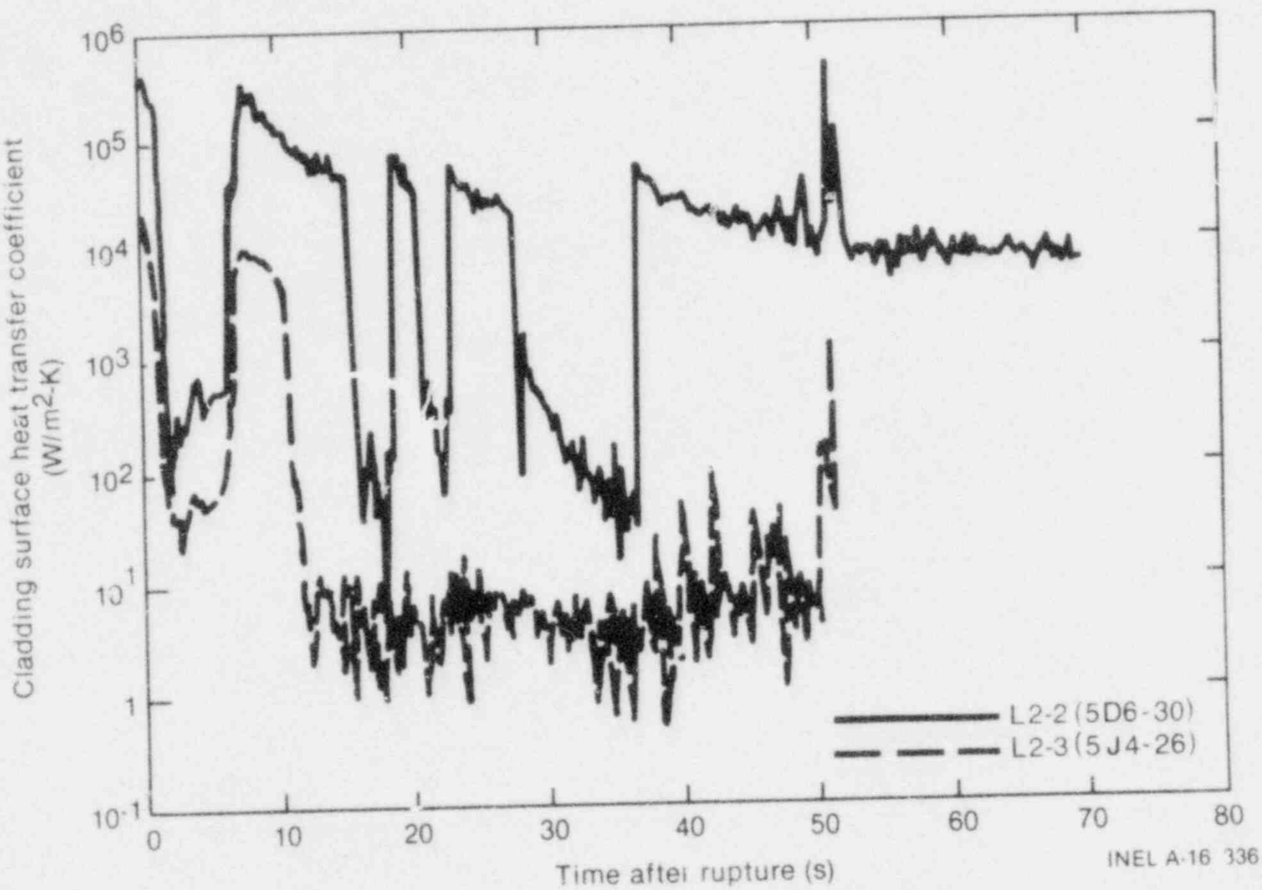

Figure 28. Nominal Cladding Surface Heat Transfer Coefficient For L2-2 and L2-3.

The transient calculations summarized in Figure 27 and 28 show that heat transfer in the first 10 to 12 seconds of the LOCE is an important influence on the fuel rod energy. The accuracy of the cladding thermocouples become important in understanding the core region heat transfer and thermal-hydraulic behavior, particularly for assessing computer code capability. Several test programs have been carried out or are now underway to evaluate the accuracy and perturbation effects of the LOFT cladding thermocouples. These tests will be reviewed in the next section in order to estimate the effects of the thermocouples during the LOFT tests.

5. THERMOCOUPLE PERTURBATION EFFECTS

The measured cladding quenches during the blowdown phase of both L2-2 and L2-3 have been questioned, primarily because of the possibility of atypical cooling of the surface thermocouples which in turn cools the entire fuel rod. These cooling effects have been observed on reflood tests utilizing electric fuel rod simulation where the presence of surface thermocouples increase both the rod cooling rates and the quench front velocity. Until recently, no experimental data was available to characterize the cooling influence of surface thermocouples for the rapid, high pressure flooding rates (150-200 cm/s) observed during the LOFT tests. This section will provide information from recent thermocouple effects tests to experimentally investigate the perturbation effects of the LOFT cladding thermocouples.

Prior to the LOFT tests, computer code calculations had predicted sustained, degraded fuel rod heat transfer after initial DNB resulting in very high cladding temperatures for many seconds before eventual ECC reflood cooling. Under these conditions, the most significant thermocouple perturbation was postulated to be a delay in initial time-to-DNB which would reduce fuel rod energy and peak cladding temperature. To quantify the delay in initial time-to-DNB caused by thermocouples, transient tests were conducted in the heat transfer laboratories of Columbia University to simulate thermal-hydraulic conditions expected during the early blowdown phase of the LOFT experiments. The surface thermocouples were found to delay the initial DNB time by less than 0.45 seconds and in most cases, less than 0.2 seconds. This delay would reduce the peak cladding temperature during the LOFT experiments by approximately 25 K. The details of these tests are reviewed and summarized in Section 5.1.

Prior to the LOFT nuclear tests, experiments were also conducted in the INEL Blowdown Facility to investigate the cooling influence of the thermocouples for high cladding temperatures during conditions of steam cooling, predicted to occur later in the LOFT tests just prior to reflood cooling. These tests were specifically intended to quantify the accuracy of the surface thermocouples at high cladding temperatures characterized by very low heat transfer, and were not intended to quantify the influence of surface thermocouples under rapid cooling transients. The LOFT thermocouple response was compared with small, 0.43 mm OD, thermocouples embedded near the cladding outer surface. These comparisons show less than 5 K difference in measured temperatures at the near adiabatic conditions of peak cladding temperature. The details of these tests are reviewed in Section 5.2.

More recent tests have been conducted in the INEL Blowdown Facility to evaluate the perturbation effect of LOFT type surface thermocouples over a range of inlet flow rates, quality, and system pressure considered to bound the thermal-hydraulic conditions in the LOFT core at the time of the blowdown quench. These tests show that the surface thermocouples indicate a cladding quench much sooner than interior cladding thermocouples and that rods without surface thermocouples do not cool or quench as rapidly as identical rods instrumented with LOFT surface thermocouples. These test results suggest that during rapid cooling conditions, the LOFT thermocouples may be measuring a temperature more representative of the coolant rather than the higher cladding temperature. The details of these tests and a summary of test results are reviewed in Section 5.3.

Recent tests have been conducted in the Power Burst Facility (PBF) and give added insight on the thermal response of nuclear rods with surface thermocouples under simulated LOCE conditions. Initial evaluation of these data suggest the surface thermocouples influence initial time-to-DNB by 1-2 seconds and that the surface thermocouples measure accurate cladding temperatures under steam cooling conditions. Care must be taken in extrapolating the DNB behavior in PBF to LOFT because of differences in thermal-hydraulic response between the two facilities.

The reflood response from the PBF tests show that rod quench occurs from 5-10 seconds earlier on rods with external thermocouples as compared to bare rods. The PBF tests are summarized in Section 5.4

Finally Section 5.5 summarizes the possible perturbation influence of the surface thermocouples on the cladding temperature response during the LOFT tests.

5.1 LOFT Transient DNB Tests

An extensive critical heat flux test program has been conducted on electrically heated rod bundles simulating the peak power region of the LOFT reactor. Steady-state DNB tests indicate that cladding surface thermocouples reduce the critical heat flux (CHF) over the pressure range of 13.8 to 16.5 MPa[6] but have an insignificant effect on CHF near 11 MPa[7] where CHF occurs in LOFT during a LOCE.

Transient CHF tests[8] were conducted on two separate bundles of stainless steel clad electrical heater rods which were identical except that one bundle had 1.17 mm OD sheaths attached to the surface of some of the heater rods simulating LOFT cladding surface thermocouples. Each bundle contained 25 rods (5 x 5 array) consisting of 22 electrically heated rods simulating nuclear fuel rods and three unheated rods simulating control rod guide tubes. The bundles correspond geometrically to a portion of the LOFT central fuel assembly and are shown schematically in Figure 29.

A sketch of the electrical rods utilized for these tests is shown in Figure 30 showing the location of the internal thermocouples used to measure cladding temperature and CHF. Internal thermocouples were installed on all rods at several axial levels. A total of 104 internal thermocouples provided the capability of measuring CHF at various points within each bundle. The internal thermocouples were located at identical positions in the two bundles to allow a direct comparison of time-to-DNB at each location.

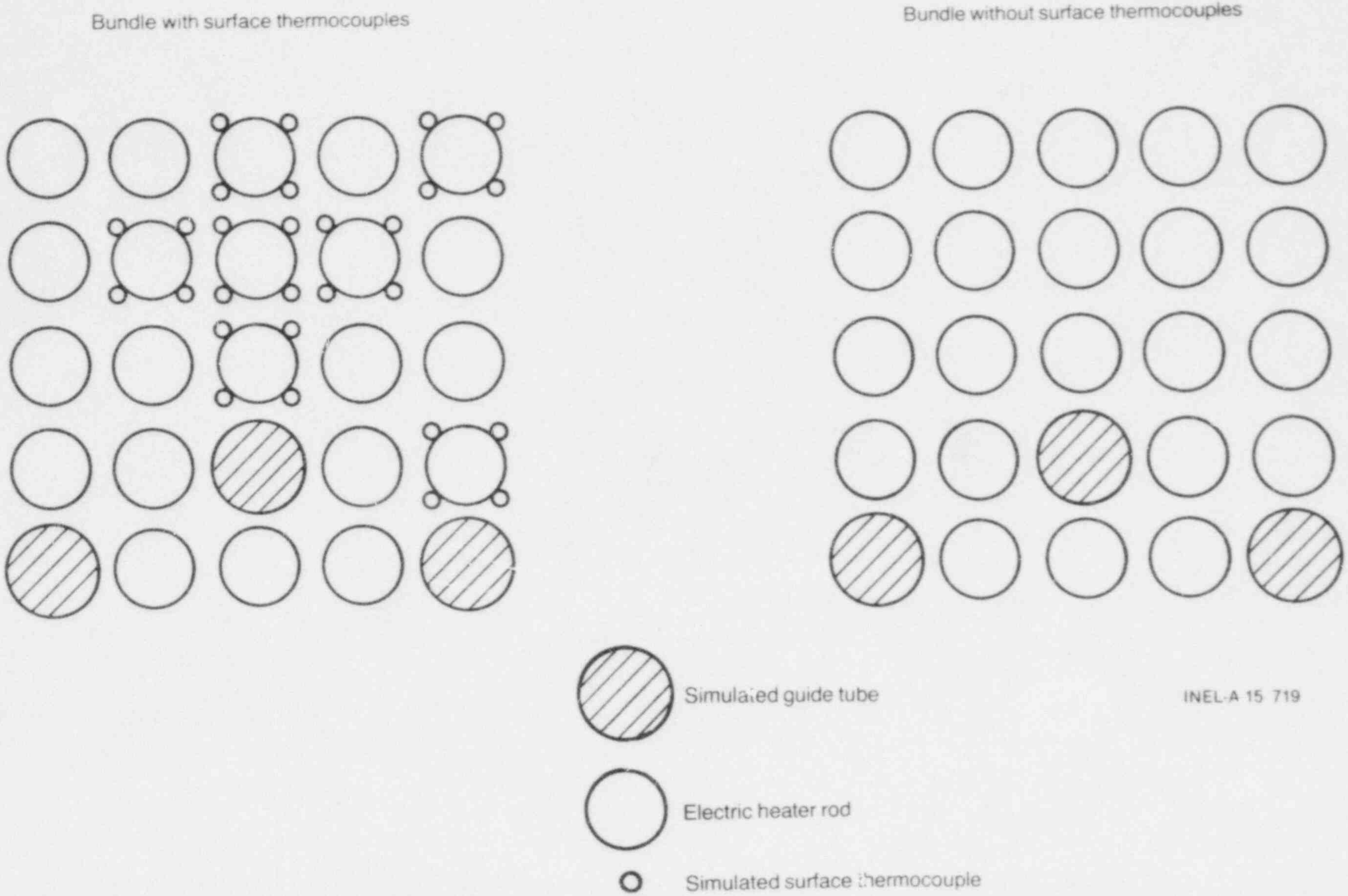

Figure 29. Bundle Configurations for LOFT Transient DNB Tests

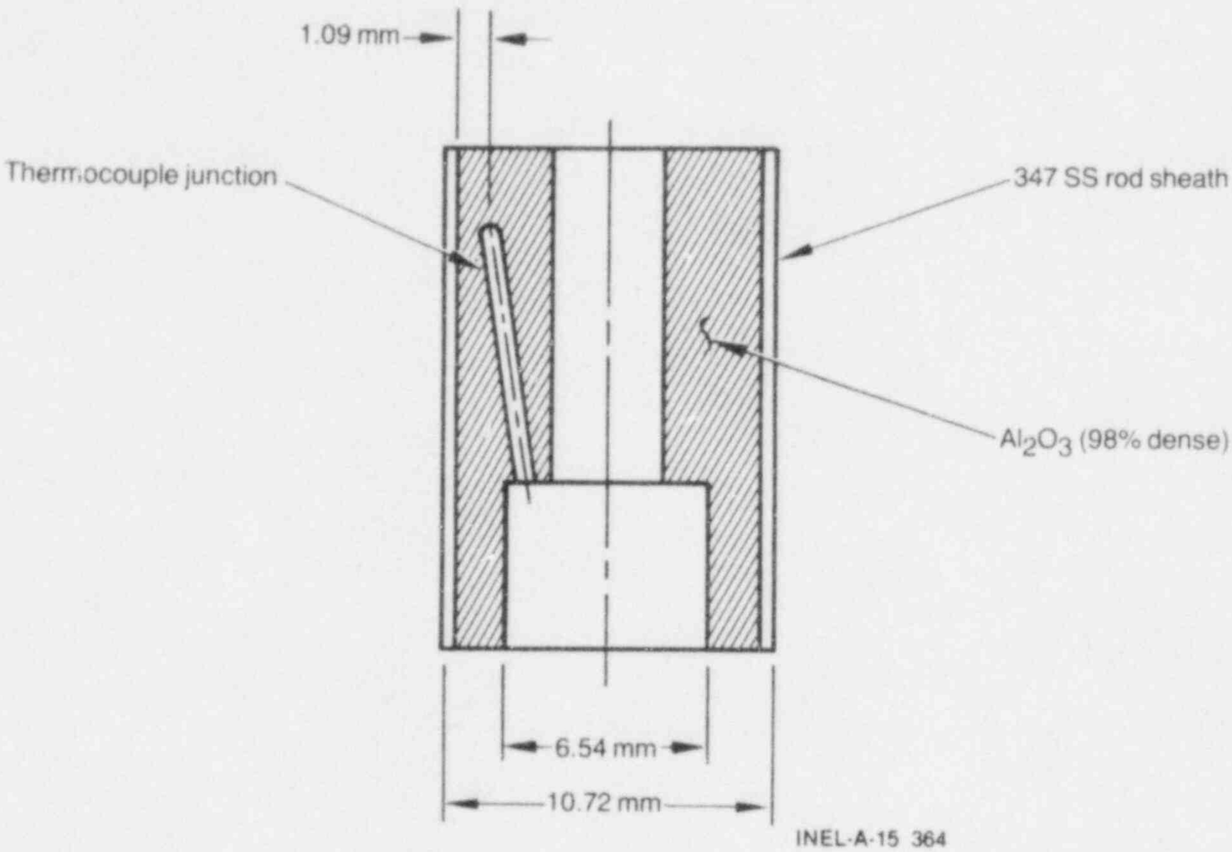

Figure 30. Electric Heater Rod Utilized for LOFT Transient DNB Tests

The transient tests were conducted at linear heat generation rates of 26, 39 and 52 kW/m and an initial pressure of 15.2 MPa. Tests at each power level were repeated six times on each bundle to determine the repeatability of time-to-DNB at each internal thermocouple location. The power level was held constant during each blowdown test in order to eliminate errors in repeating test conditions for each test. The test conditions were chosen to simulate the fluid conditions in the LOFT reactor during a large break LOCA blowdown. Since the test bundles had a uniform axial power distribution, the initial power level, mass velocity and test section inlet and outlet temperatures could not all be identical to LOFT. Analytical calculations[9] showed that the blowdown conditions in LOFT could best be simulated in the blowdown loop by maintaining the test section linear power the same as the peak linear power in LOFT and the initial test section mass velocity and outlet temperature the same as for LOFT. The inlet temperature varied for each power level tested.

Comparison of measured time-to-DNB from both bundles showed the instrumented bundle to delay time-to-DNB a maximum of 0.45 seconds and the average delay in DNB was less than 0.20 seconds. Analysis of a LOFT hot fuel rod during a 52 kW/m LOCE indicated that a 0.5 second delay in time-to-DNB would result in only a 17 K reduction in peak cladding temperature. Thus from the transient DNB tests, it is inferred that cladding surface thermocouples will not significantly affect time-to-DNB or peak cladding temperature during the LOFT LOCEs.

A comparison of time-to-DNB from these tests and the LOFT nuclear tests are shown in Figures 31 and 32 for the 26 and 39 kW/m experiments. The time-to-DNB for the two electric rod bundles and the LOFT tests are comparable. The scatter in the electric rod data is larger than the nuclear data, as would be expected since a larger number of rods are instrumented at different bundle locations and because of boundary thermal hydraulic effects on DNB at the periphery of the bundle.

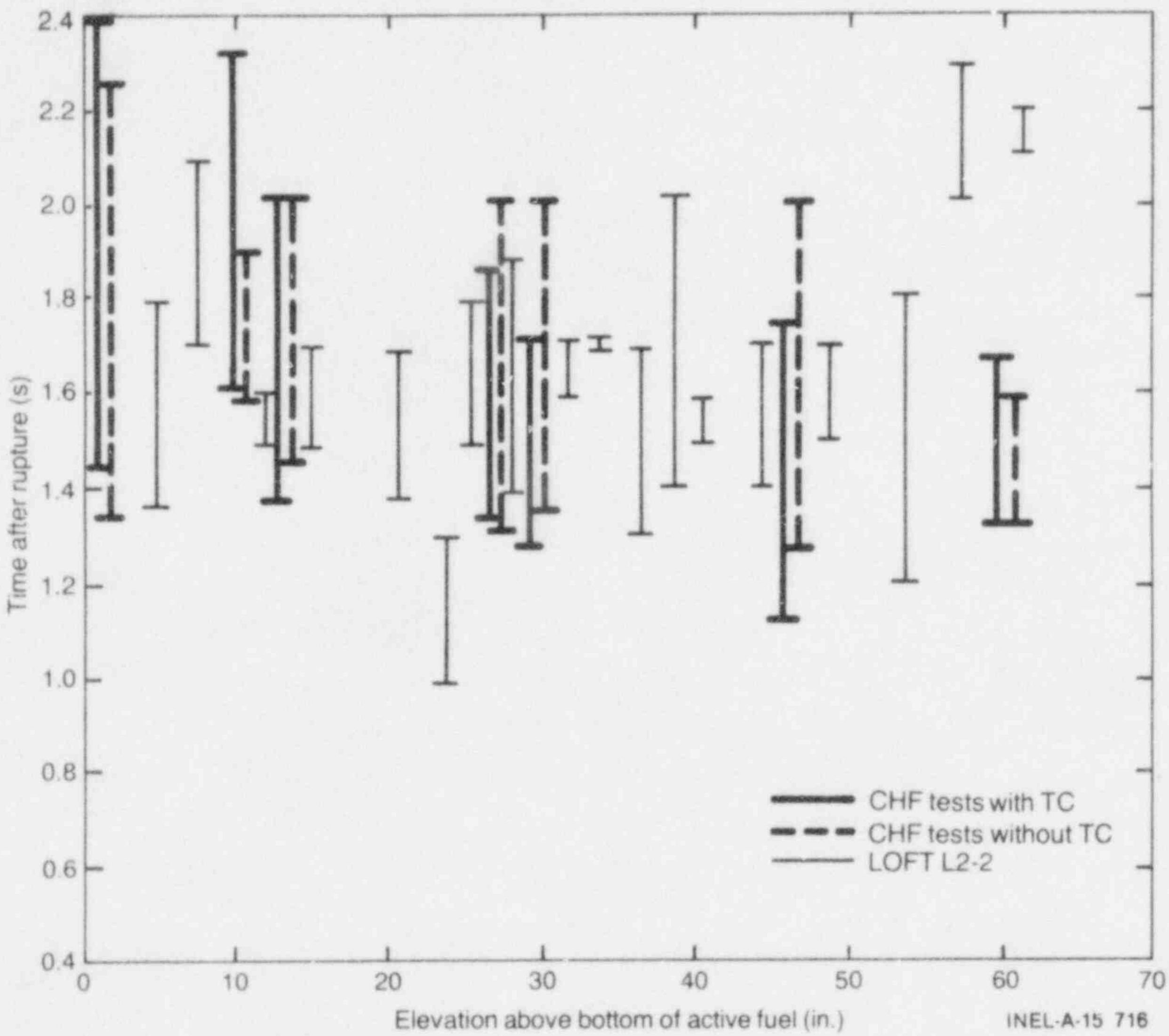

Figure 31. Comparison of Time-to-DNB for LOFT L2-2 and Transient DNB Test (26 kW/M)

