RESULTS OF THE PBF/LOFT LEAD ROD TEST SERIES

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ABSTRACT

The PBF/LOFT Lead Rod (PBF/LLR) Test Series consisted of four sequential, nuclear blowdown experiments (Test LLR-3, LLR-5, LLR-4, and LLR-4A). The primary objective of the test series was to evaluate the extent of mechanical deformation that would be expected to occur to low pressure (0.1 MPa) light water reactor design fuel rods subjected to a series of nuclear blowdown tests, and to determine if subjecting deformed fuel rods to subsequent testing would result in rod failure. The extent of mechanical deformation (buckling, collapse, or waisting of the cladding) was evaluated by comparison of cladding temperature versus system pressure response with out-of-pile experimental data and by posttest visual examinations and cladding diametral measurements. Tests LLR-3, LLR-5, and LLR-4 were performed at system conditions of 595 K coolant inlet temperature, 15.5 MPa system pressure, and 41, 46, and 57 kW/m test rod peak linear powers respectively, at initiation of blowdown. Test LLR-4 was the first test of the series during which observed cladding surface temperatures were sufficiently high (ranged from 1060 to 1170 K) to result in cladding deformation. Test LLR-4A was performed after Test LLR-4 for the purpose of subjecting the deformed rods to subsequent power histories and blowdown conditions. None of the deformed rods failed during Test LLR-4A. The PBF/LOFT Lead Rod Test Series demonstrated that low pressure, light water reactor design fuel rods can withstand multiple blowdown transients at power densities as high as 57 kW/m without failure. This information is directly applicable to the LOFT Power Ascension Test Series[2] and, in general to nuclear reactor safety.

INTRODUCTION

Preliminary results from the PBF/LOFT Lead Rod nuclear blowdown tests are presented. The PBF/LLR test series was conducted by the Thermal Fuels Behavior Program of EG&G Idaho, Inc. in the Power Burst Facility (PBF) reactor at the U. S. Department of Energy's Idaho National Engineering Laboratory (INEL) near Idaho Falls, Idaho, for the U. S. Nuclear Regulatory Commission under funding provided by Japan. The primary objectives of the PBF/LOFT Lead Rod Test Program were: (a) to intentionally subject low pressure (0.1 MPa), light water reactor design fuel rods to conditions resulting in waisting (collapse into pellet-to-pellet gaps) of the cladding, and (b) to evaluate the effects of pellet-cladding interaction (PCI) during subsequent preconditioning power transients with deformed fuel rods. The results of the PBF/LLR tests have direct application to evaluating the extent of fuel rod deformation that would be expected to occur during the LOFT LOCA Power Ascension Test Series, and the consequences of continued operation of the LOFT core with deformed fuel rods. In addition, the experimental data can be used in evaluating computer codes that are used to predict reactor system and fuel rod behavior during LOCA conditions.

Fuel rod cladding deformation that may occur as a result of a rapid system depressurization from a high power condition has been investigated out-of-pile by Olsen[1]. From these studies criteria were developed for evaluating the occurrences of cladding deformation in the form of (a) two-point buckling, (b) uniform circumferential cladding collapse, or (c) waisting, based on the cladding temperature system pressure response during blowdown.

The PBF/LLR Test Series consisted of three tests, designated LLR-3, LLR-5, and LLR-4, that were designed and performed to simulate the behavior of LOFT design fuel rods during the LOFT Power Ascension Test Series Tests L2-3, L2-5, and L2-4, respectively. Each test was performed with four, identical, separately shrouded LOFT design fuel rods. Test conditions for Tests LLR-3, LLR-5, and LLR-4 were approximately 595 K inlet coolant temperature, 15.5 MPa system pressure, and 41 kW/m, 46 kW/m and 57 kW/m peak linear power, respectively, in the test rods. Test conduct included several hours steady state operation at various power levels to precondition the fuel, at least two hours steady state operation at the desired test power level to build up approximately 80% of the maximum possible decay heat in the test rods, followed by system blowdown and subsequent reactor scram. During the preconditioning phase, changes in power levels were accomplished at ramp rates of 1.5 kW/ft/hr (LLR-3 and LLR-5) and 2.0 kW/ft/hr (LLR-4). System thermal-hydraulic parameters and fuel rod pressures, temperatures, and coolant flow conditions were monitored throughout the various test phases.

Prior to the performance of the PBF/LLR tests, and any of the LOFT tests, it was expected that Test LLR-5 would result in waisting of the cladding and that Test LLR-4 would be performed to provide information on the effects of pellet-cladding interaction during subsequent testing with deformed fuel rods. However, fuel rod cladding temperatures attained during Tests LLR-3 and LLR-5 were somewhat lower than anticipated and fuel rod cladding deformation may not occur have occurred until the highest power test (Test LLR-4) was performed. Since a major objective of the LLR tests was to investigate the effect of cladding collapse and waisting on rod behavior during subsequent power ramps and blowdown transients, Test LLR-4A was added to the test program. This experiment was performed at the same test conditions as Test LLR-4.