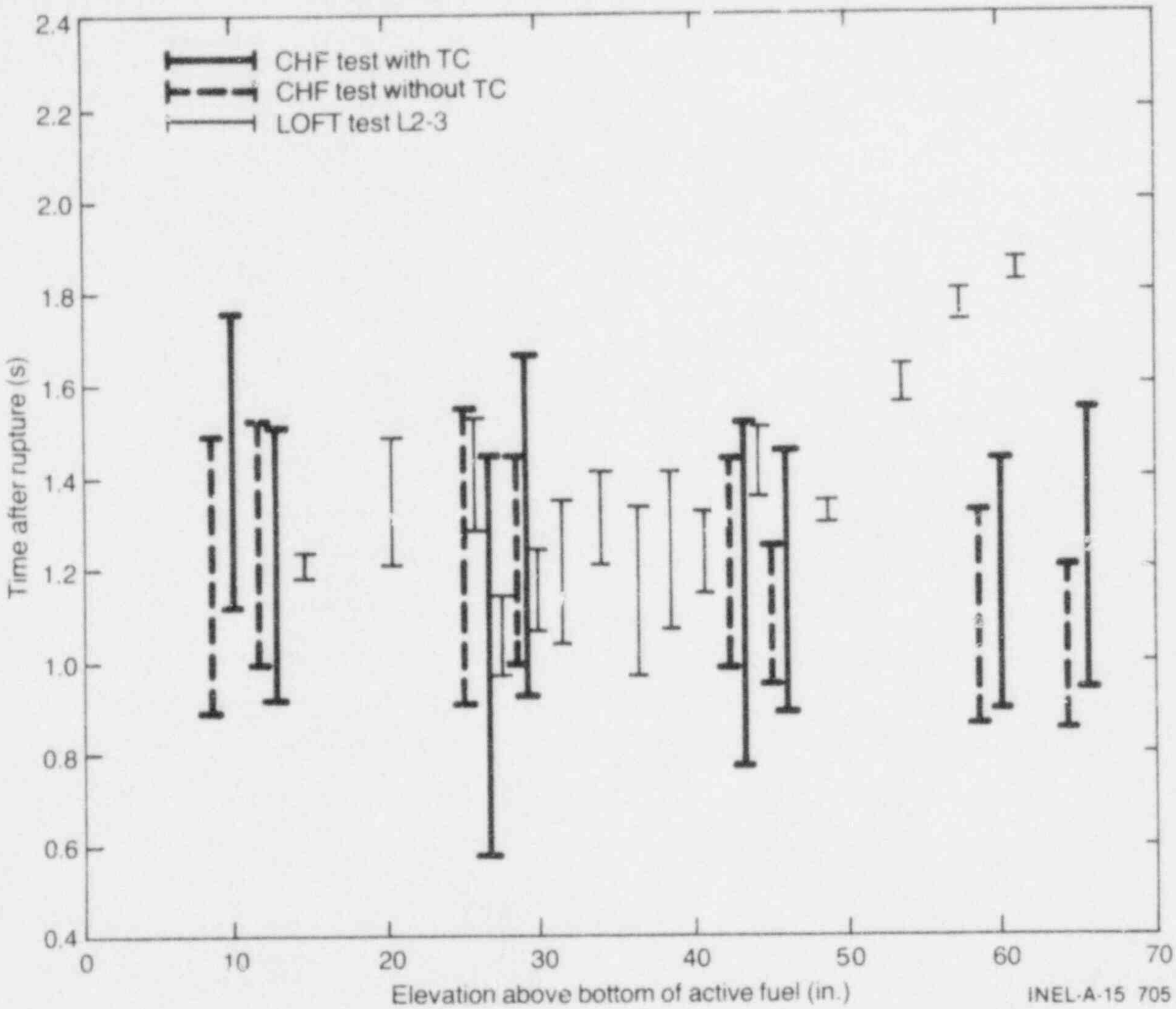

Figure 32. Comparison of Time-to-DNB for LOFT L2-3 and Transient DNB Test (39 kW/M)

5.2 INEL Blowdown Facility Accuracy Tests

To assure that the core is reusable after a LOCE transient without gross fuel rod failure, it is important to know the accuracy of the cladding surface thermocouples in measuring the peak cladding temperatures. Prior to the LOCE tests in LOFT, the peak cladding temperatures were predicted to occur between 35 and 40 seconds after rupture, just before reflood in a near adiabatic heat transfer environment. Several tests were conducted in the Blowdown Facility at the INEL to quantify the accuracy of the thermocouple measurements under simulated, near adiabatic conditions.[10,11] The rods were subjected to various hot leg blowdowns to simulate the expected temperature transients expected for the LOFT nuclear LOCEs. The accuracy of the surface thermocouples was evaluated by comparing the surface thermocouple response with that of small thermocouples embedded in the surface of the zircaloy cladding as shown in Figure 33. The surface and embedded thermocouple response for a representative test to simulate the pretest calculated cladding temperature L2-2 is shown in Figure 34 and shows that the difference in peak temperature between the surface and embedded thermocouples is less than 5 K at the time of peak cladding temperature. The tests showed that the surface thermocouples accurately measure local cladding temperatures under nearly adiabatic conditions characterized by low flow steam cooling. This conclusion is also supported by independent metallurgical examination of the cladding temperature from these test rods showing the azimuthal variation in the cladding temperature to be less than 40 K and agreement between thermocouple measurements and temperatures estimated from metallurgical techniques to within 20 K.[12]

Steady-state measurements from the surface and embedded thermocouples as a function of power level provide a means of estimating the cooling effects of the surface thermocouples during steady state power operation. Figure 35 shows the difference in cladding temperature from the embedded and surface thermocouples over the power ranges tested. Assuming the

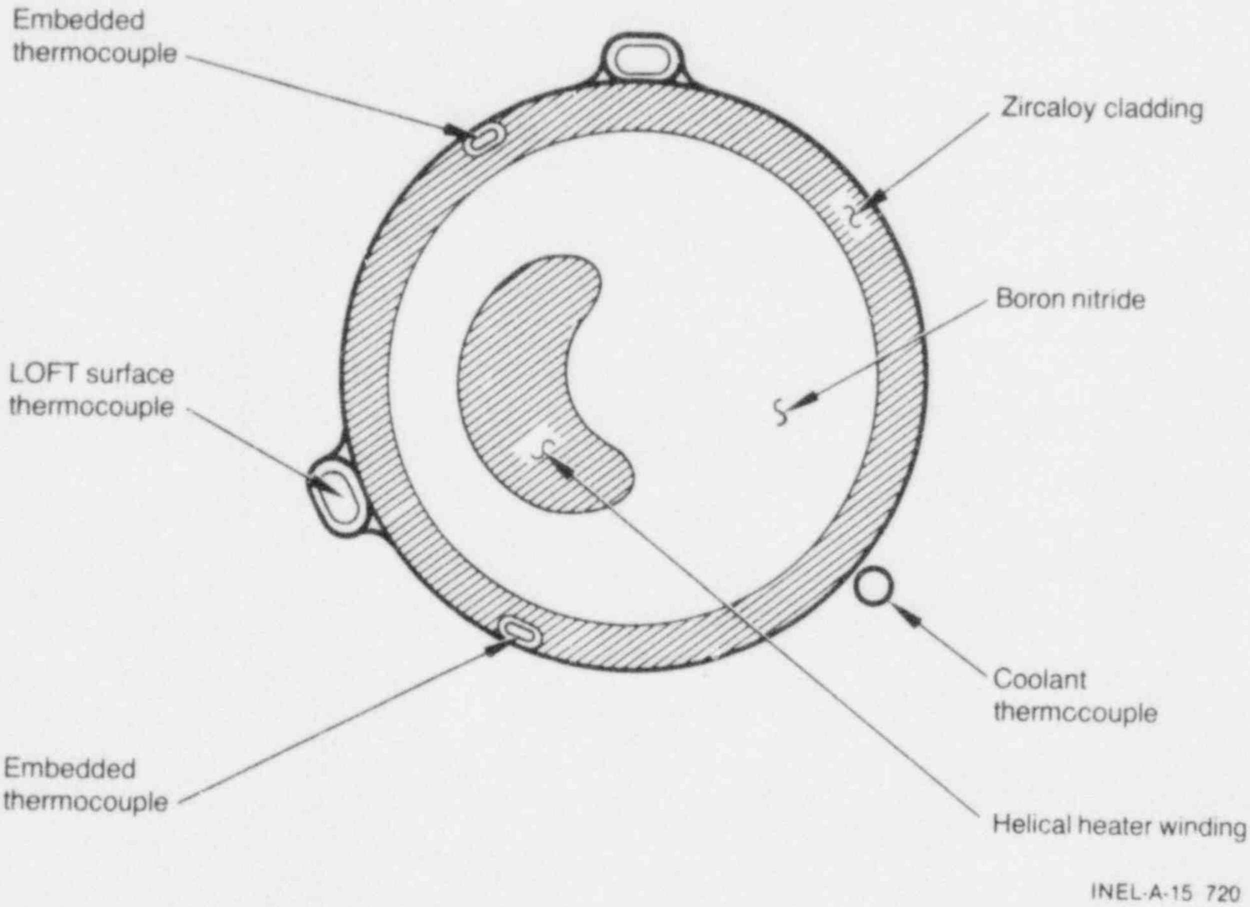

Figure 33. Thermocouple Installation for Blowdown Facility Accuracy Tests

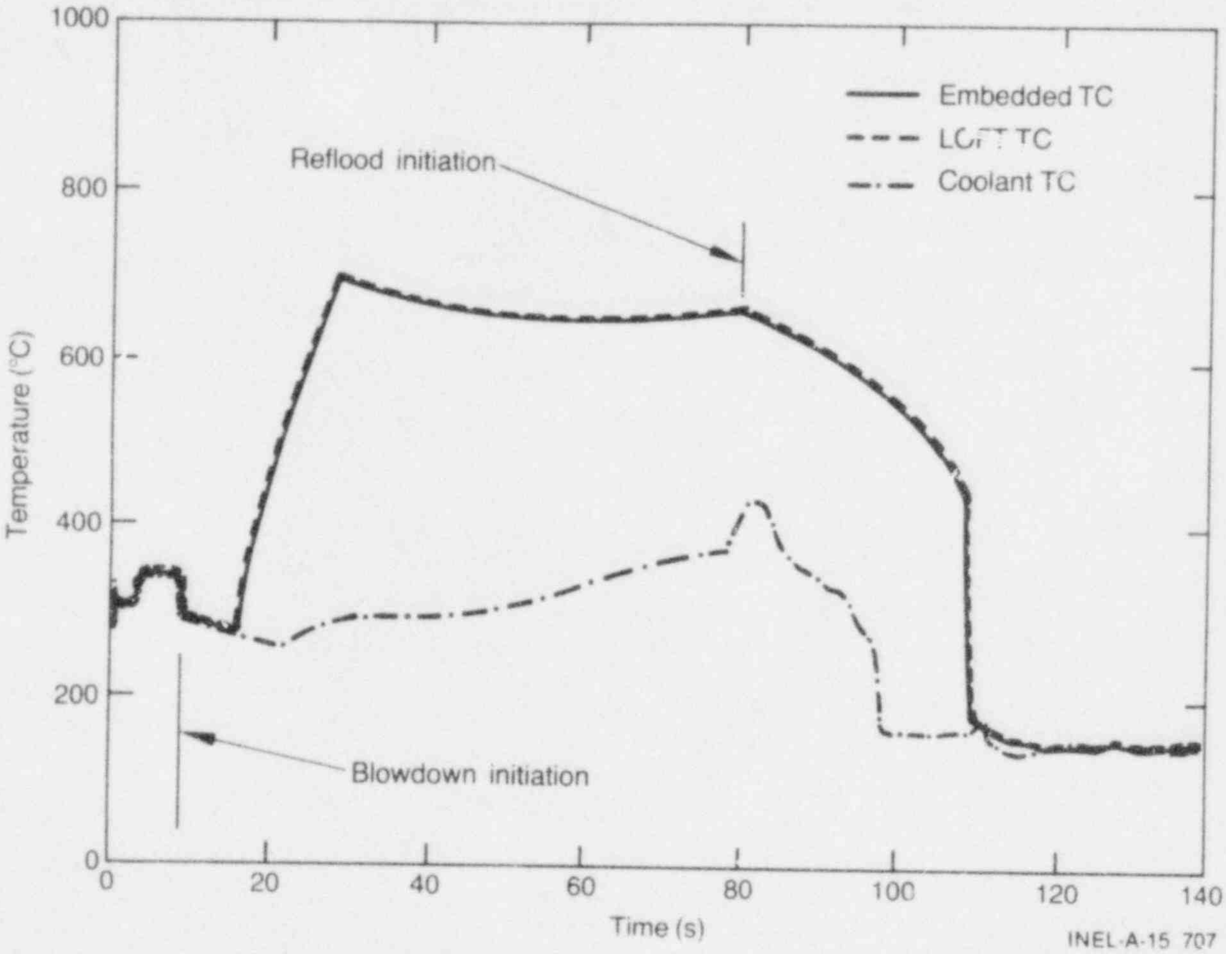

Figure 34. Thermocouple Response from Blowdown Facility Accuracy Tests

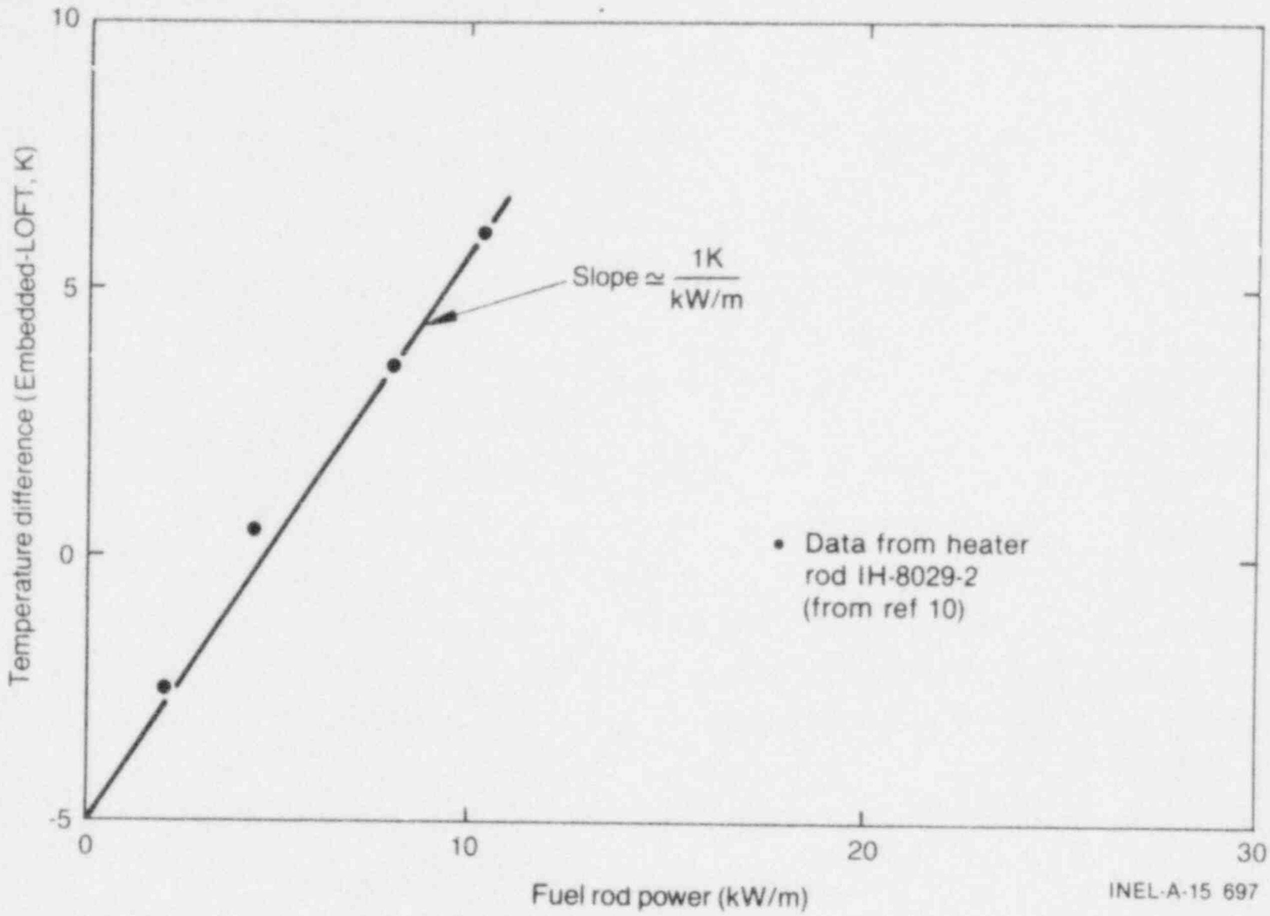

Figure 35. Steady-State 'Fin" Effect of LOFT Surface Thermocouple vs Fuel Rod Power

embedded thermocouple represents the cladding temperature, this correlation estimates the 'fin' cooling effect of the surface thermocouples during normal power operation and this difference in thermocouple measurements could be added to the surface thermocouple measurement to estimate the true cladding temperature. Applying this correction technique to the LOFT steady-state cladding temperature measurements (shown in Figure 8) results in cladding temperatures very nearly in agreement with the predicted values for the L2-2 power and flow conditions as shown in Figure 36.

5.3 INEL Blowdown Facility, High Pressure Quench Tests

After the L2-2 test showed the early rod cooling, separate effects tests were proposed to determine the influence of thermocouples on rod cooling rates during high pressure, low quality flow conditions. The first series of these tests utilizing a single heater rod were recently completed in the INEL Blowdown Facility.[13] Each test consisted of two phases, (1) a rod heating phase in a nearly adiabatic, helium environment at low rod powers and high system pressures (7 MPa) to achieve the desired initial cladding temperature, and (2) very rapid flooding of the test section with low quality coolant to cool and quench the rods while maintaining the high system pressure. Tests were run on rods with and without surface thermocouples for various flow conditions and initial cladding temperatures. By comparing measured internal cladding temperature response on rods with and without external cladding thermocouples, an assessment of the additional cooling effect of the surface thermocouples was evaluated. The tests utilized a stainless steel clad Semiscale heater rod shown schematically in Figure 37 with internal thermocouples. Certain tests were replicated and show excellent repeatability of the flow conditions and rod response from test-to-test.

Table 3 summarizes the flow conditions and initial peak cladding temperature for the single rod tests. The results of the quench tests, conducted at 1.8 m/s and zero quality inlet flow (most representative of flow conditions for the LOFT quench) are shown in Figures 38 through 40 for

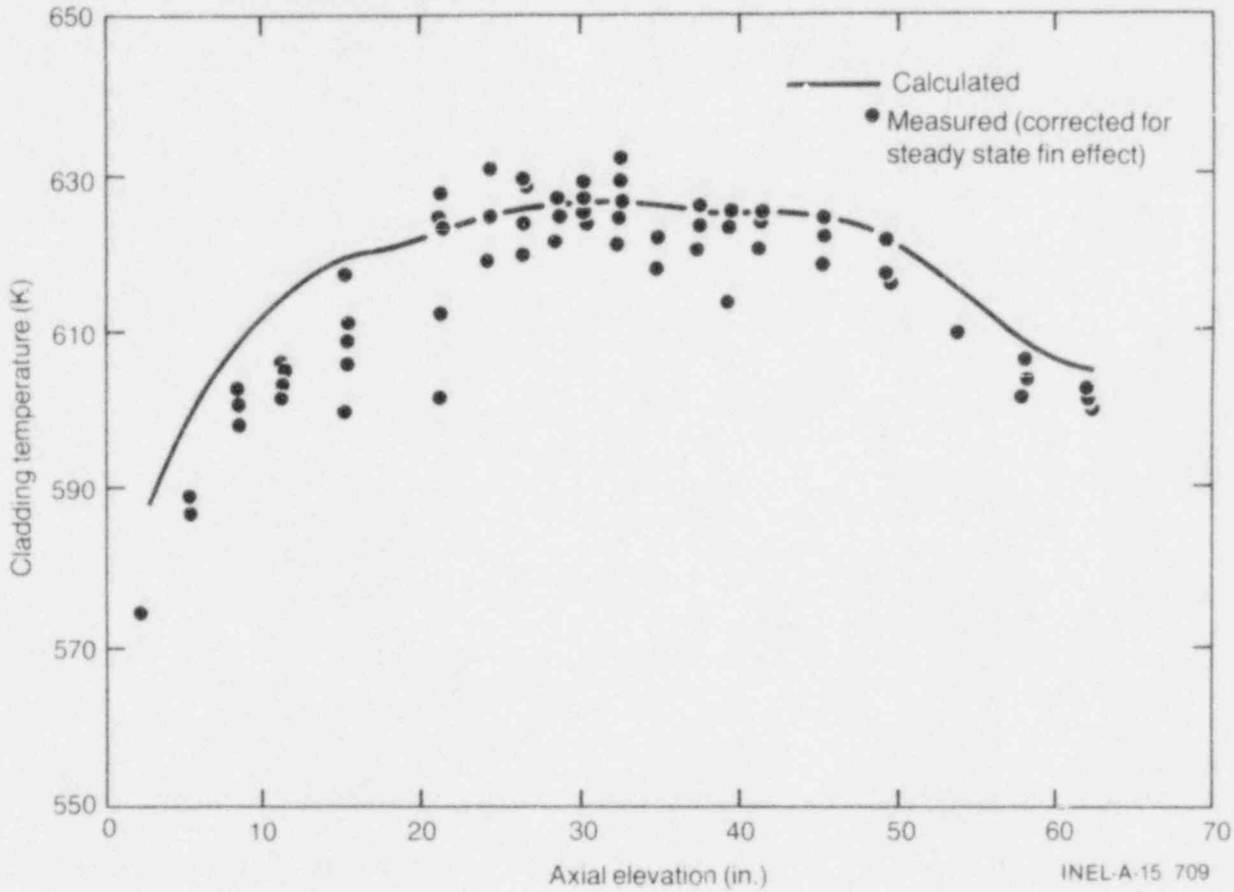

Figure 36. Steady State Cladding Temperature Measurements Corrected for 'Fin' Effect (L2-2)

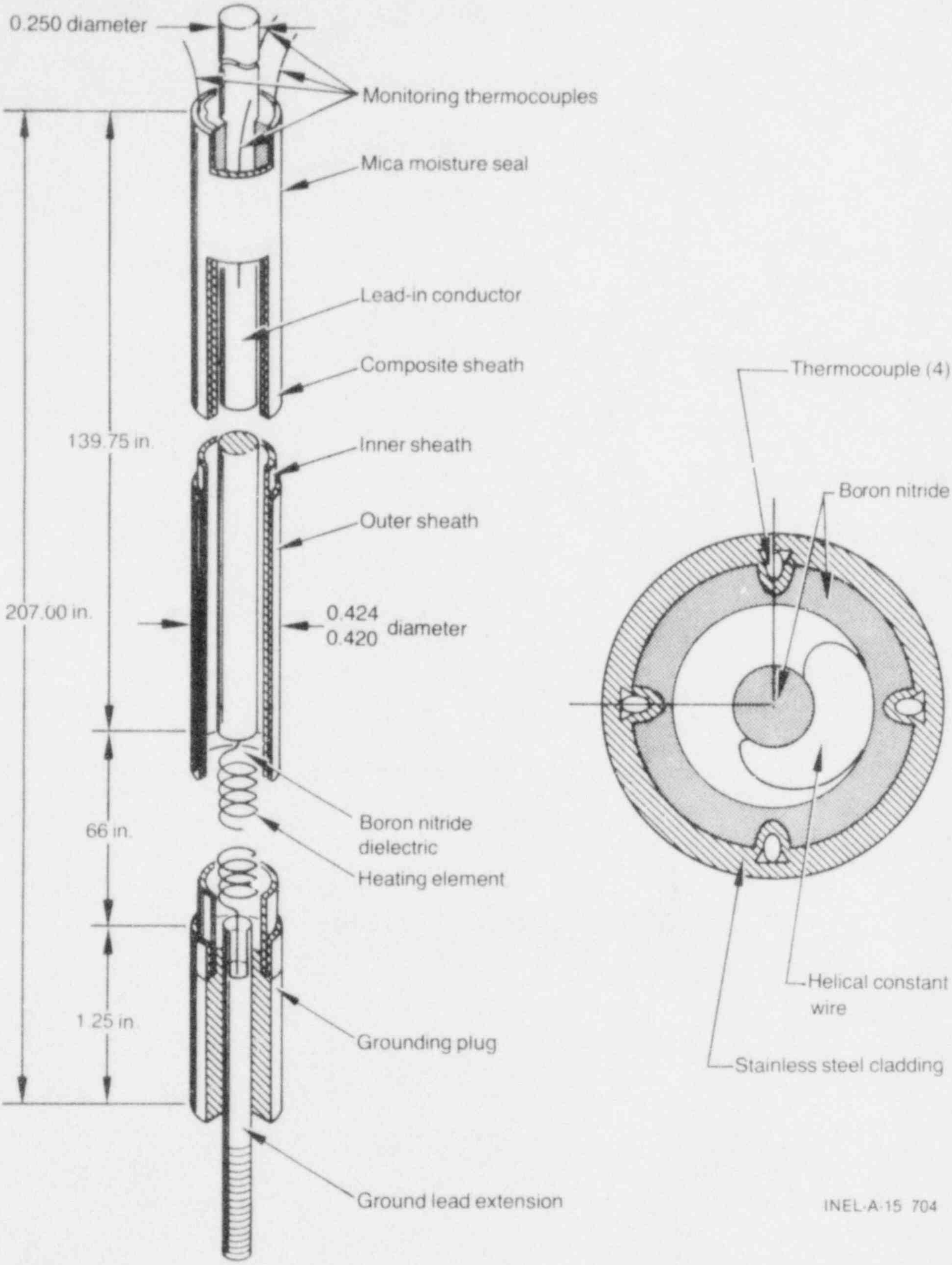

Figure 37. Schematic of Electric Heater Rod Utilized for Blowdown Facility Quench Tests

TABLE 3. NOMINAL TEST CONDITIONS FOR PHASE 1 QUENCH TESTS

Run No.	Test Section Pressure (Mpa)	Test Section Inlet Quality (Percent)	Average Test Section Inlet Fluid Velocity (m/sec)	Rod Hot Spot Initial Temperature (K)	Test Section Test Section Mass Flow Rate (Kg/sec)
1	0.1 (ambient)	69°C subcooled	0.04	1025	0.015
3	0.1 (ambient)	69°C subcooled	0.1	1025	0.037
6	7	0	0.4	775	0.11
7	7	0	0.4	1025	0.11
8	7	11	1.3	1025	0.11
10	7	0	1.8	775	0.5
11	7	0	1.8	1025	0.5
11A	7	0	1.8	1025	0.5
11B	7	0	1.8	1025	0.5
24	7	0	1.8	1025	0.5
12	7	5	3.5	1025	0.5
13	7	15	7.5	1025	0.5
14	7	0	1.8	1175	0.5
15	7	0	3.0	1025	0.83
17	7	15	11.0	1025	0.83
20	7	15	11.0	1175	0.83
21	7	0	6.0	1025	1.66
23	7	0	6.0	1175	1.66

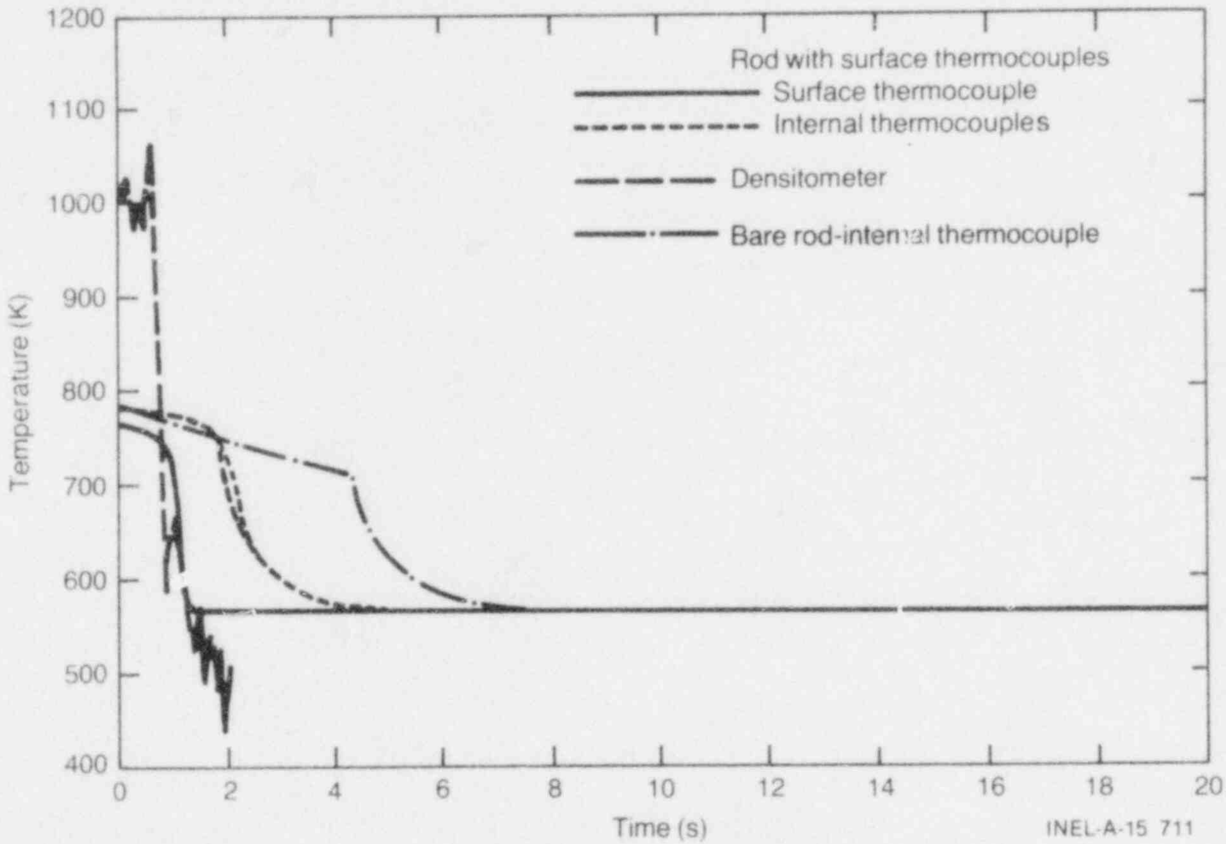

Figure 38. Quench Test Thermocouple Response - Flooding Rate, 1.8 m/s-Initial Cladding Temperature, 775 K - Zero Inlet Quality

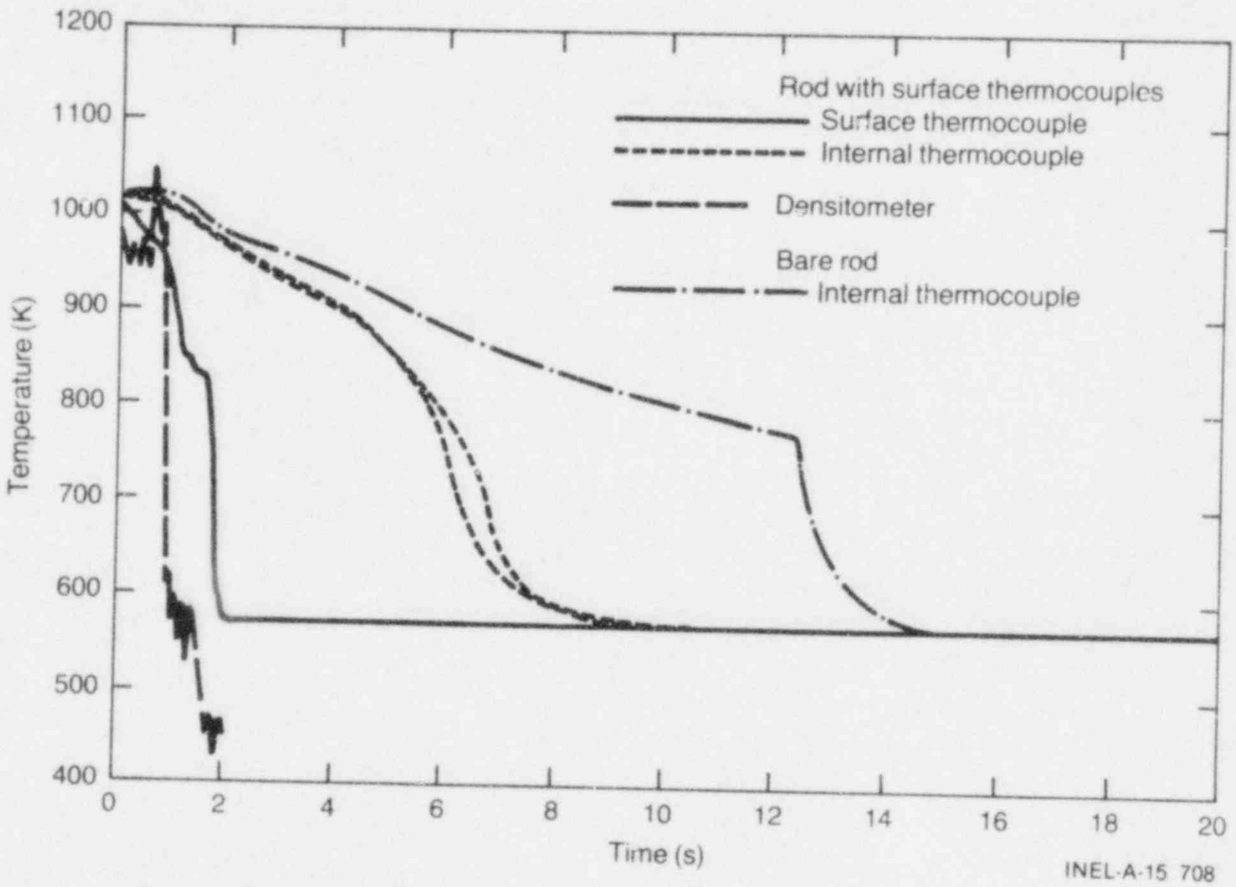

Figure 39. Quench Test Thermocouple Response - Flooding Rate, 1.8 m/s-Initial Temperature, 1025 K - Zero Inlet Quality

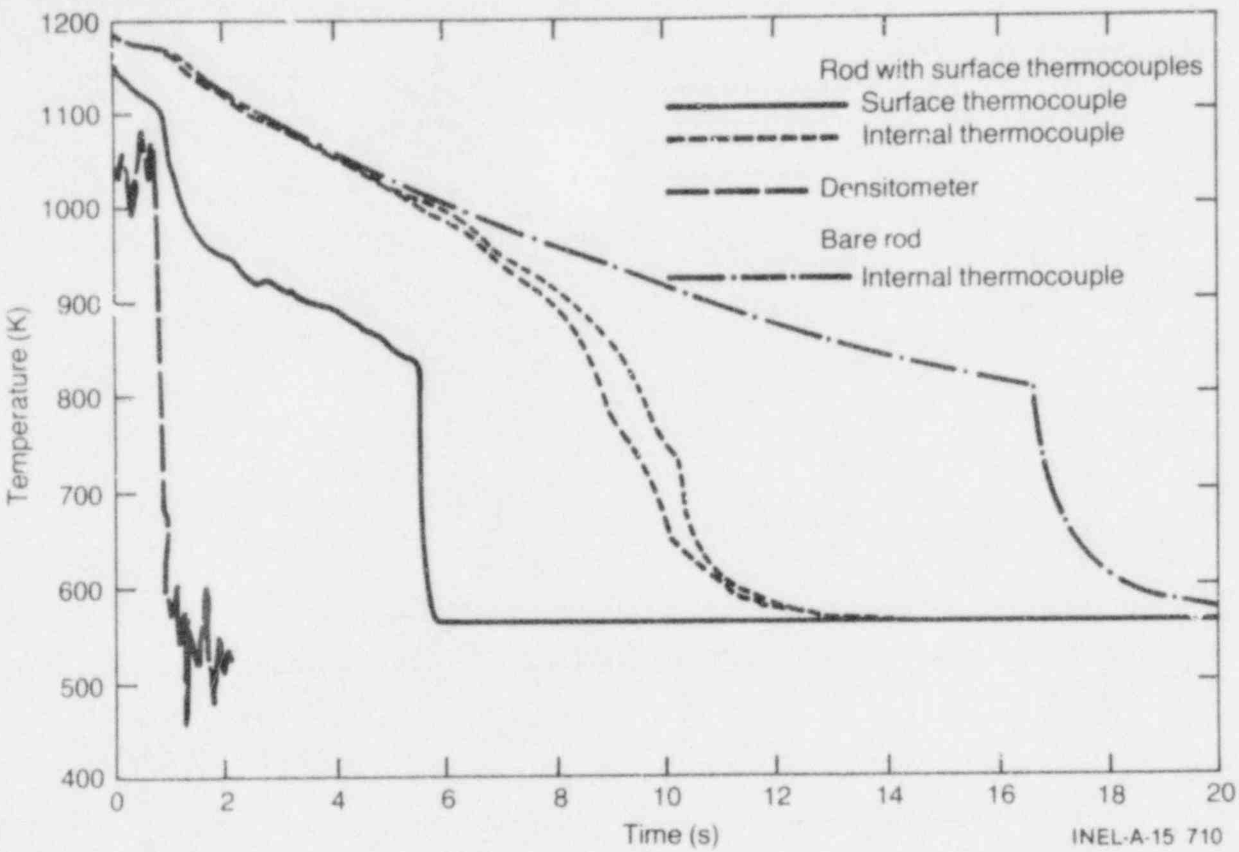

Figure 40. Quench Test Thermocouple Response - Flooding Rate, 1.8 m/s-Initial Temperature, 1175 K - Zero Inlet Quality

initial cladding temperatures of 775, 1025, and 1175 K, respectively. In these figures, the time at which the coolant arrives at the thermocouple location is also indicated by the rapid change in the test section gamma densitometer response. Thus, the quench times can be estimated with respect to the coolant arrival and can be related to the LOFT quench characteristics summarized in Figures 16 and 17. The rods with surface thermocouples are seen to cool more rapidly than rods without surface thermocouples and the surface thermocouples indicate a quench in less than one second after the coolant reaches the thermocouple location for initial cladding temperatures less than 1025 K. The time difference between coolant arrival and quench for the internal and surface thermocouples from Figures 38 through 40 are summarized in Figure 41. These quench times indicated that rods without thermocouples during L2-2 (peak cladding temperature approximately 780 K) would have required 3 seconds longer to quench than indicated by the surface thermocouples. For L2-3, the rods without surface thermocouples would have required 6 seconds longer to quench compared to the surface thermocouples data. An interesting observation is the consistency in the surface thermocouple behavior for the LOFT L2-3 test and the quench tests. From Figure 40, rapid cooling of the surface thermocouple occurs almost coincident with coolant arrival, however, the cladding is not quenched until approximately 2.5 seconds after arrival of the coolant. The difference in time between the surface thermocouple quench and cladding quench from the quench test data, corresponds well with the unstable cooling period of the LOFT thermocouples, approximately 2.5 seconds. This behavior suggests that the unstable quench cooling observed in LOFT may be the result of preferential cooling of the surface thermocouple while the cladding is not yet quenched.

Relating the high pressure quench tests results to LOFT must be done with care. Differences in test thermal hydraulic conditions between LOFT and the quench tests may be important, and differences in the thermal response of the electric heater rod and nuclear rod may also influence rod cooling. However, the quench tests suggest that uninstrumented fuel rods

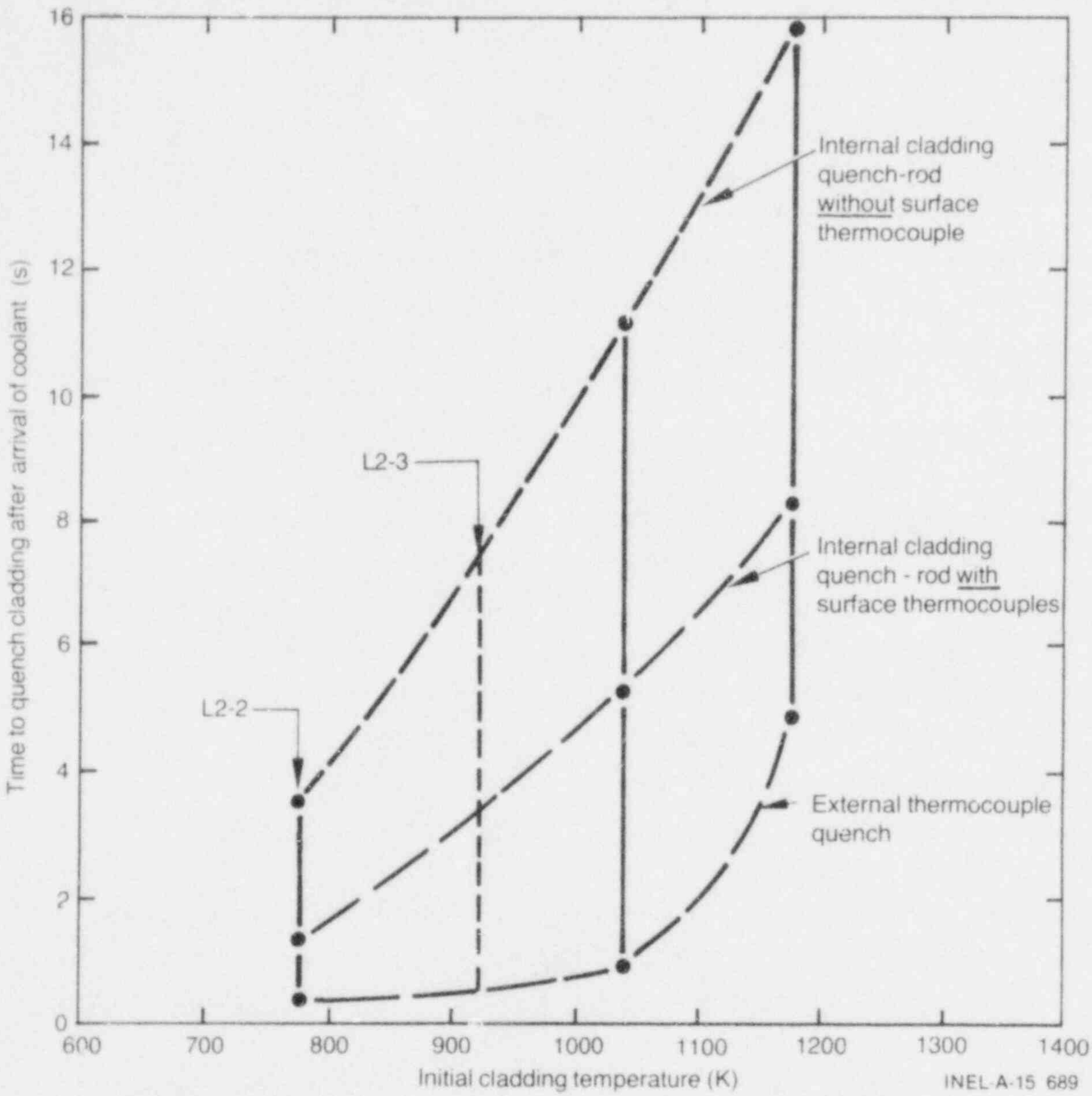

Figure 41. Summary of Thermocouple Time-to-Quench Response from Blowdown Facility Tests - 1.8 m/s, Zero Inlet Quality

in LOFT may not have experienced a complete quench during L2-3, and that the surface thermocouples may be reflecting coolant temperatures more than cladding temperatures. Additional tests are planned later in 1980 on a cluster of electric heater rods with thermal characteristics (thermal diffusivity, fuel-cladding gap, zircaloy cladding) more typical of a nuclear rod.