The following sections briefly describe the test designs, test conduct, and test results for the PBF/LLR tests.

TEST DESIGN AND CONDUCT

Each test was performed with four identical, unpressurized LOFT-type fuel rods, each surrounded by an individual circular flow shroud and symmetrically positioned in the inpile tube test space of the PBF testing facility. Design characteristics of the PBF/LLR test rods are provided in Table I. Test performance involved a preconditioning phase, a blowdown phase, and a reflood phase typical of the planned LOFT tests.

The preconditioning phase for each test consisted of (a) several slow (5% ramp rates) power ramps from low powers to successively higher powers to provide data for calibration of the test rods with the PBF core power, and (b) steady state operation for two hours at a peak linear power consistent with the LOFT counterpart test to provide approximately 80% maximum decay heat buildup. System conditions prior to blowdown were approximately 595 to 600 K inlet coolant temperature to the test rods, coolant flow rates from 0.584 to 0.80 l/s (depending on rod power) through each flow shroud, and a system pressure of 15.5 MPa. The measured initial conditions for the LLR tests prior to blowdown are shown in Table II.

TABLE II

INITIAL CONDITIONS FOR THE LLR TESTS PRIOR TO BLOWDOWN

Test	Maximum Rod Power (kW/m)	System Pressure (MPa)	Inlet Temperature (K)	Average Core Differential Temperature	Shroud Flow (l/s)
LLR-3	40.5	15.67	595.0	11.1	0.58
LLR-5	47.4	15.5	598.0	10.5	0.60
LLR-4	56.6	15.6	600.0	10.1	0.80
LLR-4A	55.6	15.5	600.0	11.5	0.78

Upon completion of the preconditioning phase, blowdown was initiated by opening two high speed blowdown valves in the cold leg of the coolant loop to simulate a 200% double-ended cold leg break LOCA. Reflood was performed by injecting coolant from a quench tank directly into the in-pile tube. After the reflood phase, additional posttest quench cooling was provided to complete quenching of the fuel.

TEST RESULTS

Preliminary evaluations of test results are based on system thermal-hydraulic response and test rod cladding temperature response during the blowdown transient. The rod cladding temperature responses and system pressure responses are evaluated to provide information on the mechanical deformation of the cladding and are compared with related data published by Olsen[1].

For the low pressure rods tested, mechanical deformation of the cladding occurs during the early part of the blowdown when cladding temperatures are near their maximum values and system pressure is still relatively high. During this time, the system thermal-hydraulic response is similar for all the PBF/LLR tests since the initial conditions at the time of blowdown were essentially the same.

System Thermal-Hydraulic Response

Figures 1 through 4 show representative plots of measured system thermal-hydraulic response during the system depressurization for Test LLR-5. Pretest calculations of the system pressure, coolant flow rate, and density at the cold leg blowdown spool piece and the volumetric flow in one typical flow shroud, as calculated using RELAP4/MOD6[a], are compared with the time-dependent measurements. In general, the comparisons between pretest calculations and experimental data are quite good.

Figure 1 compares the RELAP4 calculations with data obtained with the flush mounted pressure transducer in the cold leg spool piece. The data in Figure 1 indicate a subcooled depressurization to 10.7 MPa, which corresponds to a saturation temperature of 589 K. The

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a. RELAP4/MOD6, Update 4, Version III, Idaho National Engineering Laboratory Configuration Control Number H004418.

lower saturation temperature resulted because of difficulties in keeping the dead legs to the hot and cold leg blowdown valves at system temperature (595 K). In spite of this lower initial system temperature, the subcooled and saturated portions of the blowdown matched the predicted trends extremely well.

Figure 2 compares the predicted and measured volumetric flow rate at the cold leg blowdown spool. Following initiation of blowdown, the measured initial flow spike indicates a rapid increase to a value of 60 l/s. Upon completion of the subcooled portion of the blowdown, choked flow occurred almost instantaneously; and the measured volumetric flow decreased to approximately 40 l/s within about 1.0 second. The volumetric flow then increased to 59.5 l/s at about 4 seconds after blowdown due to the continually decreasing coolant density as the system depressurized, resulting in high void fraction steam mixtures. RELAP4 predicted the volumetric flow during both the subcooled and saturated portions of the blowdown extremely well. This result indicates that the code predicted the correct volume of two-phase mixture leaving the system.