5.4 Power Burst Facility (PBF) TC-1 Tests (Nuclear Rods)

A series of loss-of-coolant experiments were recently conducted in the PBF to evaluate the cooling effects of surface thermocouples during blowdown and reflood conditions[14]. Four individually shrouded test rods were utilized, as shown in Figure 42. Two of the rods were instrumented with surface thermocouples similar to the LOFT type, while the other two rods contained no thermocouples on the cladding outer surface. All rods were instrumented with internal fuel rod thermocouples, either in the fuel pellet near the outer surface, or directly attached to the cladding inner surface as shown in Figure 42.

The tests were intended to duplicate the transient cladding temperature and pressure loading during the blowdown phase of the LOFT LOCEs. The primary objective was to simulate fuel rod response during the rapid cooling conditions observed early in the LOFT tests. The rapid, low quality flooding of the test section was to be achieved by cycling the hot leg and cold leg blowdown valves several seconds after test initiation to produce a flow reversal in the test section. After cycling the blowdown valves and completion of the blowdown, the rods were powered for approximately 100 seconds to increase the cladding temperature to approximately 1200 K. The test section was then reflooded similar to the LOFT core reflood rates during the L2-2 and L2-3 tests (~ 10 cm/s). A representative cladding temperature response from this control sequence is shown in Figure 43 (TDC-1B test).

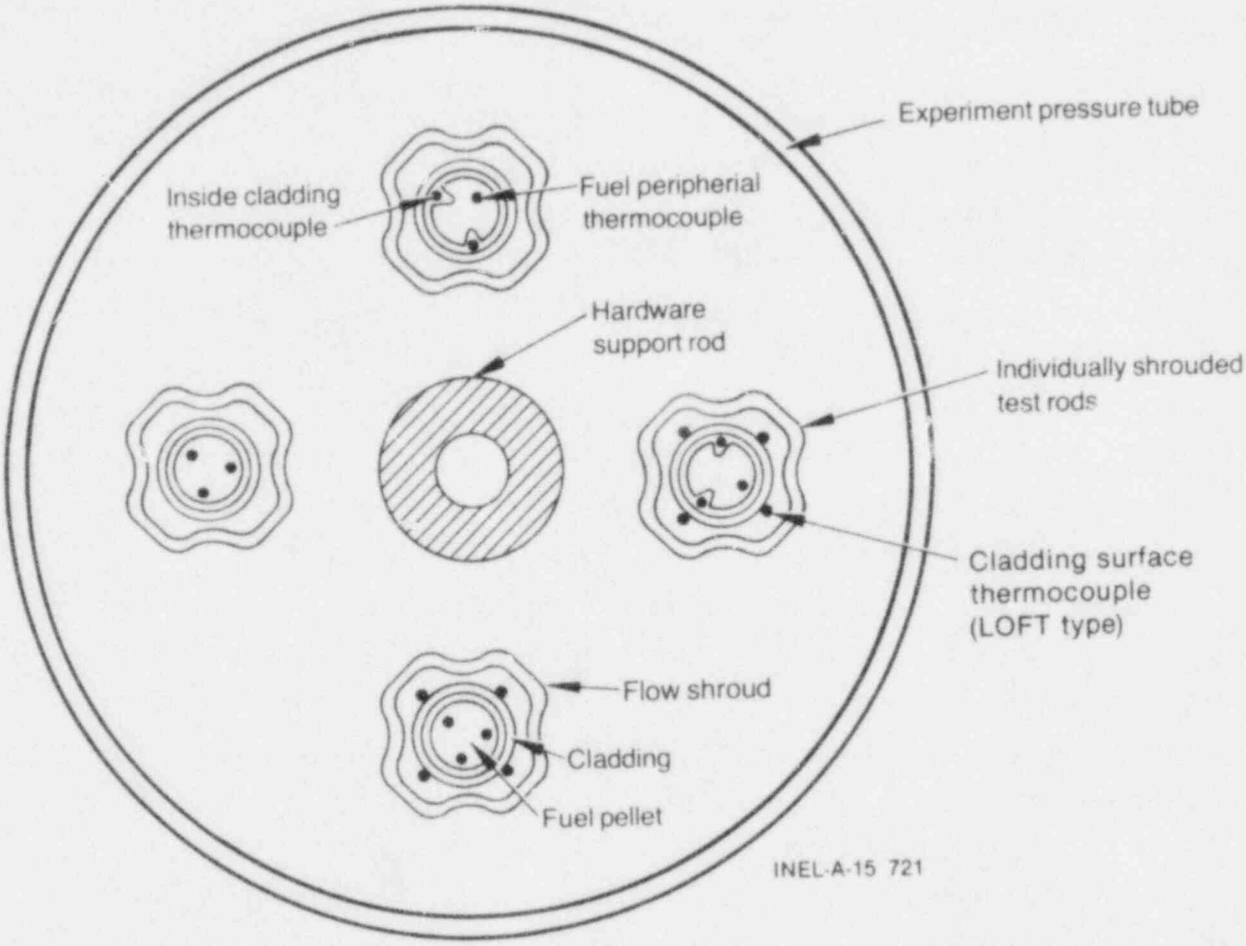

Figure 42. Power Burst Facility (PBF) Test Rod Configuration for the TC-1 Test Series

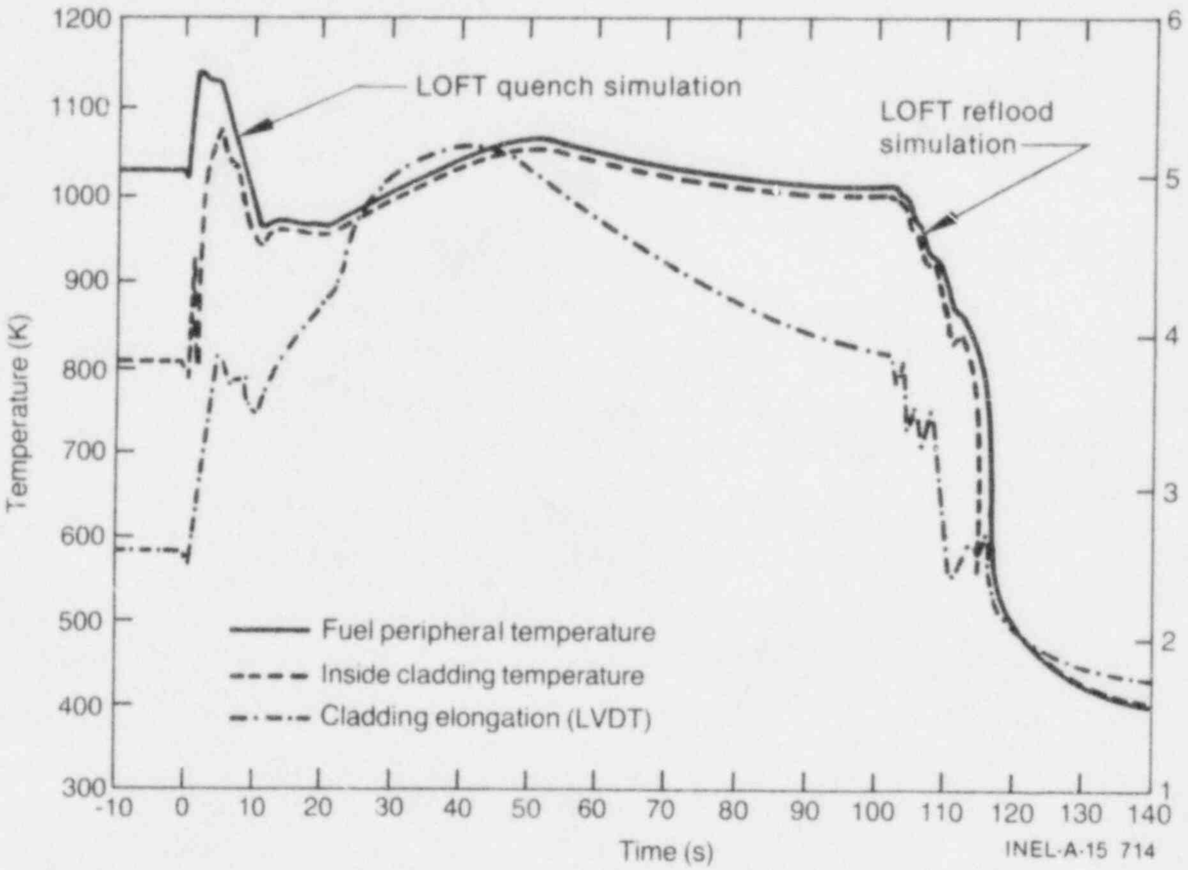

Figure 43. General Cladding Response from the PBF TC-1 Tests (TC-1B)

Four successive LOCA transients were conducted in this manner with the differences being in the blowdown valve cycling times and rod transient power. Unfortunately, the test section coolant flow, resulting from the blowdown valve cycling was predominantly steam, or very high quality two-phase flow, and did not simulate the rapid cladding quench observed in the LOFT tests. During the valve cycling time (LOFT quench simulation), a maximum steam cooling of $\sim$20 K/s was measured by the cladding surface and internal thermocouples, compared to a 200-300 K/s cooling rate measured during the LOFT quenches.

The tests showed a time-to-DNB delay on rods with surface thermocouples, although care must be taken in quantifying the time delay because of a large variability in DNB times due to non-uniform flow between the individual test rod shrouds. The tests provide data to characterize the effect of time-to-DNB on the peak cladding temperature since different time-to-DNB and peak cladding temperatures were observed on the test rods. Figure 44 presents the time-to-DNB vs peak cladding temperature data; by comparing the data from rods with and without surface thermocouples, the cooling influence of the surface thermocouples on the peak cladding temperature is estimated to be approximately 50 K.

All four tests show very clearly the cooling influence of the surface thermocouples during the final reflood cooling ($\sim$10 cm/s reflood rate). Figure 45 shows the internal rod thermocouples response during reflood for the TC-1B test, which is representative of the response from all four tests; notice that the rods with surface thermocouples are seen to quench 5 to 10 seconds earlier and at higher cladding temperatures than the bare rods. However, the cooling rates of all rods prior to quenching are nearly the same. Figure 46 compares surface thermocouple and internal rod thermocouple response during reflood, and indicate that the cladding surface thermocouples quench at nearly the same time as the internal cladding and fuel thermocouples. These results suggest that during reflood cladding surface thermocouples do not appreciably affect cooldown rate but enables the cladding to quench at higher (50 to 100 K) temperatures.

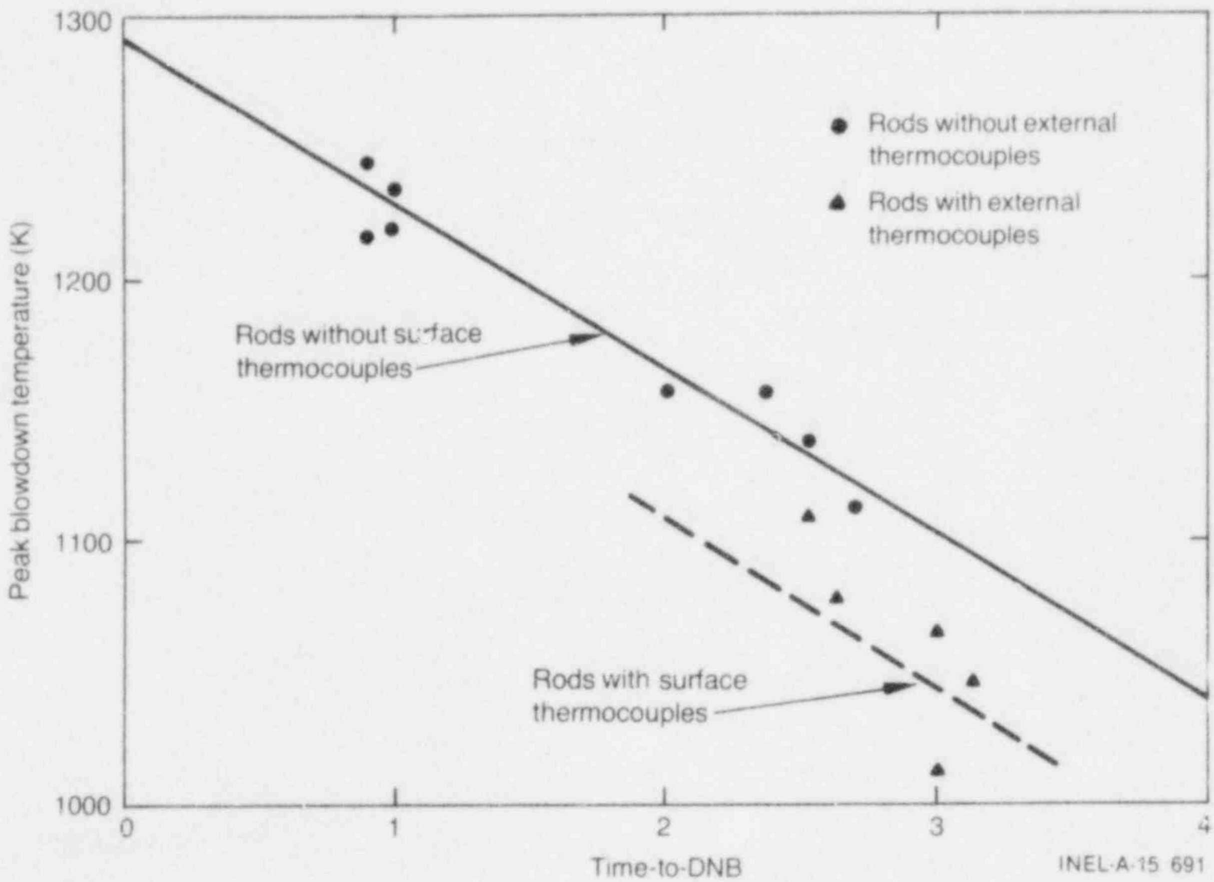

Figure 44. Time-to-DNB vs Peak Cladding Temperatures from the PBF TC-1 Tests

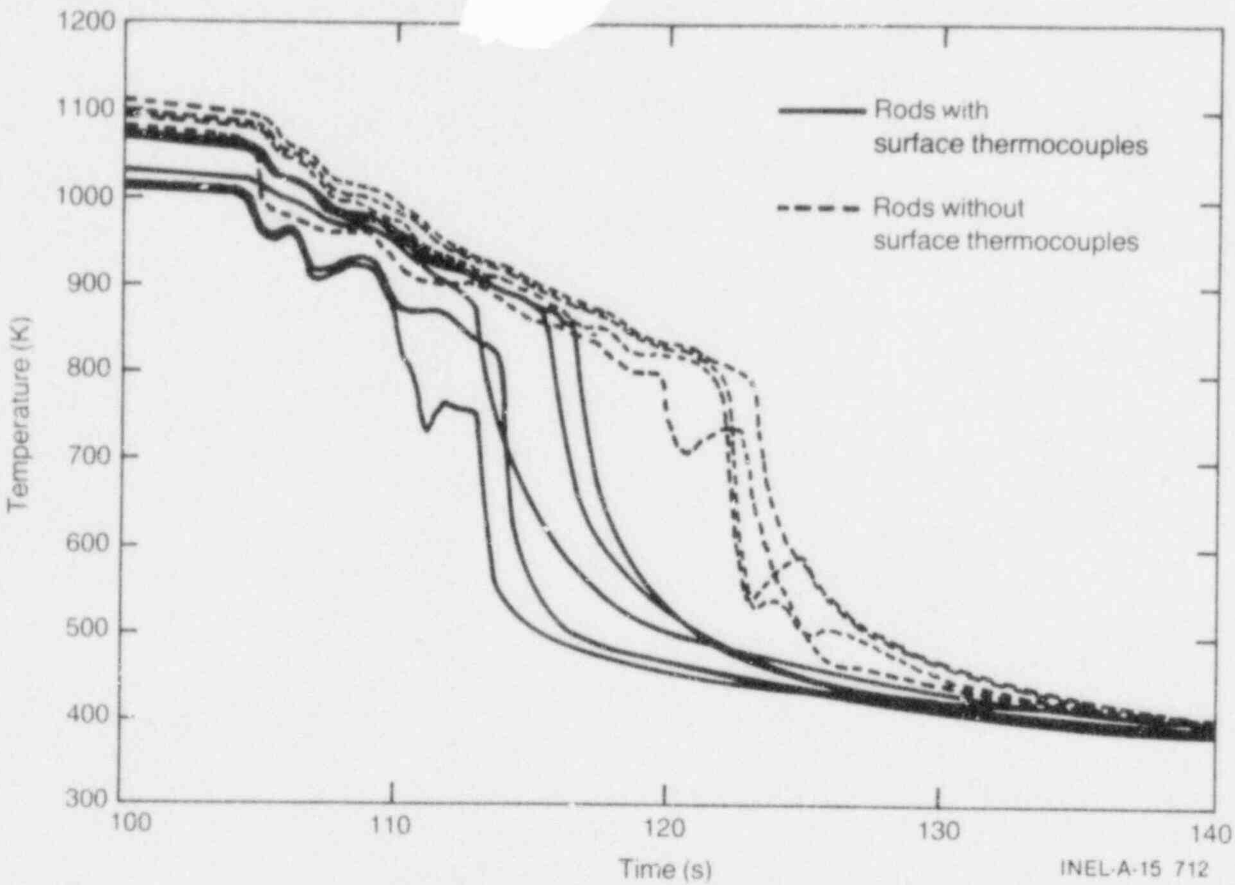

Figure 45. Comparison of All Internal Rod Temperatures During Reflood from PBF TC-1B Test

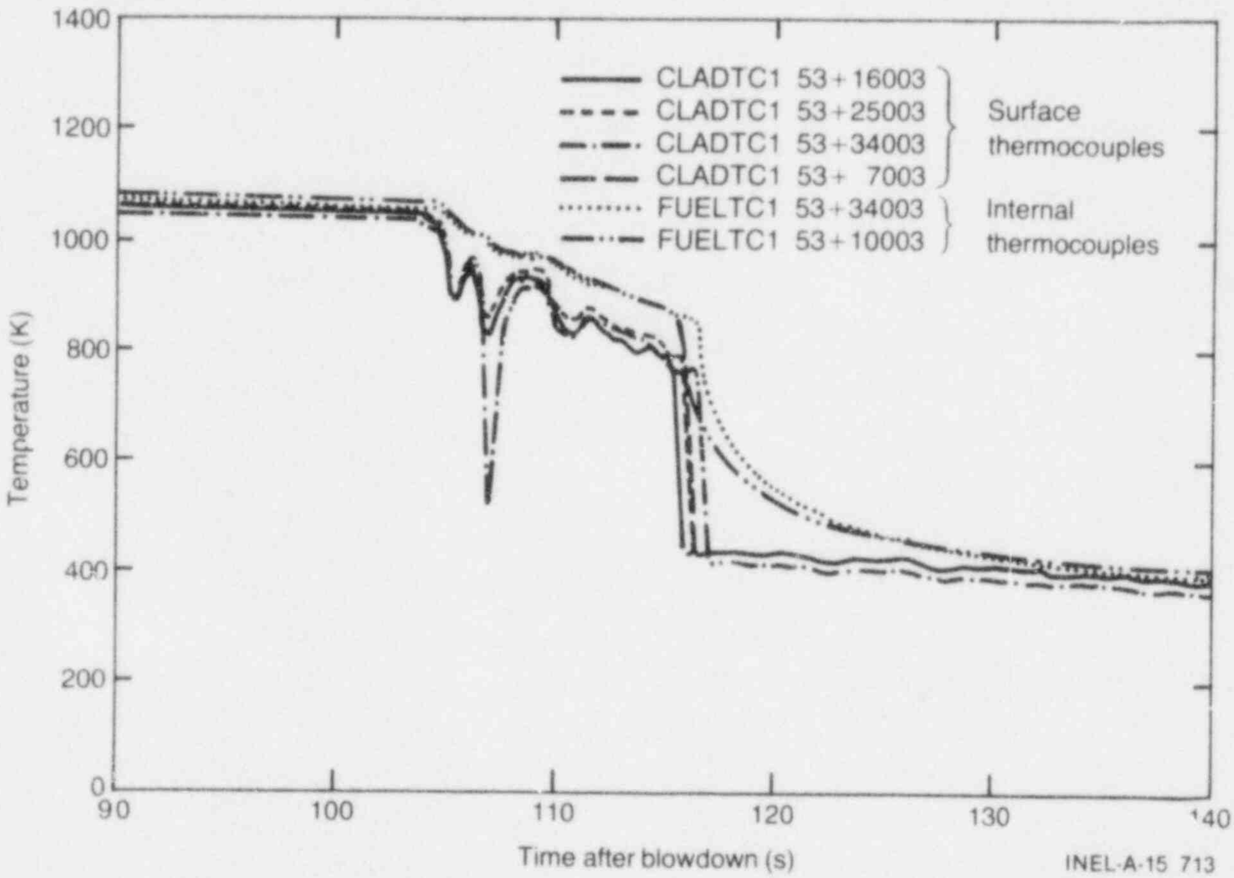

Figure 46. Comparison of Cladding Internal and External Thermocouples During Reflood from PBF TC-1B Test

Another series of PBF tests (designated TC-3) will be conducted during 1980, similar to the TC-1 sequence except that the quench simulation will be more representative of the initial quench conditions observed in the LOFT tests.