Figure 3 shows the predicted and measured coolant density as a function of time at the cold leg spool piece. The experimental curve is based on data obtained from a three-beam gamma densitometer. The RELAP4 prediction compares well with the experimental data. Beyond approximately 12.5 seconds, the experimental data exhibit a slightly higher density.

A comparison of the RELAP4 prediction with the corresponding volumetric flow rate measured by the fuel rod shroud lower turbine meter for Rod 312-1 is shown in Figure 4. For the most part, both the data and predictions for the other test rods follow the trends of this measurement. With the initiation of the cold leg blowdown, flow reversal occurs and, the shroud check valves shut instantaneously due to the differential pressure reversal from the lower to upper plenum. The sudden flow reversal results in an initial negative flow spike that saturates the turbine meter at -1.5 l/s. Beyond this point, the data indicate significant volumetric flow for the next 2.5 seconds, and then flow stagnation for the duration of the transient.

Test Rod Thermal and Mechanical Response

The fuel rod thermal-mechanical responses observed during each test are discussed in the following subsections. Some comparisons with pretest calculations are also shown.

Test LLR-3

In Test LLR-3, two of the rods (Rods 312-1 and 312-2) were surrounded by zircaloy flow shrouds, and the other two rods (Rods 312-3 and 312-4) were surrounded by stainless steel flow shrouds. The two different coolant shroud materials were used to provide (a) peak power densities in the zircaloy shrouded rods corresponding to the expected peak power densities in the centrally located (high power) LOFT fuel rods, and (b) peak power densities in the stainless steel shrouded rods corresponding to the expected peak power densities in the peripheral (low power) LOFT fuel rods.

The maximum cladding temperatures attained during test LLR-3 were: Rod 312-1, 950 K; Rod 312-2, 925 K; Rod 321-3, 1005 K; and Rod 312-4, 870 K.

Figure 5 illustrates representative measured cladding surface temperature, coolant temperature, and cladding elongation responses, and the calculated cladding surface temperature response for Rod 312-1 (zircaloy shrouded) during the first 20 seconds following initiation of blowdown. In addition to lower measured maximum rod cladding temperatures (as compared with the predicted values), the cladding temperature and the cladding elongation measurements indicated a delay in critical heat flux (CHF) of approximately two seconds from the time to CHF calculated by RELAP4.

Measured cladding temperature is plotted as a function of system pressure in Figure 6 for Rod 312-1. The measured cladding temperature-system pressure response falls below the cladding buckling region determined by Olsen[1], which indicates that no permanent cladding deformation would be expected to have occurred to Rod 312-1.

Cladding surface temperatures during blowdown are shown in Figure 7 for Rod 312-3, which reached the highest cladding temperature (1005 K) of all four rods in Test LLR-3. Following the test, a high level of radiation was detected in the blowdown tank, indicating possible failure of one or more of the test rods. Rod 312-3 was determined to have failed during the blowdown transient, apparently due to water-logging that resulted in subsequent ballooning (up to 50% di meter increase) and rupture. The plenum pressure in Rod 312-3, which had consistently remained at a high value throughout the precon'itioning portion of the test (saturation of the sensor at 7 MPa), followed the system depressurizaton quite closely after the rod apparently burst at 12.3 seconds. Comparison of the Rod 312-3 plenum pressure response with the system pressure is shown in Figure 8. The response of the pressure transducer in Rod 312-3 indicated that the rod apparently failed when the system pressure was reduced to approximately 5 MPa. Apparently, Rod 312-3 had a small leak in the cladding throughout the test, which would account for the saturated (7 MPa) indication by the plenum pressure transducer and would permit waterlogging, which resulted in ballooning and rupture during the blowdown.

In conclusion, the LOFT desired system depressurization and test rod power densities were attained during Test LLR-3. The sequencing of the blowdown valves was as planned. Although the maximum measured fuel rod cladding surface temperatures were lower than expected (1000 K as compared with the expected 1080 K), the temperatures attained on the zircaloy shrouded rods were close to the expected temperatures on the LOFT L2-3 test peripheral rods, indicating that the data will be appropriate for evaluating the expected response of the LOFT peripheral rods.

Test LLR-5. Following Test LLR-3, the two stainless steel shrouded rods, Rod 312-3 (failed) and Rod 312-4, were replaced with two fresh, zircaloy shrouded rods, Rods 345-1 and 345-2, respectively. In keeping with the planned test sequence for LOFT, Test LLR-5 then preceded Test LLR-4, and involved a second test cycle for Rods 312-1 and 312-2 and a first test for Rods 345-1 and 345-2.

Since no permanent mechanical deformation occurred during Test LLR-3 because of the low cladding temperature, an attempt was made to attain higher rod cladding surface temperatures during the blowdown transient for Test LLR-5 by maintaining the PBF reactor power at the steady state power level for two seconds after initiation of blowdown.