5.5 Summary of Possible Thermocouple Effects During L2-2 and L2-3

The effect of the surface thermocouples on initial DNB are somewhat controversial. The LOFT transient DNB tests, indicate surface thermocouples affect DNB occurrance by less than 0.5 seconds, while the PBF TC-1 tests indicate the time-to-DNB may be affected by as much as 1-2 seconds. As noted earlier, care must be taken in interpreting the PBF results because of differences in flow conditions between each of the flow shrouds and differences in hydraulic conditions between LOFT and PBF. Since initial DNB occurred before 1.5 seconds in the LOFT tests and correlated with the core flow stagnation, it is likely that time-to-DNB in LOFT was affected by less than 0.5 seconds as suggested by the transient DNB tests on simulated LOFT bundles.

The blowdown facility accuracy tests and the PBF TC-1 tests indicate that the LOFT cladding surface thermocouples accurately measure the cladding temperature response under nearly adiabatic cooling conditions characterized by high quality or steam cooling conditions.

For cooling transients characterized by low quality two-phase cooling, the thermocouples may not indicate cladding temperatures, but rather coolant temperatures. For the early temperature quench during the L2-2 and L2-3 tests, the Blowdown Facility high pressure quench tests indicate the surface thermocouples may be measuring the low quality coolant temperatures.

During final core reflood, it is clear from the PBF TC-1 tests that the thermocouples provide earlier quenching by as much as 10 seconds and allow the rod quench to be initiated from higher (50-100 K) cladding temperature. The PBF TC-1 test data are perhaps the best data showing this effect. However, the data indicates that the precursory cooling rate (before quench) is not affected by the surface thermocouples.

The effects of these surface thermocouple cooling influences on the LOFT nuclear rod response is addressed in the next section.

6. UNCERTAINTY BOUNDS FOR LOFT L2-3 CLADDING TEMPERATURE RESPONSE

Because the cladding surface thermocouples enhance cooling of the rod, the measured data represent a lower bound for the cladding temperature. The upper bound temperature, representing a rod without surface thermocouples can be approximated by adjusting the measured data by the known thermocouple cooling influences as summarized in the previous section.

The upper bound temperature response for the LOFT L2-3 test is estimated based on the estimated possible thermocouple cooling effects. These cooling influences may not be as large for the LOFT tests as in the separate effects tests, but in order to insure conservatism of the upper bound, all known effects were chosen so as to maximize the LOFT estimate. The following boundary conditions were utilized to estimate the upper bound cladding temperature for the L2-3 test:

1. Initial DNB occurred 0.5 seconds earlier than measured by the thermocouples based on the LOFT transient DNB tests.

2. From the time of DNB to the initiation of the early quench, the heat transfer from the instrumented rods was assummed to be increased by 30 percent due to the increased surface area for heat transfer which aids in cooling the rod (fin effect).

3. During the quench time period as indicated by the surface thermocouples, the cladding thermocouples were assumed to be measuring coolant temperature. The cladding temperature decrease during this time was assumed to be represented by the high pressure quench test data (see Section 5.3, Figure 39) as 26 K/second.

4. The early part of secondary heatup phase of the experiment is also assumed to be characterized by thermocouple selective cooling. Therefore, the heat transfer from the time of secondary DNB initiation to onset of final core flooding is represented by the average heat transfer during the 25-35 second time interval which is characterized by nearly adiabatic heat transfer.

5. During final reflood cooling, the measured LOFT precursory cooling rates (5.5 K/second) are assumed to represent the cooling rate of the uninstrumented rods based on the data from the PBF TC-1 test series. The upper bound cladding temperature was assumed to cool at this rate until a cladding temperature of 750 K was reached, after which a rapid quench was assumed.

The estimated upper bound temperature response calculated under these assumptions is compared to the measured data in Figure 47. An uncertainty of 100 K exists as reflected by the peak cladding temperature envelope. Also a difference of approximately 25 seconds exists in the final reflood temperature quench. The upper bound estimate is compared to the RELAP4/MOD6 pretest predictions in Figure 48, and shows the calculated cladding temperature cooldown during the time period from six to twelve seconds is similar to the estimated upper bound. The fuel rod stored energy for the bounding cases are shown in Figure 49, which shows the importance of the heat transfer during the first ten seconds of the transient.

Resolution of the peak cladding temperatures from the LOFT tests are not likely from metallographic examination of the fuel rods, since for a peak cladding temperature of less than 1100 K, accurate determination of cladding temperatures from zircaloy microstructures or oxidation characteristics is not possible. Evaluation of the cladding temperature from posttest cladding deformation will also be marginal, since, for the L2-3 bounding cladding temperatures, little or no cladding deformation is expected based on out-of-reactor cladding deformation experiments[15], as shown in Figure 50.

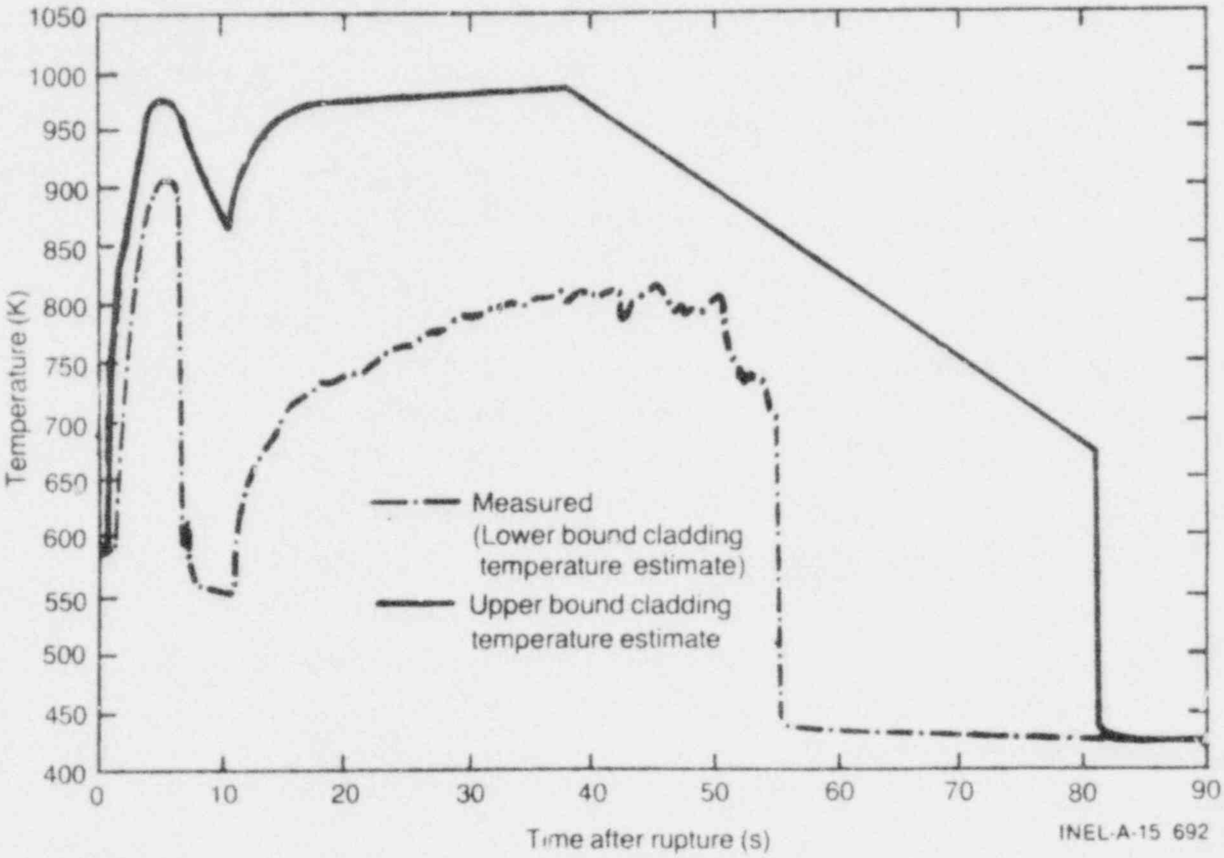

Figure 47. Estimated Upper Bound Cladding Temperature for L2-3 Based on Corrections to the Thermocouple Data

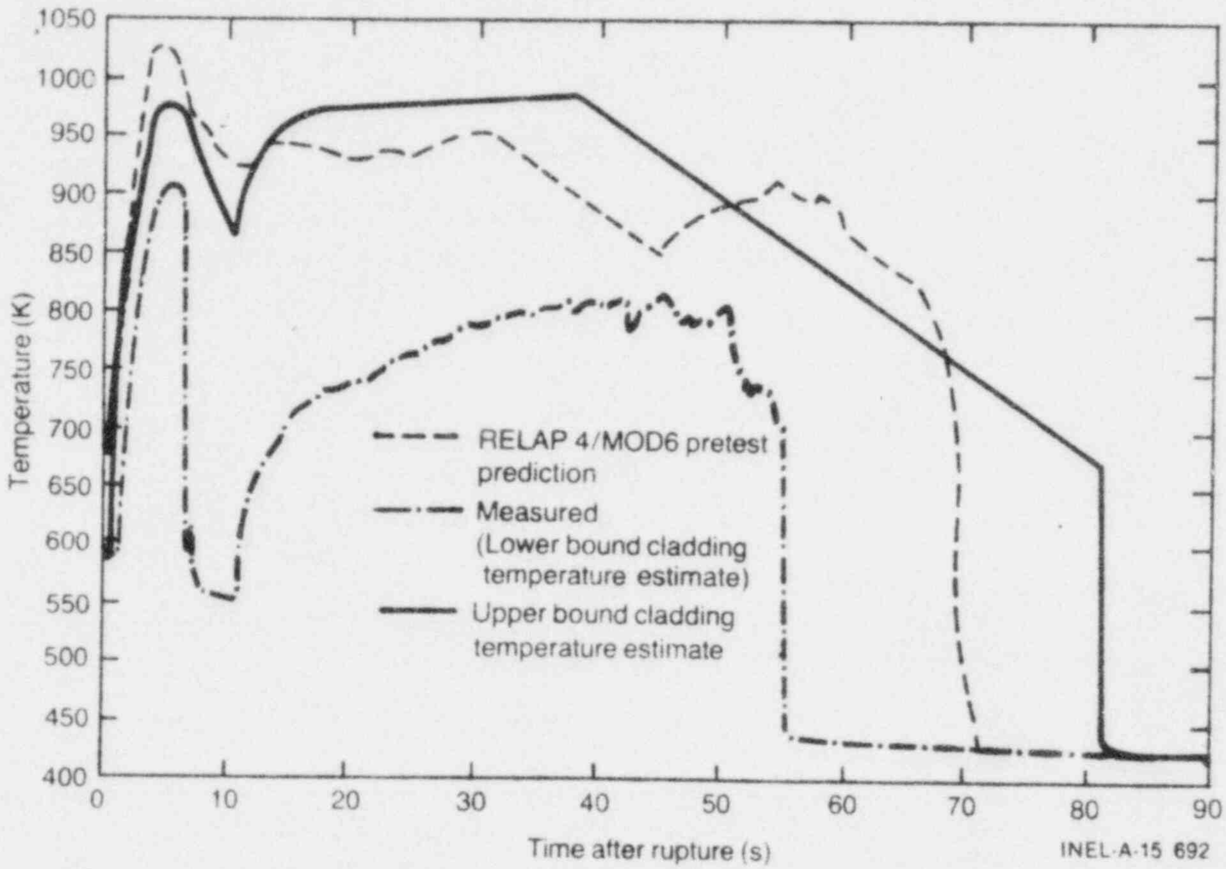

Figure 48. Comparison of L2-3 Peak Cladding Temperature Envelope to RELAP4/MOD6 Pretest Prediction

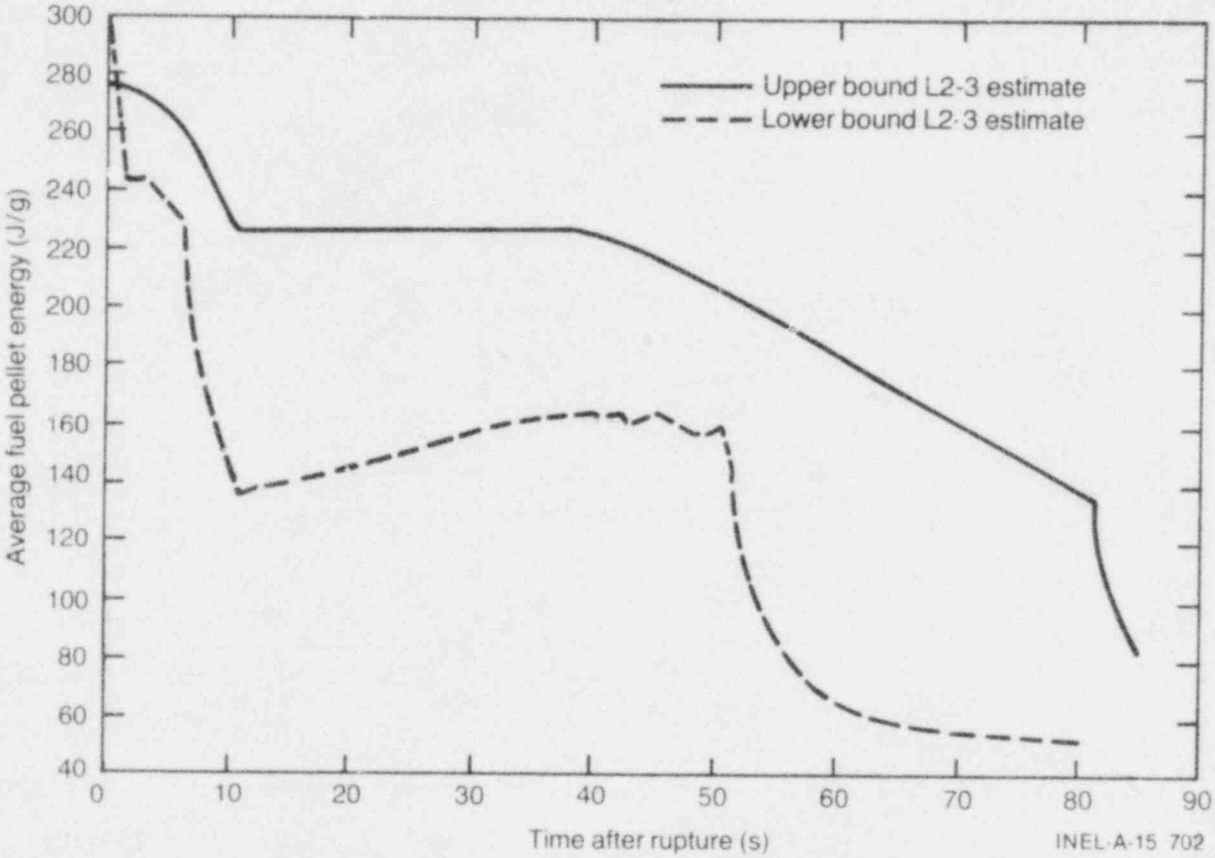

Figure 49. Fuel Rod Stored Energy vs Time for Upper and Lower Bound Fuel Rod Responses During L2-3

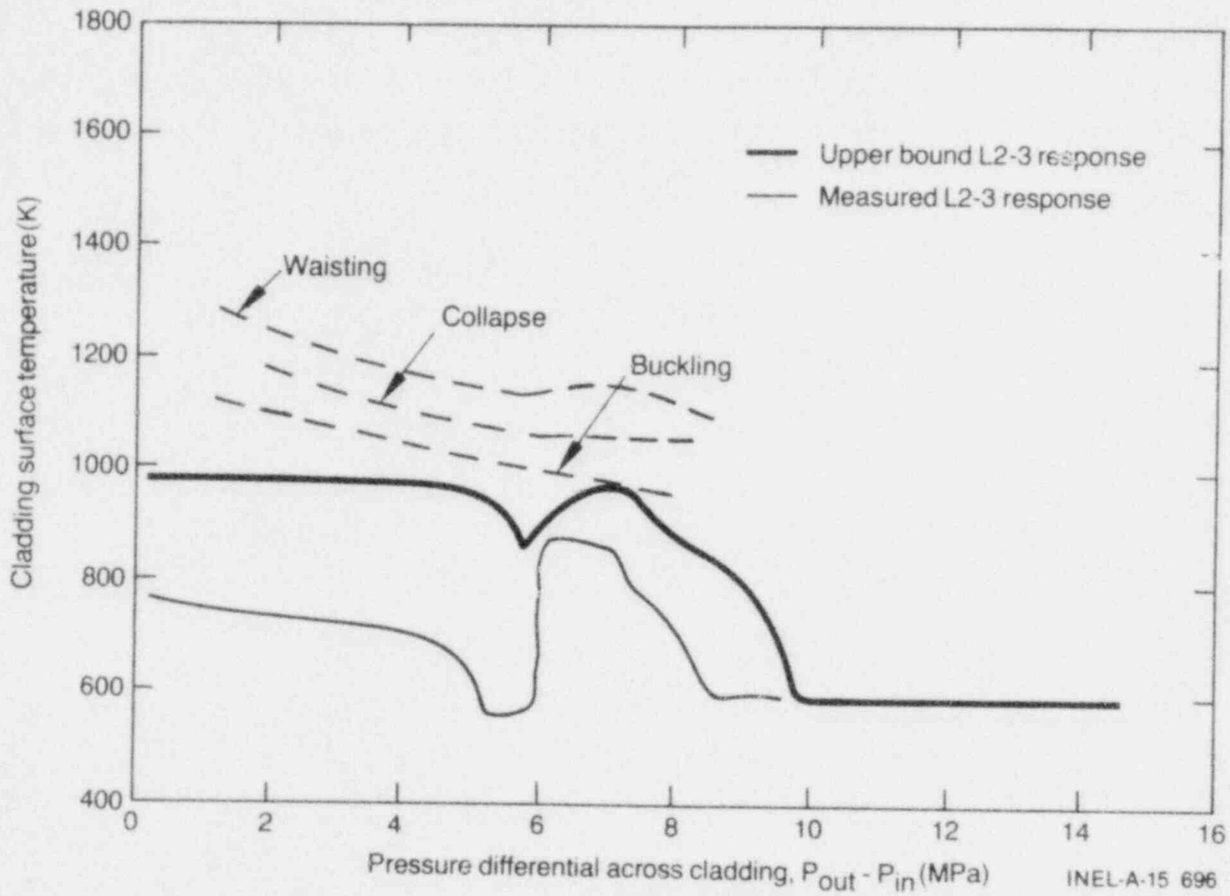

Figure 50. LOFT Cladding Deformation Expected for Upper Bound Fuel Rod Responses during L2-3

Resolution of the true cladding temperature response is likely to require replication of either, or both, the L2-2 and L2-3 tests with instruments specifically designed to measure the cladding temperature during rapid cooling transients. Methods of improving the cladding temperature measurements have been developed over the past several years in support of the LOFT and PBF programs and for other NRC supported research programs. It is within the present technological capability to improve the cladding temperature measurement. Recommendations are presented in the next section for (1) additional analysis tasks and separate effect experiments to evaluate the thermocouple perturbation effects during the LOFT tests, and (2) improvements in the LOFT fuel rod response measurements.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1. LOFT Cladding Temperature Response.

   a. The measured LOFT cladding temperature response during L2-2 and L2-3 was consistant and correlates with the measured hydraulic response.

   b. The measured early cladding quench was a result of a rapid propagation (150-200 cm/s) of low density coolant through the core.

   c. Measured peak cladding temperatures occurred during the first six seconds of the test.

   d. Final core reflood (from ECCS) occurred in less than 15 seconds.

2. Estimated Effects of LOFT Surface Thermocouples on LOFT Fuel Rod Response.

   a. LOFT surface thermocouples affect time-to-DNB by less than 0.5 seconds.

   b. LOFT, surface thermocouples do not significantly affect rod thermal response during film boiling conditions.

   c. LOFT surface thermocouples can significantly affect rod thermal response during two-phase cooling.

d. The effects of LOFT surface thermocouples on the L2-3 peak cladding temperature are estimated to be (1) a reduction in cladding temperature just prior to the measured blowdown quench of 60 K, (2) a reduction in cladding temperature just prior to core reflood by 175 K, and (3) a premature reflooding quench by as much as 25 seconds.

7.2 Recommendations for Reducing the Uncertainty in the LOFT Fuel Rod Response

The previous sections discuss the measured cladding temperature during the LOFT tests and the estimated fuel rod response based on these measurements. Separate effect tests have provided a basis to quantify the possible cooling effects of the surface thermocouples during the L2-2 and L2-3 tests and corrections to the measured LOFT data were made to estimate an upper bound for the L2-3 peak cladding temperature. To resolve the difference between the measured (lower bound) and corrected (upper bound) temperatures will require (1) additional analysis work to better quantify the effects of the surface thermocouples during the LOFT tests, and (2) additional experiments in the PBF and LTSF to better quantify the perturbation effects of the LOFT surface thermocouples, and (3) additional LOFT tests with improved fuel rod measurements. Recommendations in each of these areas is discussed below.