The maximum measured cladding temperatures attained during Test LLR-5 were: Rod 312-1, 995 K; Rod 312-2, 1015 K; and Rod 345-1, 1005 K. Rod 345-2 was not instrumented with cladding thermocouples.

During the first 20 seconds following the initiation of blowdown, the system thermal-hydraulic response was the same as for Test LLR-3.

Figure 9 shows the cladding temperature and cladding elongation responses for Rod 312-2, the rod that indicated the highest cladding temperature (1015 K). Both cladding thermocouples and the cladding displacement, as measured by a linear variable differential transformer (LVDT) indicated DNB occurred at about two seconds, with the temperature measurement at the 0.533-m elevation indicating rewetting at 2.25 seconds and a second DNB indication at 2.8 seconds. Again, on the basis of comparisons with Olsen's data, no mechanical deformation is believed to have occurred on any of the Test LLR-5 rods.

Test LLR-4. Test LLR-4 was performed with the same fuel rods used in Test LLR-5. Since Test LLR-5 did not attain cladding temperatures sufficiently high to induce mechanical deformation, the PBF reactor power was maintained at the steady state power level for 2.6 seconds following initiation of blowdown.

From initiation of blowdown until approximately 15 seconds into the transient, the system thermal-hydraulic behavior was the same as for Tests LLR-3 and LLR-5. At approximately 15 seconds, the primary coolant system isolation valves and the blowdown valves malfunctioned and began to flutter open and shut, permitting primary coolant to enter the in-pile tube and blowdown system. The unintentional valve sequencing resulted in premature quenching of the fuel rods, with subsequent increases and decreases in cladding temperatures, but did not affect the overall test rod thermal and mechanical response, as the maximum cladding temperature had been attained prior to the inadvertent valve sequencing.

Figure 10 shows the cladding temperature response for Rod 312-2, the rod that, again, provided the highest measured cladding temperature (1170 K) during the transient. At approximately 15.4 seconds the cladding surface thermocouples indicated quenching from the inadvertant valve sequencing as explained above. On the basis of comparisons with Olsen's data, the mechanical deformation of Rod 312-2 would be expected to include waisting (cladding collapse into pellet-to-pellet interfaces), as shown in Figure 11. Waisting on Rod 312-2 has been confirmed by preliminary posttest examination. With an indicated peak cladding temperature of 1130 K, Rod 312-1 would also be expected to have experienced waisting. The maximum measured cladding temperature of 1060 K, on Rod 345-1 would indicate two-point buckling of the cladding.

In conclusion, Test LLR-4 was a highly successful experiment. The LOFT desired system depressurization and test rod power densities were attained. Elevated cladding temperatures in the range of 1060 to 1170 K were attained, which resulted in significant mechanical deformation of the fuel rods, including buckling and waisting.

Test LLR-4A. Since a major objective of performing the PBF/LLR Test Series was to evaluate the effect of cladding collapse and waisting on rod behavior during subsequent power ramps and depressurization transients, an additional LLR test, Test LLR-4A, was performed at the same test conditions as Test LLR-4. Since both rods 312-1 and 312-2 experienced waisting during Test LLR-4, Rod 312-1 was removed prior to performing Test LLR-4A. Removal of Rod 312-1 provided an intact sample of a rod with waisting. Replacement of Rod 312-1 with a fresh rod, designed 399-2, permitted testing the mechanical deformation to be expected on a rod subjected to a single blowdown transient initiated from a power level of approximately 56 kW/m. Test LLR-4A used the following rods: Rod 312-2, which had been subjected to three previous transients and had probably experienced waisting; Rods 345-1 and 345-2, which had been subjected to two previous transients and had probably experienced buckling of the cladding; and Rod 399-2, a fresh rod. During the power calibration and preconditioning power ramps, there were no observable indications that the condition of the cladding on Rods 312-2, 345-1, and 345-2 affected the response of the rods in any way.

Following three hours of steady state operation at a peak power density of 56 kW/m, blowdown was initiated. For Test LLR-4A, the PBF reactor shutdown was delayed beyond initiation of blowdown by 2.85 s. As shown in Figure 12, the thermal and mechanical response of Rod 312-2 was essentially the same as during Test LLR-4, with the rod reaching a maximum cladding temperature of 1150 K. Rod 345-1 reached a maximum cladding temperature of 1075 K, within 60 K of that attained during Test LLR-4, and the new rod, 399-2, reached the highest measured cladding temperature of 1205 K. Rods 312-2 and 399-2 are believed to have experienced waisting, and uniform cladding collapse is believed to have occurred on Rod 345-1. No fuel rod failures were detected as a result of Test LLR-4A.