7.2.1 Analysis Tasks to Estimate LOFT Thermocouple Perturbation Effects.

Resolution of potential thermocouple perturbation effects can be estimated from analysis of the separate effect tests utilizing most recent thermal-hydraulic computer codes. In addition, these analysis will provide a basis to evaluate current heat transfer models.

The LTSF Quench test provides a simple geometry, well quantified inlet coolant conditions to the test section, and accurate cladding temperature measurement, all of which are necessary for code evaluation. The recommended sequence of analysis tasks is shown schematically in

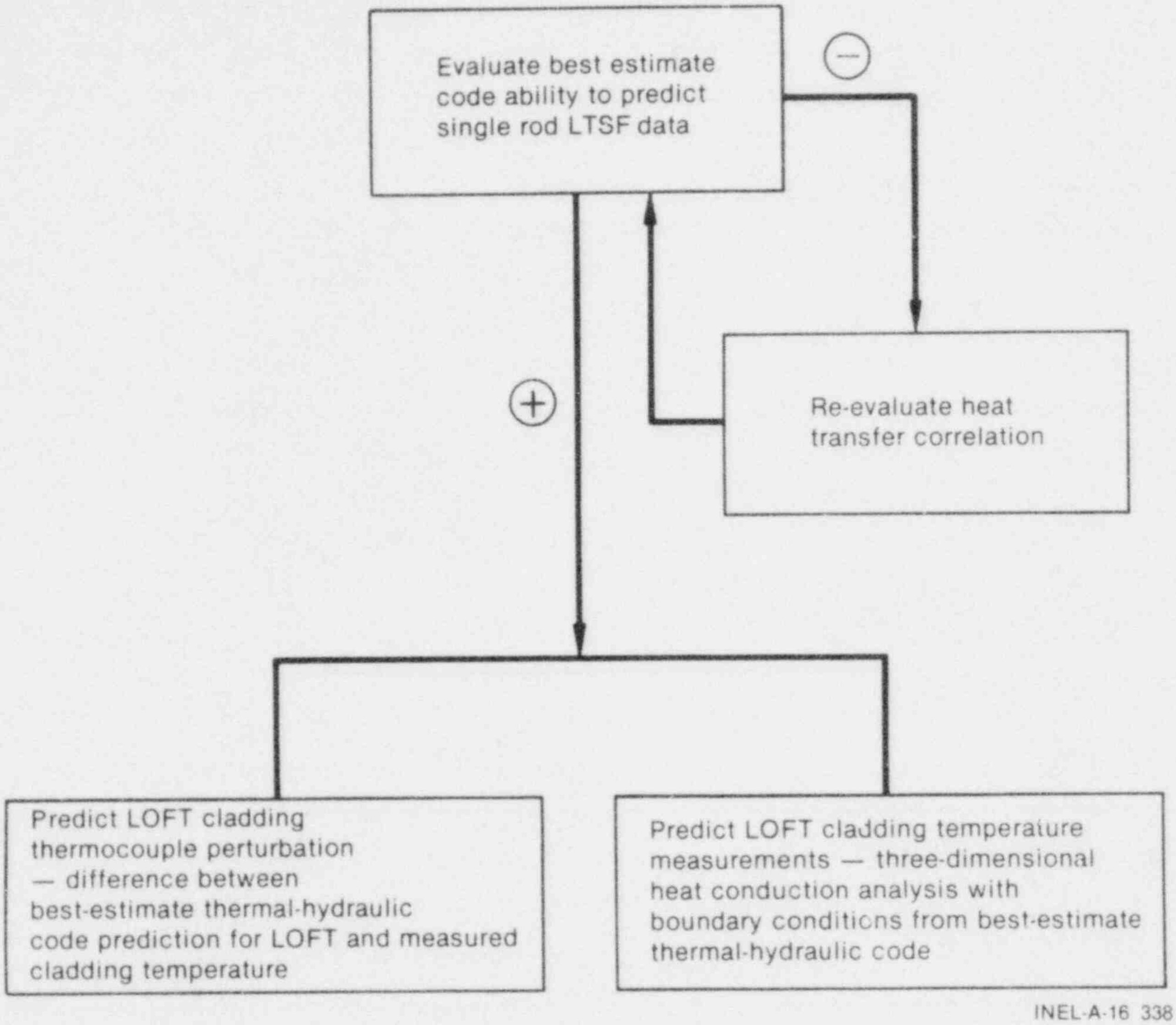

Figure 51. Analysis Tasks to Estimate LOFT Thermocouple Perturbation Effects and Best-Estimate Heat Transfer Model Capability.

Figure 51. The first step of the analysis will require assessment of current heat transfer models to assure the codes can predict the cladding temperature response (with no surface thermocouples). After assurance that the best-estimate thermal-hydraulic code is capable of predicting the LTSF data, the code can be utilized to predict the cladding temperature response for the LOFT tests. Differences in the LOFT cladding temperature response between the best-estimate calculation and the measured temperature is due to either the thermocouple perturbation effects and/or code inadequacy to predict the LOFT core hydraulics and/or heat transfer. To further quantify the thermocouple perturbation effects, three-dimensional heat conduction calculations on the LOFT fuel rod can be performed using the hydraulic boundary conditions from the previous best-estimate LOFT prediction and modeling the heat transfer from both the fuel rod and the surface thermocouple using the best-estimate heat transfer models. This latter approach would require a versatile three-dimensional heat conduction code with provisions for specifying the hydraulic boundary conditions through user specified subroutines. It is not presently clear that the 3-D codes exist with these capabilities; it is recommended that availability of 3-D codes be evaluated for this application.

7.2.2 Additional Separate Effects Tests.

As shown in Figure 47, considerable uncertainty exists in the high pressure quenching response of the nuclear rods during the blowdown phase of the LOFT tests. The LTSF quench data utilizing stainless steel clad heater rods are the only data characterizing the rapid quenching behavior and may not be directly applicable to the LOFT nuclear rods because of the cladding material and the lack of a simulated fuel-cladding gap, both of which would tend to make the semiscale heater rod more difficult to quench. Thus, additional data, perferably on nuclear rods is required to reduce the uncertainty in the cooldown and quench characteristics of LOFT fuel rods.

PBF quench tests (TC-3 test series) on LOFT type (unpressurized, PWR) nuclear rods are planned during the later part of 1980, in which the response of rods instrumented with and without surface thermocouples will be compared. These tests will provide needed quench data on zircaloy clad nuclear rods and will allow assessment of surface thermocouple effects under quench conditions similar to those experienced in the LOFT tests.

Additional tests in the LTSF are also planned on a bundle of zircaloy clad heater rods with a simulate fuel-cladding gap as shown in Figure 52. These tests are scheduled in the first quarter of 1981 and will provide additional data for evaluating heat transfer characteristics during rapid cladding cooling. Together with the PBF results, these tests will provide a basis for reducing the uncertainty in the peak cladding temperature response during the LOFT tests. The data from these tests will also provide an expanded baseline for assessment of heat transfer models as discussed in the previous section.

7.2.3 Additional LOFT Tests with Improved Fuel Rod Instrumentation.

The LOFT tests have shown the importance of fuel rod heat transfer particularly during the blowdown phase of a LOCA, which was not well predicted prior to the tests. Uncertainty exists in the measured cladding temperature which precludes an accurate quantification of the heat transfer during the tests.

The analysis work and separate effects tests as discussed in the previous two sections will allow the uncertainty in the LOFT cladding temperatures to be quantified with less uncertainty than represented in Figure 47, however, questions regarding the typicality of the separate effects tests in representing the LOFT thermal-hydraulic response will result in uncertainty in regard to complete understanding of the LOFT fuel rod response based on the separate effort tests.

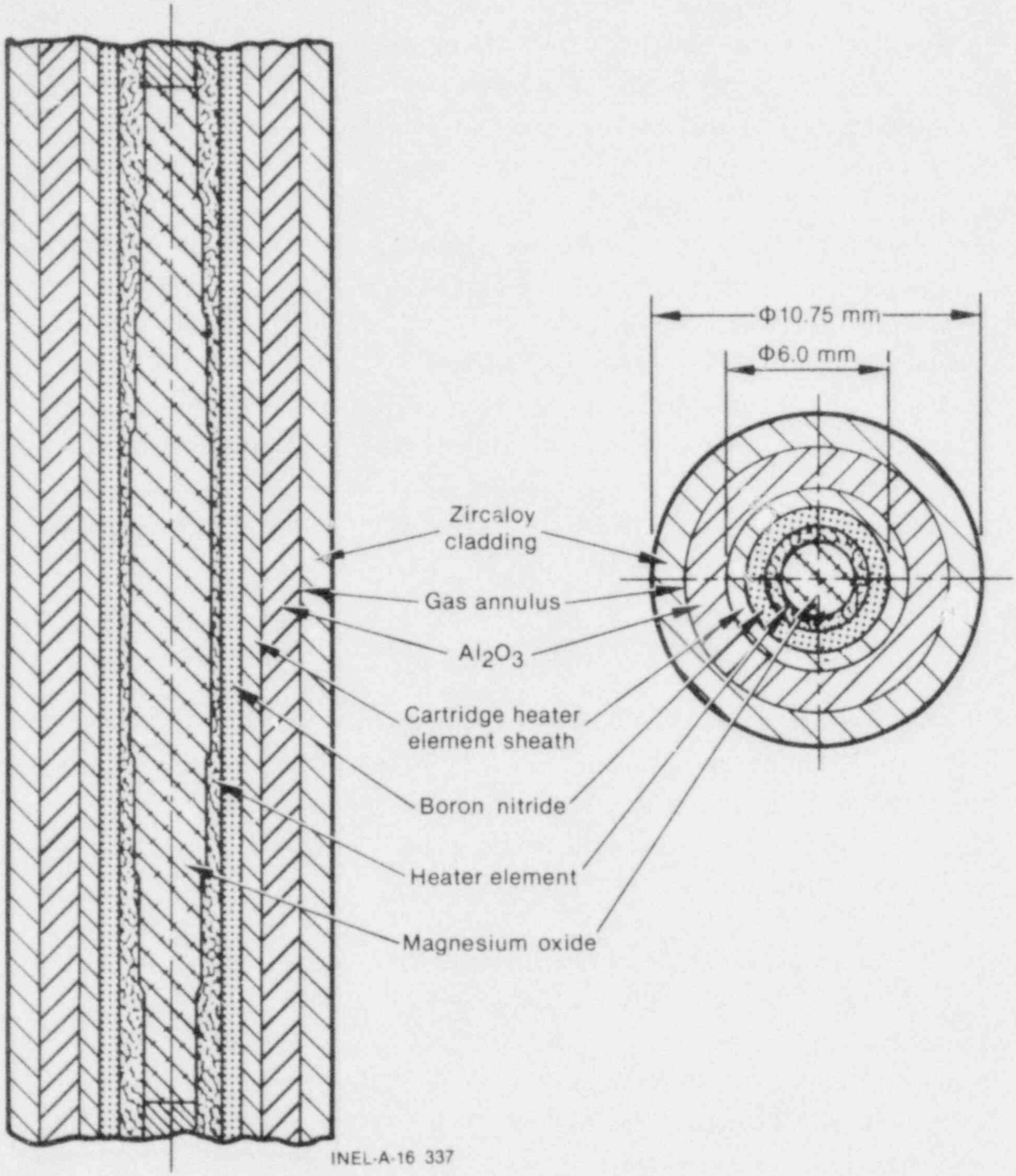

Figure 52. Schematic of German REBEKA Heater Rod To Be Used For The LTSF 9-Rod Bundle Quench Tests.

To provide unquestionable data concerning the importance of heat transfer during a LOCA will require additional large break LOCEs in LOFT with improved fuel rod instrumentation. It is recommended that for future large break testing in LOFT, fuel modules be utilized with improved instrumentation including, UO_2 fuel pellet temperature measurements, axial cladding elongation measurements, and interior, embedded cladding thermocouples. Each of these measurement areas is discussed below.

7.2.3.1 Fuel Pellet Thermocouples. The PBF tests have shown that a rapid cladding quench can be inferred from the UO_2 pellet temperature response. The centerline temperature is less responsive to cladding quenches than fuel measurements near the periphery of the fuel pellet. Thus, it is recommended that peripheral fue' pellet thermocouples be utilized in future LOFT tests.

Current peripheral pellet thermocouples to be utilized in future LOFT fuel rods are 0.51 mm OD and are placed in 0.71 mm diameter holes in the fuel pellet similar to the installation utilized in the PBF TC-1 test series (See Section 5.4). Thus, a significant thermocouple-pellet gap can exist and exact location of the thermocouple in a region of steep temperature gradient limits the absolute pellet temperature measurement accuracy to several hundred degrees K. The peripheral thermocouples installed in this manner are largely to determine if, and when, a cladding temperature quench occurs, and not necessarily as an indicator of absolute pellet temperatures. Improvements in the measurement accuracy of the peripheral thermocouples may be possible by decreasing the pellet-thermocouple gap and utilizing thermocouples capable of measuring higher temperatures. Sensitivity calculations are recommended to determine if improvements in measurement accuracy are warranted, particularly if more accurate cladding temperatures are possible as discussed in Section 7.2.3.3.

The centerline fuel temperature measurements, although not as responsive to changes in surface heat transfer as the peripheral fuel thermocouples are important to charaterize the initial fuel stored energy which must be known for assessment of fuel behavior codes and heat transfer during the transient. Several centerline thermocouple designs are in use, differing mainly in the properties of the insulation and sheath materials. The LOFT centerline thermocouples utilize a hafniam insulator and a rhenium sheath as shown in Figure 53. Physics calculations to evaluate the effect of the hafnium on fuel rod power production show that the rod power is decreased by approximately ten percent and the radial fission profile is significantly altered near the centerline hole. FRAP-T5 calculations which model these effects indicate a reduction in the measured temperature by as much as 200-300 K, as shown in Figure 54. It is recommended that additional studies be carried out to further evaluate the perturbation effects of the centerline thermocouples and to develop methods for estimating unperturbed pellet temperatures based on the measurement data.

7.2.3.2 Cladding Elongation Measurements. The fuel behavior experiments in the PBF program have shown the usefulness of the cladding elongation measurements in determining large, rapid cladding temperature changes. The measurements have been one of the most sensitive in determining CHF during the power-coolant-mismatch tests (high power, film boiling) and are indicative of initial rod CHF during the LOCA tests.

The cladding elongation measurements are made utilizing linear variable differential transformers, LVDTs. LVDTs are inductance coil devices consisting of a primary and two secondary windings. An alternating current is supplied to the primary, which induces a voltage in each secondary coil. The relative voltage induced in each is proportional to the location of a movable ferromagnetic core that is attached to the fuel rod. Differences in the voltage between the secondary coils provide the output signal, which is calibrated to give total cladding elongation.

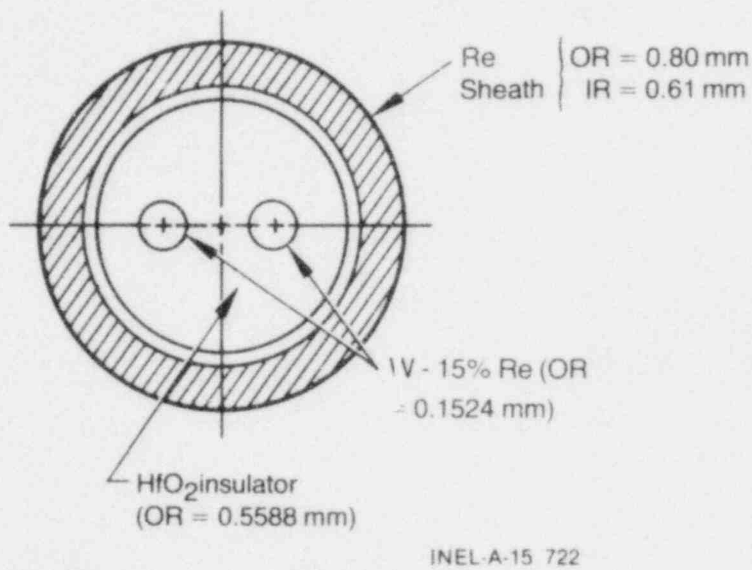

Figure 53. LOFT Fuel Pellet Centerline Thermocouple

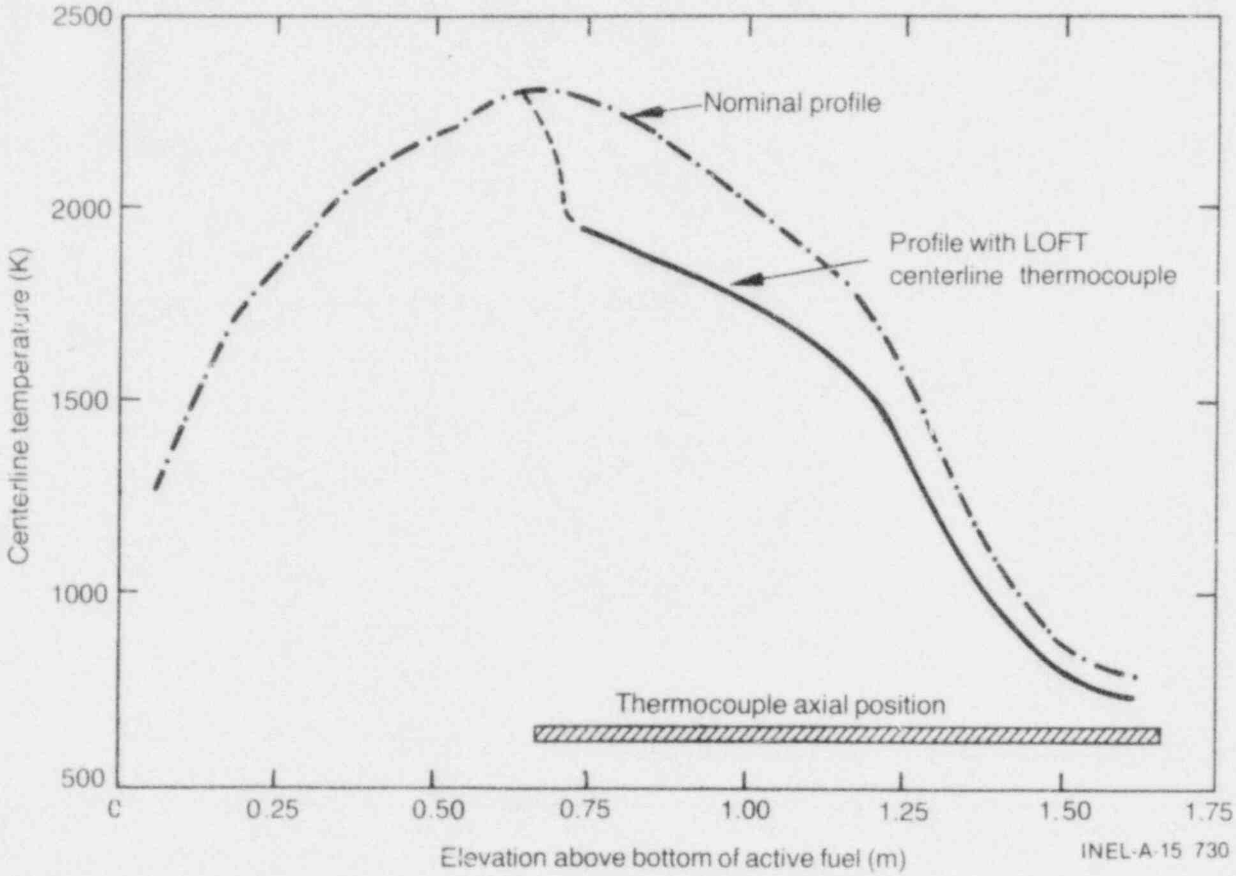

Figure 54. Estimates of Perturbation Effect on Centerline Fuel Pellet Temperature using LOFT Centerline Thermocouple

Several of these instruments will be utilized for future LOFT fuel bundles such that rods with and without surface thermocouples are instrumented with LVDTs and will allow assessment of the effects of cladding surface thermocouples, particularly regarding initial DNB and rapid rod quenches.

7.2.3.3 Cladding Thermocouples. Cladding temperature measurements can be improved significantly by utilizing small embedded thermocouples. Separate effect tests have successfully utilized small, 0.40-0.43 mm, embedded thermocouples in the outside surface of zircaloy and stainless steel clad heater rods. Also, successful nuclear fuel rod experiments have been performed in the PBF under steady state and LOCA conditions utilizing internal rod thermocouples in which the measurements leads were routed through slotted regions of the fuel pellets. Based on this experience, it is proposed that LOFT cladding temperatures be measured with small thermocouples embedded on the inside of the cladding surface as shown in Figure 55. The leads of such thermocouples could be routed through the fuel pellet as shown in the Figure. Recent developmental work at EG&G, Idaho shows that zircaloy thermocouples as small as 0.25 mm OD can be successfully embedded on the inside surface of typical zircaloy cladding segments, as shown in Figure 56. If these segments can be welded into the cladding with no serious mechanical limitations, it is recommended that these thermocouples be developed for use in future LOFT fuel assemblies, since utilization of these thermocouples will have little or no perturbation effect on the rod thermal or mechanical response in the region of the cladding measurement and will provide accurate cladding temperature data.