In conclusion, Test LLR-4A was essentially a repeat at Test LLR-4 conditions. The test was totally successful in terms of (a) attaining cladding temperatures in the range of 1075 to 1205 K, (b) inducing mechanical deformation to the fuel rods that included collapse and waisting, and subjecting deformed fuel rods to subsequent preconditioning and LOCA cycles.

Conclusions

The PBF/LLR Test Series fuel rods experienced the maximum mechanical deformation that would be expected to occur to the LOFT fuel rods during the LOFT L2 Power Ascension Tests. The program demonstrated that low pressure, light water reactor design fuel rods, and specifically LOFT design fuel rods, probably will be able to with stand successive LOCA tests without failure, at least to the extent that will be required for completion of the planned LOFT program. Posttest examinations of Rods 345-1 and 312-2, which incurred probable mechanical deformation of the cladding and underwent subsequent power ramping and LOCA conditions, will provide significant additional information on the actual physical condition of the rods and the effect of continued preconditioning and LOCA transients on deformed fuel rods. Significant thermal hydraulic and fuel rod thermal and mechanical response data were obtained that can be used for evaluating and modifying the FRAP computer code.

REFERENCES

1. C. S. Olsen, "Zircaloy Cladding Collapse Under Off-Normal Temperature and Pressure Conditions," TREE-NUREG-1239, April 1978.

2. D. L. Reeder, "LOFT System and Test Description," TREE-NUREG/CR-0247, TREE-1208, July 1978.

3. K. R. Katsma, et al., "RELAP4/MOD5 - A Computer Program for Transient Thermal Hydraulic Analysis of Nuclear Reactors and Related Systems," ANCR-NUREG-1335 (September 1976)

   (a) RELAP4/MOD6 is available from the Idaho National Engineering Laboratory, Configuration Control Number H004411B.

TABLE I

PBF/LOFT LEAD ROD TEST FUEL ROD DESIGN CHARACTERISTICS

Characteristics	Nominal Value
Fuel	
Material	UO_2, (References 4 & 5)
Pellet OD	0.9294 ± 0.00127 cm (0.3459 ± 0.0005 in.)
Pellet length	1.524 ± .0635 cm (0.600 ± 0.025 in.)
Pellet enrichment	9.5 ± 0.5 wt%
Density	93.0 ± 1.5% TD
Fuel stack length	0.9144 m (36.0 in. ± 0.3)
End configuration	Dished
Burnup	0 MWd/t
Centerhole diameter	0.185 cm (0.073 in. ± 0.002)
Insulator Pellet	
Material	Al_2O_3 (99% pure, ASTM D2442)
Length	0.508 ± 0.0254 cm (0.2 ± 0.010 in.)
Diameter	0.889 ± .005 cm (0.35 ± 0.002 in.)
Cladding	
Material	Zircaloy-4 (Reference 6)
Tube OD	1.07 ± 0.0038 cm (0.424 ± 0.0015 in.)
Tube ID	0.948 ± 0.0038 cm (0.3734 ± 0.0015 in.)
Thickness	0.061 cm (0.0243 in.) nominal
Yield strength	(6)
Ultimate strength	(6)
Maximum bow	(6)
Overall length	99.06 cm
Fuel Rod	
Plenum void volume	2.95 cm^3 (0.18 $in.^3$ ± 5%)
Filler gas	He
Filler gas purity	94.9% He, Ar, 0.1% impurities
Initial gas pressure	0.1034 MPa (15 psia)
Diametral gap	0.0191 cm (0.0075 in.)
Overall length	99.8601 cm