Another possible method of measuring cladding temperature which has been suggested is by use of thin film thermocouples. Possible utilization of those thermocouples has been reviewed and for multiple high temperature LOCE transients thin film thermocouples are limited due to:

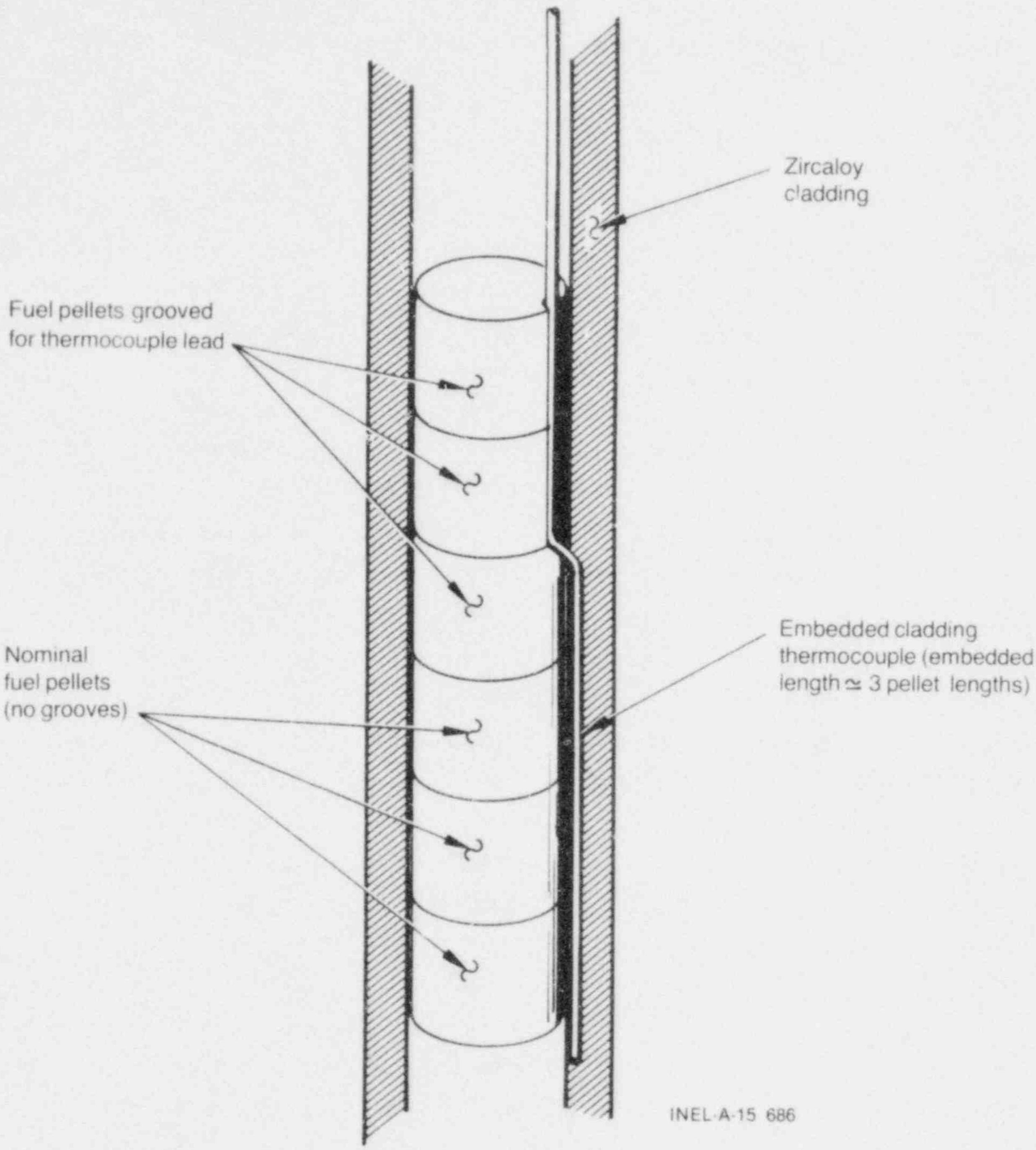

Figure 55. Proposed Geometry of LOFT Internal, Embedded Cladding Thermocouple

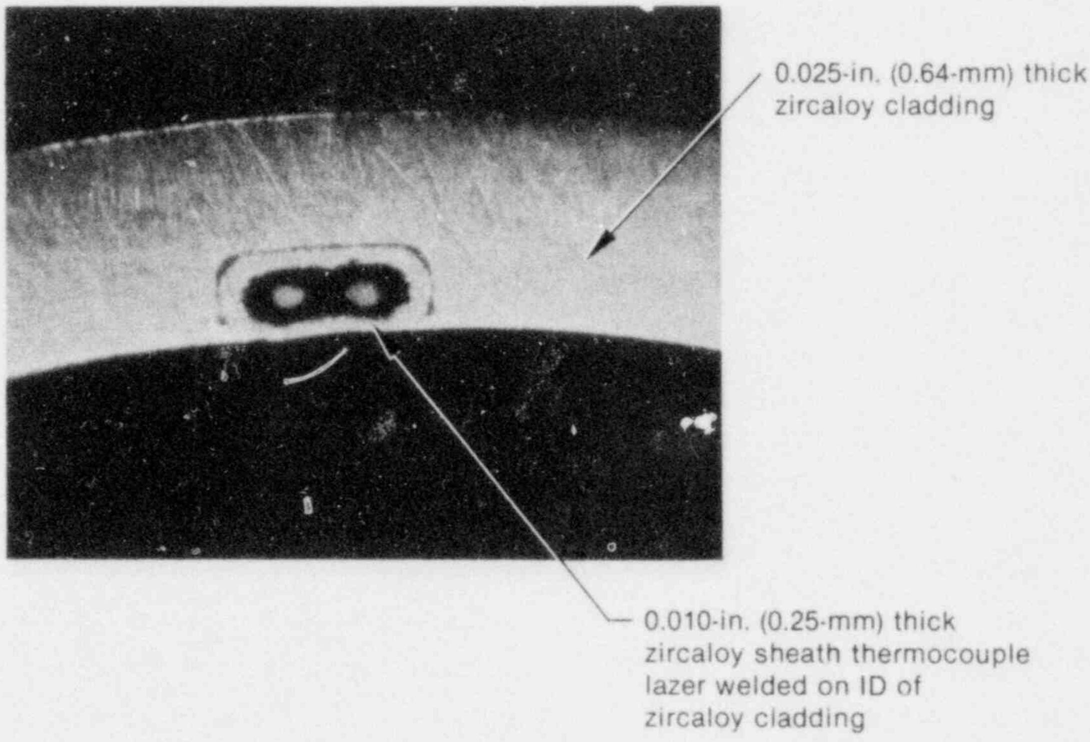

Figure 56. Cross Sectional View of 0.25 mm Thick Embedded Thermocouple Proposed For LOFT Fuel Rods.

1. Large, rapid variations in the system pressures and temperature may adversely affect the mechanical stability of the thermocouple

2. Water steam oxidation would degrade thermocouple response for multiple LOCE tests

3. Crud deposition may affect instrument sensitivity

4. Radiation environment may affect instrument calibration.

Because of these limitations, and the current success in embedding small thermocouples in zircaloy cladding, it is not recommended to undertake a large developmental program for utilizing thin film thermocouples at this time. Appendix A presents a review summary relating to thin film applications in the nuclear industry.

7.2.3.4 Cladding Temperature via Microwave Techniques. Recent scoping studies completed at EG&G, Idaho suggest that cladding temperatures may be measured using microwave radiometry methods. Appendix B summarizes the initial scoping study to evaluate this method.

To measure cladding temperatures via measurements of the radiated energy intensity requires three basic elements; an antenna, a receiver, and a data aquisition system. For a cladding temperature application, the antenna would be comprised of three components: a reflector lens, a horn, and a waveguide as shown in Figure 57. The function of the reflector lens is to focus the incident thermal radiation of interest and reflect it into the horn which is designed to intercept radiation of the desired wavelength and initiate propogation of the desired wavelength up the wave guide to be processed by the receiver.

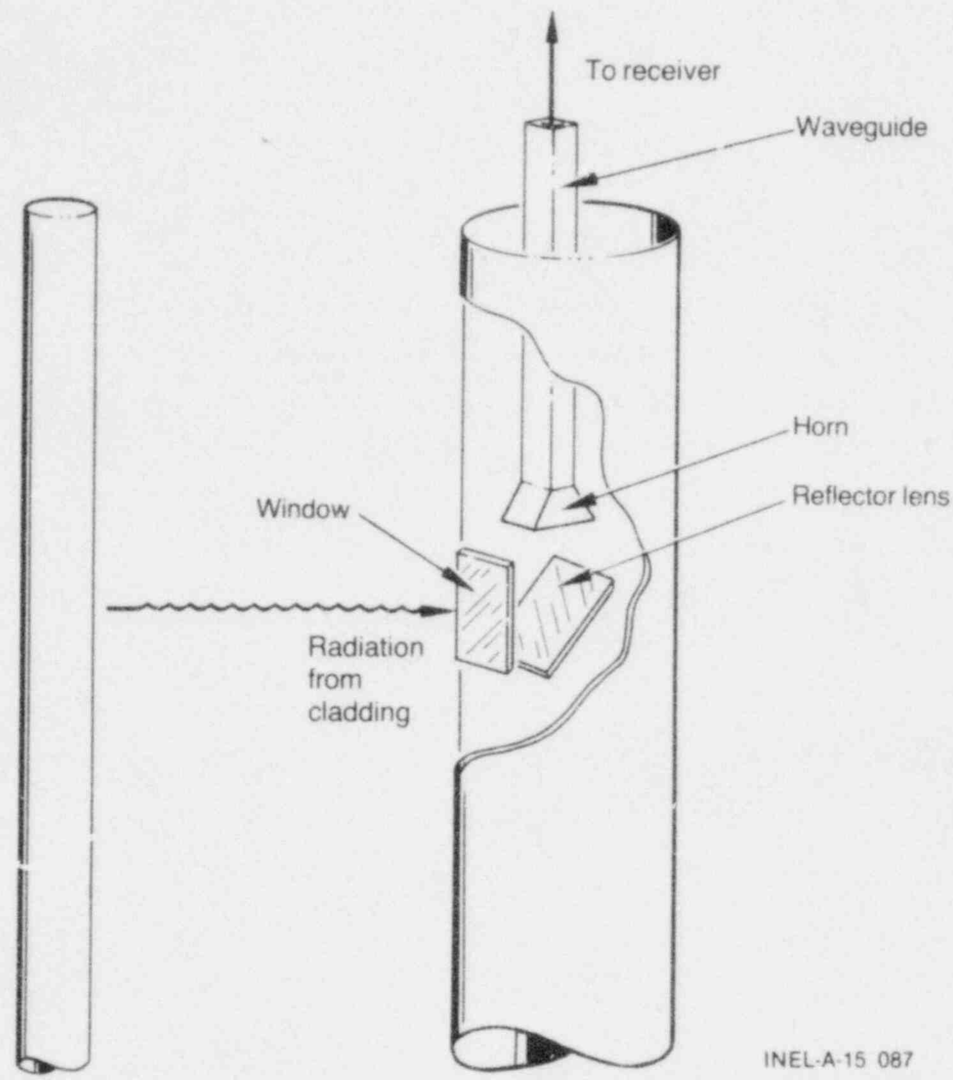

Figure 57. Conceptual Components Required for Cladding Temperature Measurement by Radiometry Techniques

The energy transmitted to the measuring system would originate from the cladding and any high temperature material between the cladding and the radiation detector, i.e., the system coolant. In addition, the medium between the cladding and the detector would attenuate the energy emitted from the cladding. However, for radiation in the radio wavelengths, ~1 mm (300 GHz) water is a poor absorber, so that the attenuating influence of the coolant would be negligible.

The advantage of this technique is that no direct perturbation of the fuel rod is necessary. However, the method is only at the conceptual level, and more development work is necessary. Application of the method would be conceivable for a large commercial nuclear core however, since the system may be made completely passive in the core region. Development of the method would be beneficial to both LOFT and the nuclear industry. The LOFT facility would be an ideal facility to test such a measurement system. It is recommended that developmental work be continued to evaluate hardware for proof testing in LOFT.

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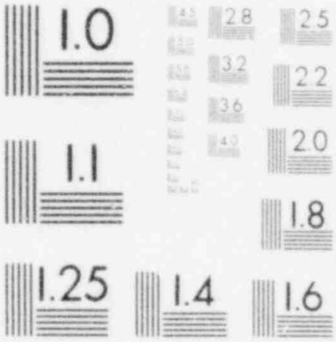
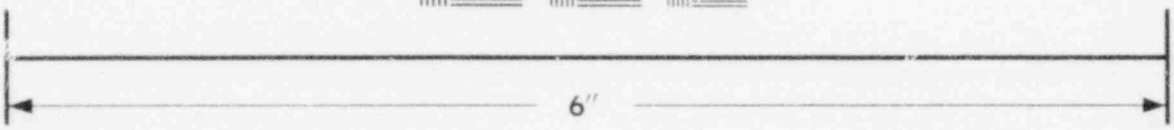
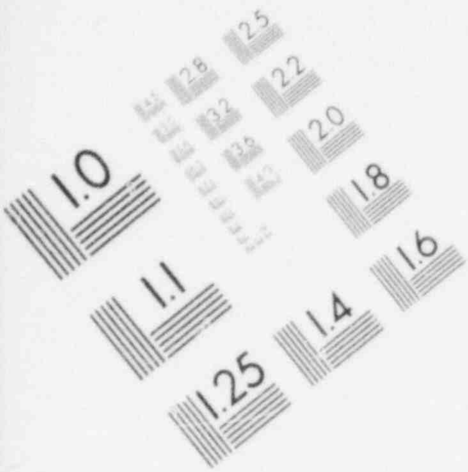
IMAGE EVALUATION
TEST TARGET (MT-3)







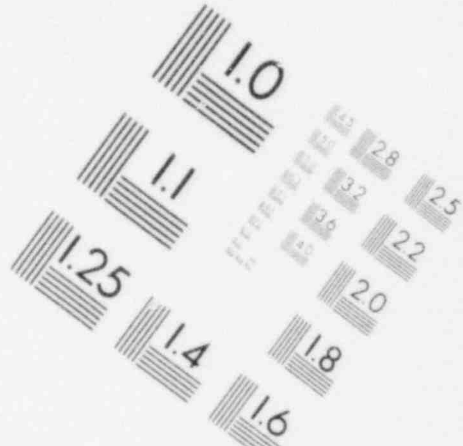
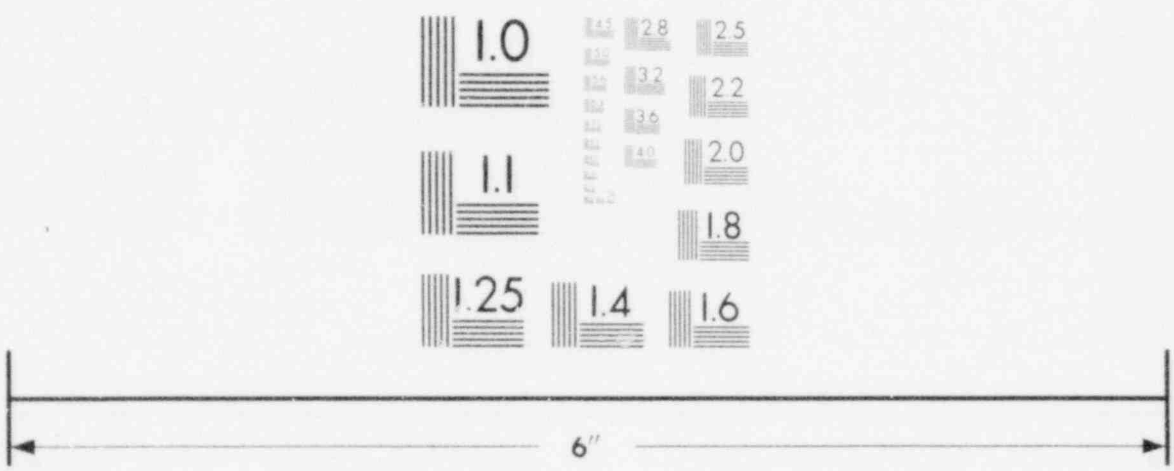
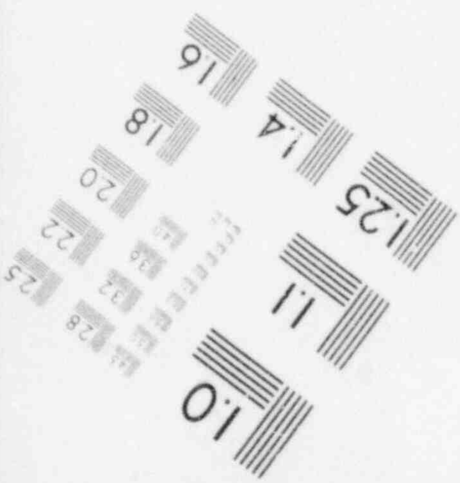
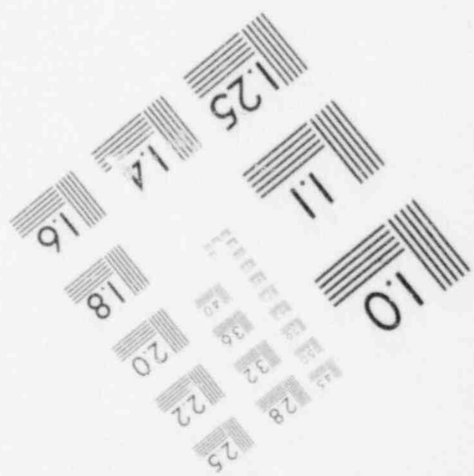


IMAGE EVALUATION
TEST TARGET (MT-3)







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APPENDIX A

REVIEW OF THIN FILM THERMOCOUPLE APPLICATIONS IN THE NUCLEAR INDUSTRY

By:

M. L. Carboneau

INTRODUCTION

A thin film thermocouple (TFTC) is a special type of thermocouple having a relatively large response area and and a very small thickness (typical film thicknesses usually vary from 0.1 to 1 μm).[a] A schematic of a TFTC is shown in Figure A1. Fabrication of TFTCs is accomplished by vacuum deposition of metal films on a substrate material (usually quartz) which acts as an electrical insulator and base for the thermocouple[A1,A2].

The small size, low mass, and negligible thermal capacity of thin film thermocouples allows for the accurate measurement of rapidly fluctuating temperatures[b] and practically eliminates any perturbation effects caused by surface geometry changes.

Current Thermal Applications of TFTCs

Typical applications of TFTCs include temperature measurements of aerodynamic surfaces and blade temperatures in gas turbines.[A3,A4] In each case, since the surface topograph can be significantly affected by macroscopic protuberances (e.g. standard sheathed TCs), thin film thermocouples offer the only viable means of determining these surface temperatures. In the case of gas turbine blade temperature applications, experience has shown that TFTCs can be fabricated to withstand temperatures exceeding 1300 K and survive the centrifugal force and vibrations associated with the turbine blade spinning at nearly 20 thousand revolutions per minute.

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a. The total thickness of a completed TFTC (including the substrate) can be as small as 50 μm, or even smaller, but practical dimensions for reactor applications may be substantially larger.

b. Response times are of the order of milliseconds.

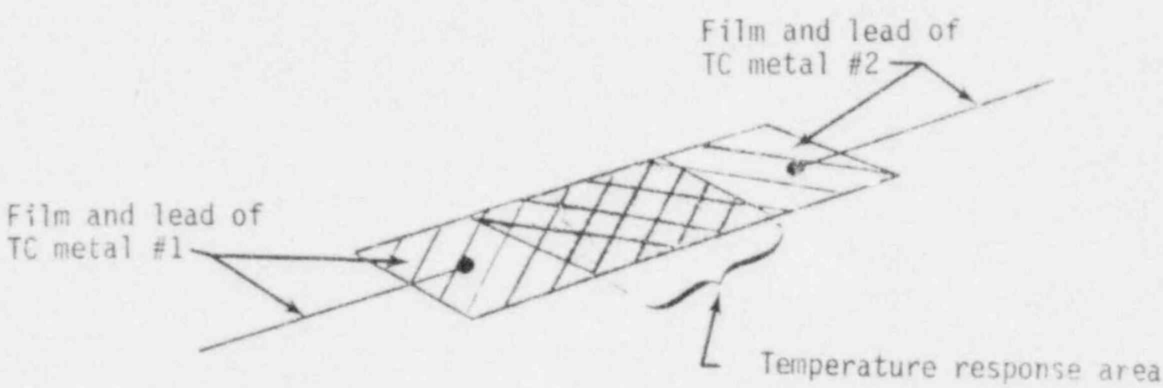

Figure A1. Schematic of Thin Film Thermocouples

Several film thermoelectrode metals and metal alloys have been used for various applications. Table A-1 below presents a short list of a few TFTC design parameters and the corresponding measurement applications.

TABLE A-1. Some Current Applications of TFTCs

Film Metal	Substrate(s)	Application	Temperature Range (K)	Ref.
Cu/Ni	Glass/Plastic	Surface Temp. of Aerodynamic Models	300 - 360	3
Platinum*	High Temp. Enamels	Gas Turbine Blade Temp.	1273 - 1373	4
Ni/Mo	SiO	Plasma Heat Flux Detector		5
Chromel/Alumel	Al_2O_3/glass	Fission Detector	673 - 773	6,7

* The second thermoelectrode of the TC is the turbine blade.