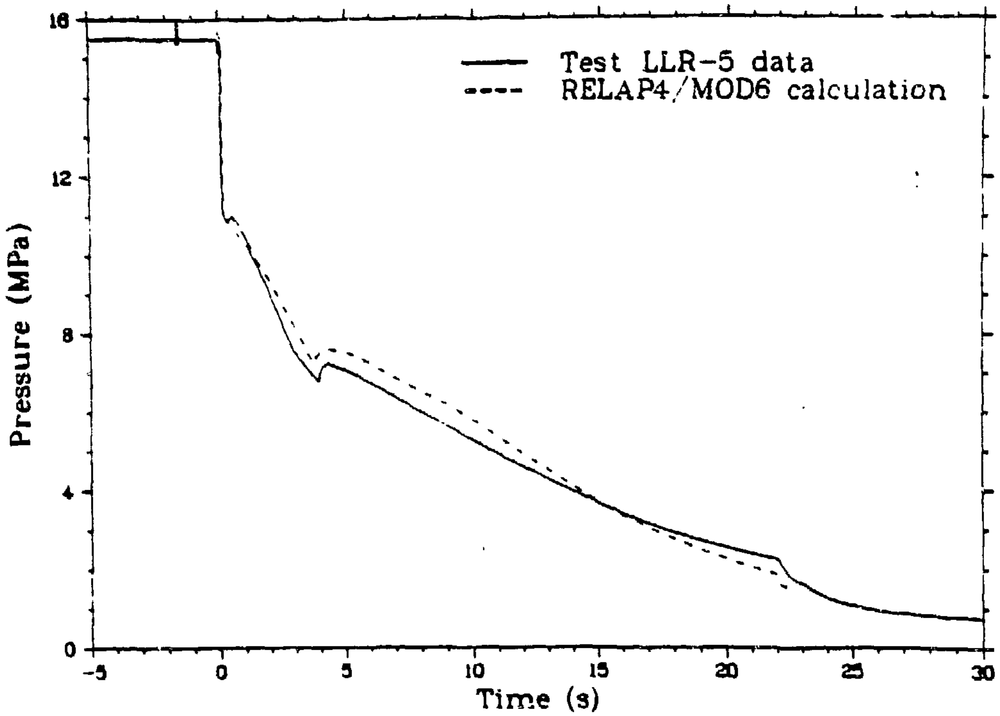

Fig. 1 Comparison of calculated and measured system depressurization in cold leg blowdown spool during Test LLR-5.

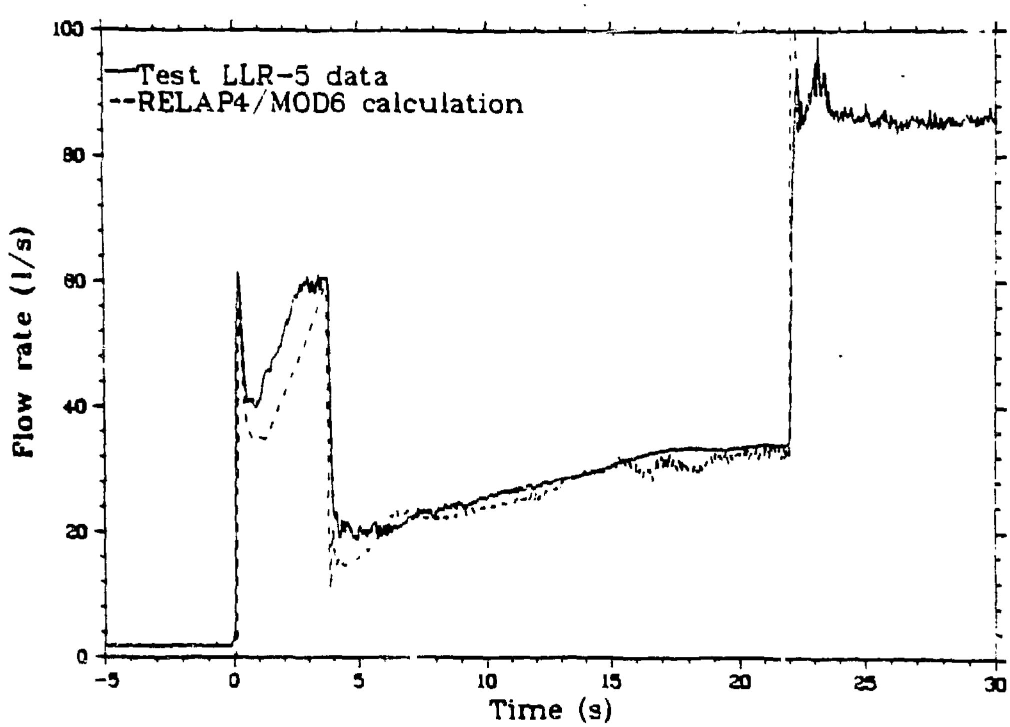

Fig. 2 Comparison of calculated and measured system volumetric flow rate in cold leg blowdown spool during Test LLR-5.

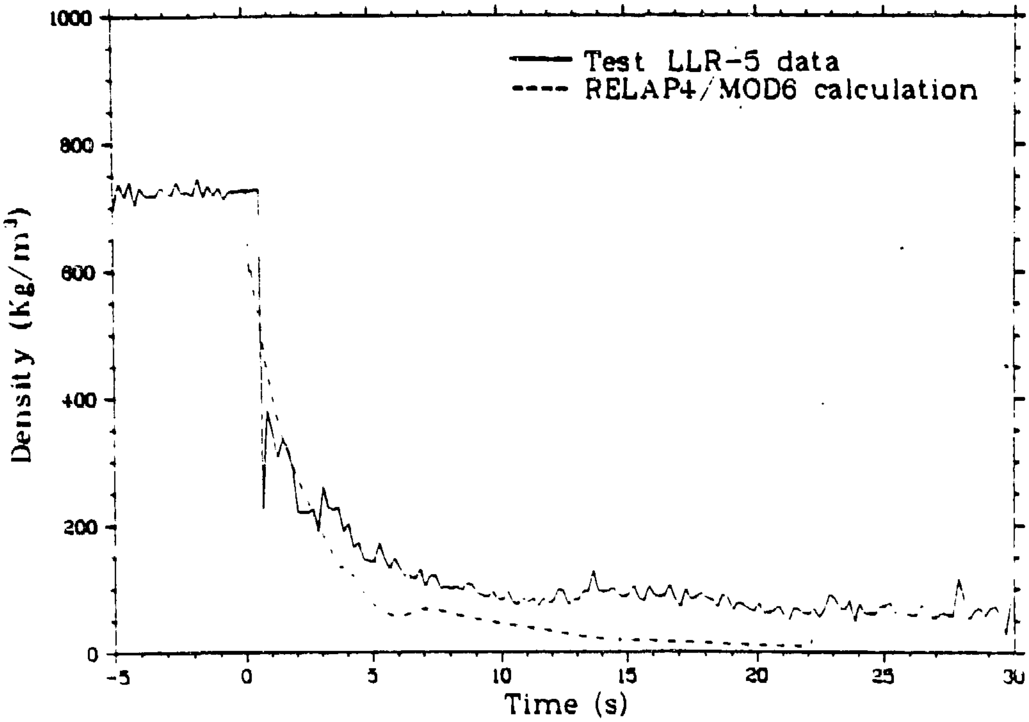

Fig. 3 Comparison of calculated and measured density in cold leg blowdown spool during Test LLR-5.

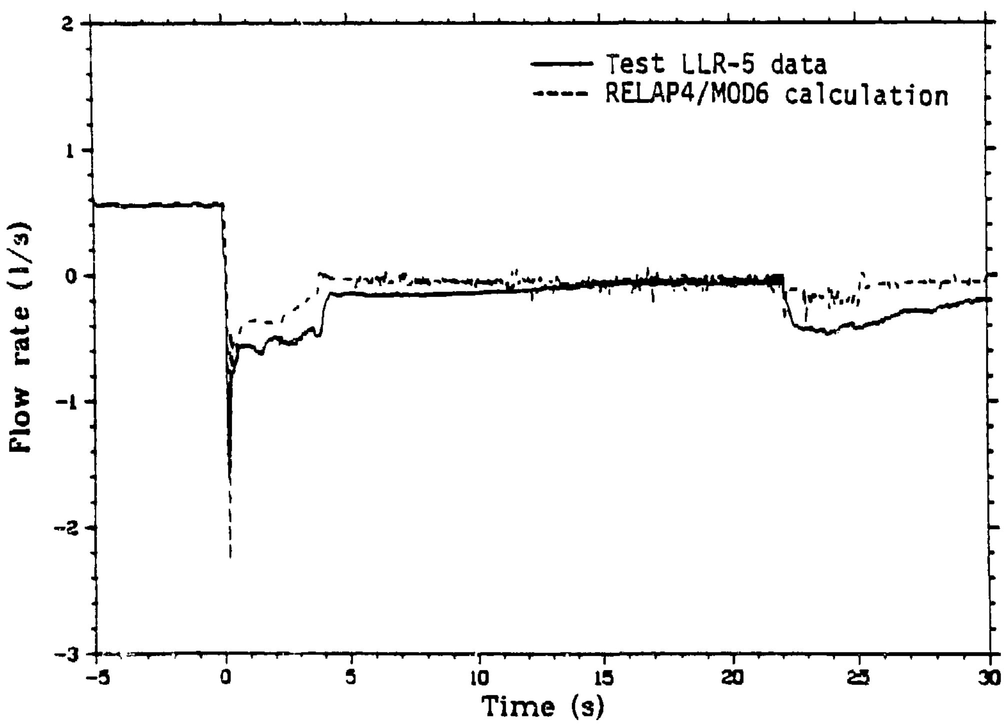

Fig. 4 Calculation of calculated and measured lower turbine flowrate during Test LLR-5.