In addition to the film metals and substrates listed in Table A-1, many other TFTC materials have been studied in various other applications. Aside from the metals listed above, other film metals that have been studied include: Sb-Bi, Au-Ni, Cu-Fe, Bi-Ag, and several metal alloys. While most TFTC applications have used quartz as a substrate material, many other materials have been considered for high temperature applications. These include: Al_2O_3, SiO, MgO, NiO, BeO, and the high temperature enamels EVK-14 and EZh-1000. Also, a great deal of work has been concentrated on using glass as a substrate material.

Generally, film thermocouples utilizing the deposition of metal alloys are more difficult to make because the compound materials tend to fractionate on evporation and produce unpredictable thermal EMFs, however, much work already exists in this area and TFTCs utilizing film alloys should not present an insurmountable obstacle in the development of such thermocouples for nuclear reactor applications[A2]. In fact, as we shall see, more serious problems will need to be resolved before a TFTC can be reliably used in LOFT to measure fuel rod cladding temperatures. Nevertheless, there does exist an interesting TFTC design that has been used in a nuclear reactor to measure neutron and gamma radiation fields, and we shall consider this as a possible application for LOFT.

Factors Influencing the EMF of TFTCs

There are several factors that must be considered in the design of any TFTC. Perhaps one of the most important parameters is the thermal EMF or power output of the thermocouple. The thermal electric output of any thermocouple is affected by several design and environmental factors; however, film thermocouples are generally more sensitive to such changes than bulk or standard sheathed thermocouples. Among the several items that can influence the EMF of a TFTC are: (a) film thickness, (b) film structure and metals, (c) internal stresses and thermal shock, (d) radiation, and (e) oxidation effects.

Unlike macroscopic (or bulk) thermocouples, the thermoelectric output of a TFTC can be affected by the relative thickness of the two thermocouple metals, and for films thinner than 100 A, TFTC EMFs can be sensitive to the material of the substrate. In addition, temperature gradients across the sensitive junction of the TFTC can also affect the Seebeck coefficient and subsequently the thermocouple EMF output in unpredictable ways. All of these factors must be carefully considered in the design of any thin film TC, and perhaps more so for nuclear reactor TFTC applications.

LOFT Temperature Applications and Recommendations

Since it appears that cladding surface thermocouples can adversely influence the behavior of an instrumented fuel rod, and perhaps even nearby uninstrumented rods, an alternative cladding temperature instrument that would mnimize surface perturbation effects would be advantageous. The fact that TFTCs can be constructed to withstand some rather severe conditions is encouraging when one considers the possibility of adopting this technology for nuclear reactor applications. Unfortunately, it appears that the conditions surrounding a nuclear fuel rod (especially in LOFT during a loss-of-coolant experiment (LOCE)) would likely surpass the structural capabilities of presently available TFTC designs. This results because of a combination of several adverse conditions that are unique to nuclear reactors and in particular to a test facility like LOFT. For instance, factors that could influence the performance of TFTCs in LOFT include: (a) large and sudden variations in temperature and pressure, (b) transient thermal stresses, (c) water-steam corrosion problems, (d) cladding-thermocouple material incompatibilities (i.e., eutectic formation), (e) crud deposition, (f) cladding oxidation, and (g) the unavoidable thermocouple composition changes that would result from neutron irradiation, subsequently affecting the TFTC EMF.

The above factors represent formidable difficulties in the design of a TFTC that would reside on the surface of a nuclear fuel rod. To alleviate some of the problems encountered with fuel rod surface locations of TFTCs, alternative sitings could be considered. For example, because of the small size of TFTCs, it might be feasible to locate the thermocouples on the inside cladding surface of a fuel rod or perhaps at the fuel pellet surface. At these locations, external cladding phenomena would not affect the response of the thermocouple; however, other mechanical effects might adversely interfere with the thermocouple. For instance, pellet-clad mechanical interactions may interfere with, or even destroy, a fragile TFTC.

Since a cursory review of the literature has not identified any previous applications of TFTCs to measure nuclear fuel rod temperatures, it is not known at this time if currently available designs could be expected to adequately measure LOFT fuel rod cladding temperatures during one, and necessarily several, blowdown experiments. This does not preclude the possibility of researching a new design that could survive LOFT reactor conditions during a LOCE; however, the required design effort could become expensively prohibitive. Therefore, before a commitment is made on developing a LOFT fuel rod TFTC, other thermocouple design possibilities (e.g. ultra thin sheathed and embedded TCs) uld first be considered. In the event that it is deemed advisable to proceed with a study directed at the utilization of TFTCs for LOFT fuel rod temperature measurements, the following recommendations are made:

1. A thorough search of the literature should be made to determine:

   a. The present TFTC fabrication technology.

   b. If any past experience exists for measuring nuclear fuel rod temperatures with TFTCs.

   c. Identify likely metal films and substrate materials that would be compatible with LOFT reactor materials (i.e. zircaloy) and endure the thermal-hydraulic and nuclear environmental conditions that would exist during a large break test.

2. Proceed with involving the advanced instrumentation branch of EG&G Idaho in any preliminary and ongoing theoretical and prototype TFTC designs.

Thin Film Fission Thermocouples

Perhaps one of the most interesting and novel applications of TFTCs is the detection and measurement of neutron and gamma radiation. This is accomplished by utilizing a modified TFTC called a thin film fission thermocouple (TFF TC). Much of this work has been done at Sandia Laboratories.[A6,A7] These detectors have been used to monitor the power densities in large commercial reactors and the neutron flux spectra in pulsed reactors. In addition to providing high temperature fast response micro-miniature radiation detection, TTF thermocouples are being studied for potential applications as in-core fuel motion monitors.

The TFF detectors fabricated at Sandia avoid some of the construction problems and TFTC fragility that is associated with other designs. This is accomplished by adapting the fabrication techniques of micro-circuit electronics. Figure A2 shows a schematic of a thin film fission TC detector. As fissions occur in the uranium (10% molybdenum) chip, heat is produced and is rapidly conducted (because of the small thickness of the chip) to the underlying thermocouple junction. This heat causes the thermocouple to produce an electrical signal that is subsequently proportional to the number of fissions, and therefore the neutron flux in the uranium chip. This type of self-powered neutron detector (SPND) can be modified by replacing the uranium chip with other fissile materials to vary the detector's neutron energy sensitivity. For instance, by using depleted uranium chips, a detector of fast neutrons can be fabricated. Also, by using non-fissile chips, compensations can be made for gamma heating effects.

Recommendation Concerning TFF TCs for LOFT Applications

Following along the lines of development work accomplished at Sandia, it is believed that TFTCs used as thin film fission thermocouples could be adapted for LOFT radiation measurement applications. For example, by positioning the TFF TCs at locations in the LOFT core so that the thermocouples were not in direct contact with the core fluid (e.g. inside fuel rods or even inside dummy sheathed TCs), data could be obtained on the reactor's neutron flux, and spectral changes during a blowdown experiment. This data might supply an indirect means of measuring local fluid changes and perhaps providing fluid quality information on the core hydraulics during a LOCE. This occurs because water, instead of steam, will attenuate gamma rays and moderate neutron energies. Consequently, specially designed TFF TCs might supply in-core densitometer information.

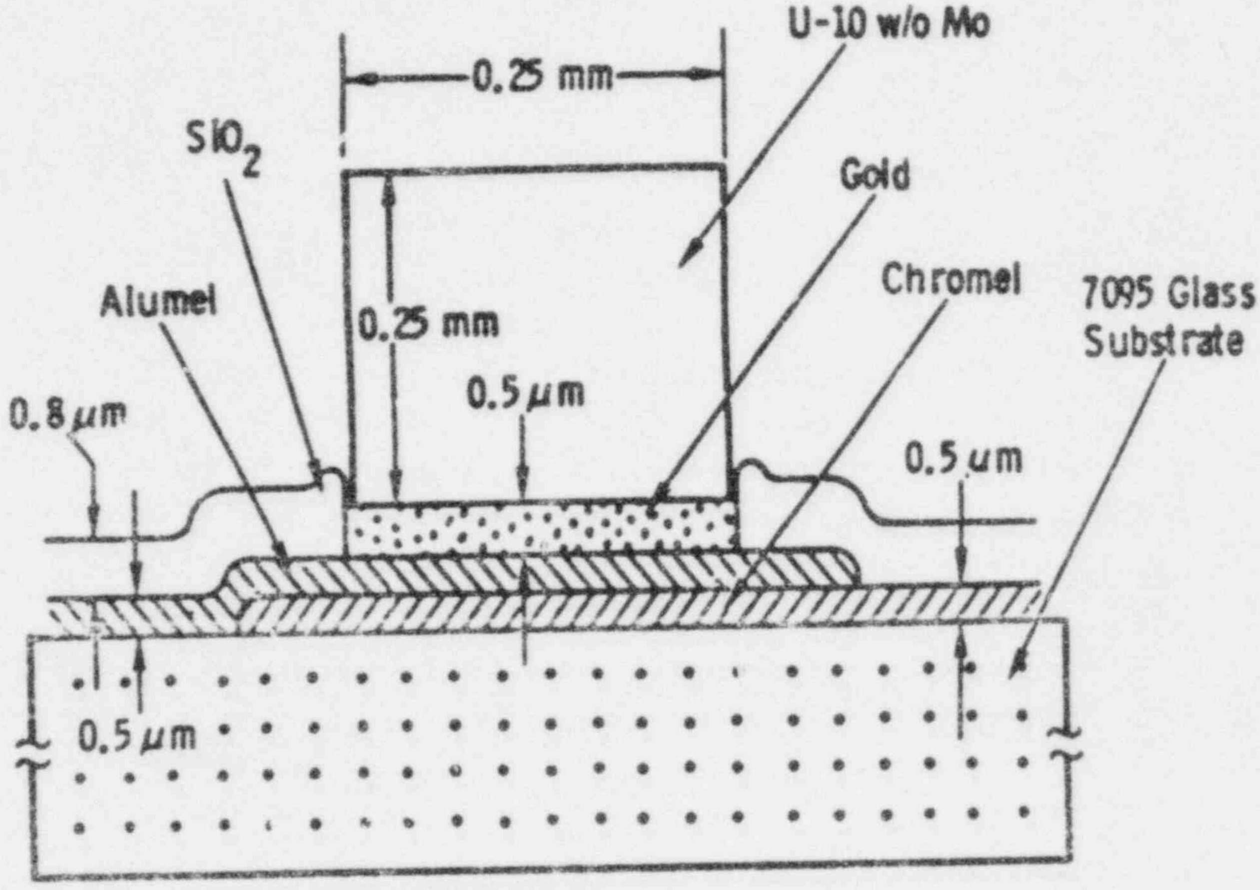

Figure A2. Schematic of a Thin Film Fission Thermocouple

To proceed with the recommendation that LOFT consider using TFF TCs for in-core radiation measurements, it is suggested, that initial conversations with Steve A. Wright at Sandia (8-475-4316) be followed up with a request for detailed fabrication and operational data pertinent to TFF TCs.

Summary

Two recommendatins concerning LOFT utilization of TFTC instrumentation are summarized as follows:

1. Due to the absence of previous experience involving TFTCs for measuring fuel rod cladding temperatures, and since it is felt that documented non-nuclear TFTC performance cannot be extrapolated to reactor environments, LOFT utilization of cladding TFTCs would necessitate an intricate research, development, and testing program. This program would necessarily be protracted and expensive. Since alternative means of measuring fuel rod temperatures are currently being pursued (e.g. ultra thin sheathed TCs, continuous weld surface cladding TCs, embedded TCs, fuel pellet TCs etc.), it does not at present seem advisable for LOFT to follow through with this form of instrumentation. If at some future time it can be demonstrated that TFTCs can be adequately attached to the cladding of fuel rods and subsequently survive multiple LOCEs, and in particular blowdowns, then reconsideration of this option would be warranted.

2. Since much of the research and development work involving TFF TCs has already been done; namely at Sandia Laboratories, adoption and/or extension of this technology for LOFT applications is considered to be feasible and within currently available LOFT resources. Among the possible TFF TC applications that might be of interest include: (a) ultra thin neutron and gamma ray flux detectors, (b) fuel motion monitors, and (c) in-core densitometers.

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APPENDIX B

CONCEPTUAL EVALUATION OF MEASURING IN-CORE CLADDING TEMPERATURE VIA RADIOMETRY TECHNIQUES

By:

R. N. Falotico

It is possible to remotely measure temperatures due to the relationship between an object's temperature and the intensity of the thermal electromagnetic radiation it emits. The intensity of this radiation is given by Planck's law:

$$I = \frac{2hf^3}{c^2(e^{hf/kt}-1)} \text{ watts m}^{-2} \text{ Hz}^{-1} \text{ ster}^{-1} \qquad (1)$$

where

h = Planck's constant = 6.625×10^{-34} JS

f = frequency in Hz

c = velocity of light = 3×10^{8} m/s

k = Boltzmann's constant = 1.38×10^{-23} J/K

T = temperature in K

For the radio region of the EM spectrum, the situation exists where $hf \ll kT$ (for temperatures greater than 5 K and frequencies less than 10^{11} Hz). Under these conditions, Equation (1) reduces to the Rayleigh-Jeans Law:

$$I = 2kT/\lambda^2 \qquad (2)$$

where

λ = wavelength in m

Up to this point, the discussion has dealt with objects perfectly coupled to the electromagnetic field such as an isothermal black body radiator. However, when considering a reactor application it is necessary to consider an extended medium which may be present, for example, the fluid environment between a fuel rod and a guide tube. The intensity of the emerging radiation is related to the temperature distribution of the medium weighted by the radiation coupling coefficient. The Rayleigh-Jeans relationship (Equation 2) can be used to define the brightness temperature, $T_B(f)$, as that temperature which a black body radiator would require in order to equal the given radiation intensity. The brightness temperature of radiation traveling from Z_{max} (the claddng surface) through a medium towards an observation point (tne guide tube) at $Z = 0$ is:

$$T_B(f) = T_{Bo} \exp \left[-\int_0^{Z_{max}} \alpha\ (Z)\ dZ \right] + \int_0^{Z_{max}} T(Z)\ \alpha\ (Z) \exp \left[-\int_0^{Z} \alpha\ (Z) dZ \right] dZ \quad (3)$$

where

T_{Bo} = brightness temperature incident upon the far side of the medium (the brightness temperature of the cladding surface).

$T_{(Z)}$ = Temperature distribution within the medium.

$\alpha_{(Z)}$ = absorption coefficient of medium - m^{-1}

Expressed in words, the brightness temperature, $T_B(f)$, of the emerging radation is equal to the temperature, T_{Bo}, beyond the medium, attenuated by the medium, plus the temperature, $T_{(Z)}$, of the medium, weighted by the absorption coefficient and attenuated by that portion of the medium which lies between Z and the observation point. If the medium absorbs poorly, $T_B(f)$ will equal the brightness temperature of the background, T_{bo}. For wavelengths near 1 mm (300 GHz), water is a poor absorber.

Most microwave radiometer systems are comprised of three basic elements: an antenna, a receiver and a data acquisition system. Manufacturers of such systems include Honeywell and Aerojet Electrosystems among others. The purpose of the antenna is to selectively gather a specific polarization of the incoming radiation from a certain direction. Additionally, the antenna is to provide a match between the medium in which the radiation is propagated and the receiver in order to optimize the energy transferred. The function of the receiver is to translate the energy delivered from the antenna into a useable signal in such a manner as to minimize its own contribution to the signal noise. In order to assure constancy in the gain and offset parameters of the transfer characteristic of the receiver, special techniques such as automatic gain control, input chopping and gain modulation are employed. Unfortunately, these techniques tend to increase the complexity of the receiver but result in enhanced sensitivity. The sensitivity of a microwave radiometer can be expressed as follows:

$$\Delta T_{rms} = R \frac{T_s}{(\beta\gamma)^{1/2}} \tag{4}$$

where

T_{rms} = minimum detectable signal equal to the rms noise level of the radiometer in K.

T_s = radiometer system noise temperature in K.

β = predetection equivalent bandwidth in Hz.

γ = postdetection integration time in sec.

R = radiometer sensitivity constant (usually about 2).

For a receiver at 300 GHz with a system noise temperature of 1000 K, a 1000 MHz bandwidth and an integration time of 0.1 seconds, the senstivity would be:

$$T_{rms} = \frac{2 \times 1000}{(10^9 \times 10^{-1})^{1/2}} = 0.2 \text{ K}$$

However, due to uncertainties in the amounts of radiation reaching the back and side lobes of the antenna, absolute accuracies of 2 to 3 K are the best that should be expected.

In a reactor application, the antenna most likely will be comprised of three components: a reflector-lens, a horn and a waveguide. A tentative design for an antenna located in a guide tube is presented in Figure B1. The purpose of the reflector-lens is to focus the incident thermal radiation of interest and reflect it into the horn. Additionally, this segment of the antenna will serve as a pressure boundary but will have to be designed so that its reflections are equal in magnitude yet 180° out of phase with those of the horn in the desired direction of transmission. This is done in order to minimize the coupling impedance. The function of the horn is to launch the thermal radiation of the desired wavelength into the waveguide where it will be transmitted out of the radiation environment to the receiver. The solution to Maxwell's field equations for the electric and magnetic forces results in two basic types of waves that can be propagated in the wave guide, transverse magnetic (or E waves) and transverse electric (or H waves). The lowest order H wave, H_{10}, is of particular interest since the propagation constant and critical frequency are dependent only upon the dimension a (see Figure B2). The critical wavelength is given by

$$\lambda = 2a$$

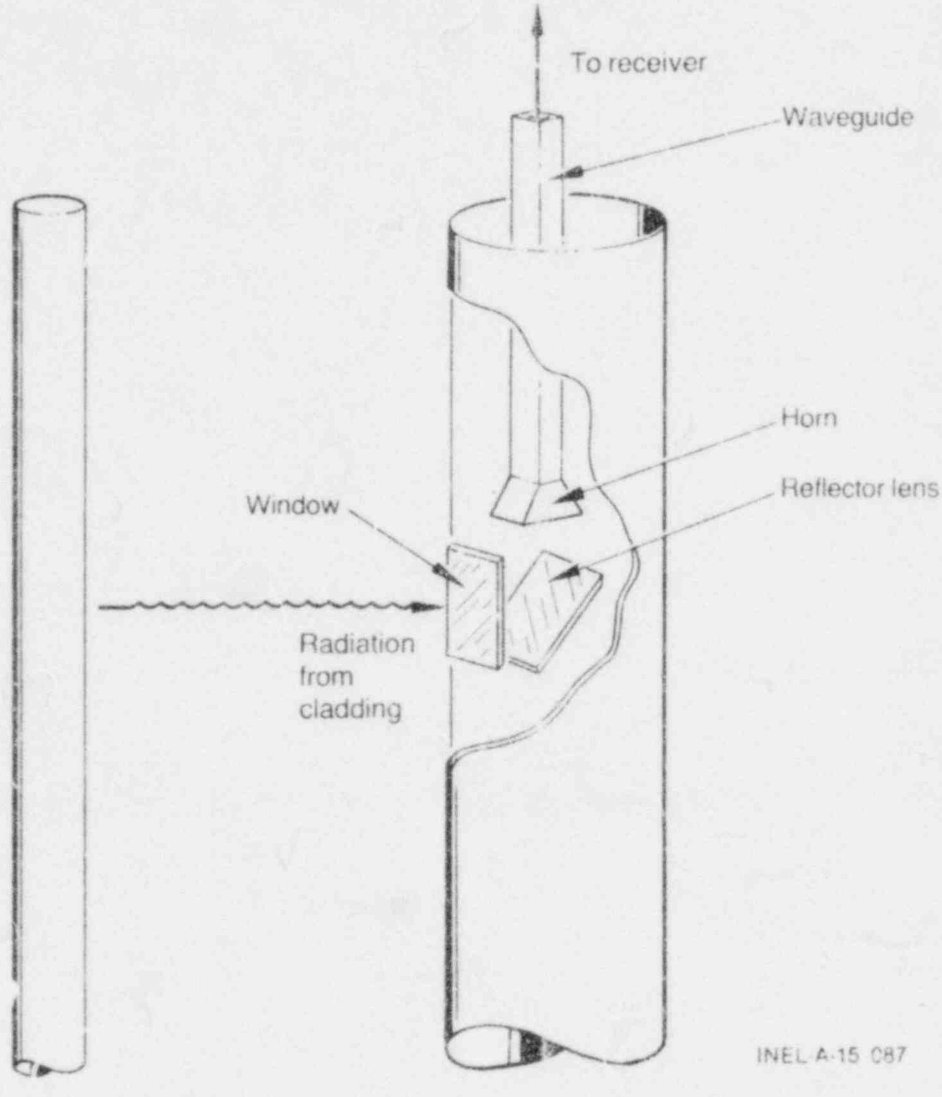

Figure B1. Schematic of Antenna Located in a Central Rod Guide Tube

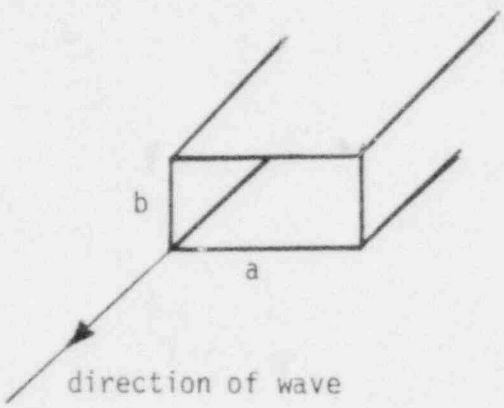

Figure B2. Waveguide Schematic

For λ = 1 mm, a is 0.5 mm. In order to avoid simultaneous propagation of higher modes, the wave guide should be of the approprite dimensions so that only one wave type is transmitted. To achieve propagation of only the H_{10} mode, the following conditions should exist:

$\lambda = 4a/3$ or $a = 3\ /4$