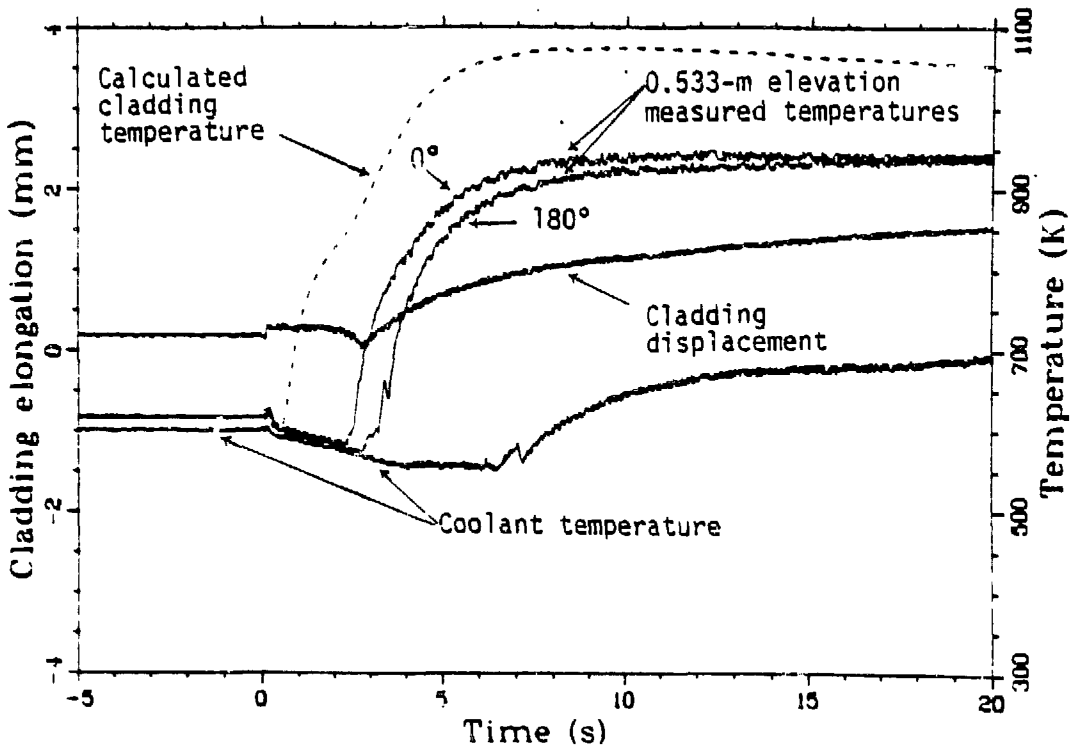

Fig. 5 Coolant temperature, rod elongation (cladding displacement), and calculated and measured cladding temperature for Rod 312-1 during Test LLR-3.

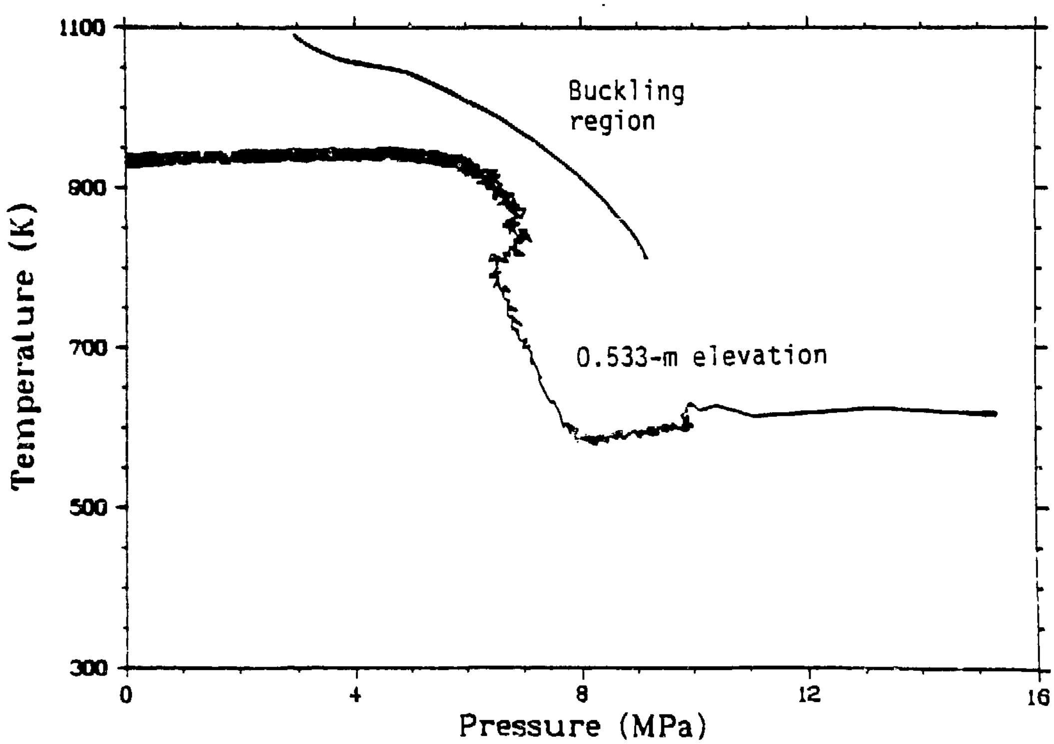

Fig. 6 Rod 312-1 measured cladding temperature versus pressure response during Test LLR-3.

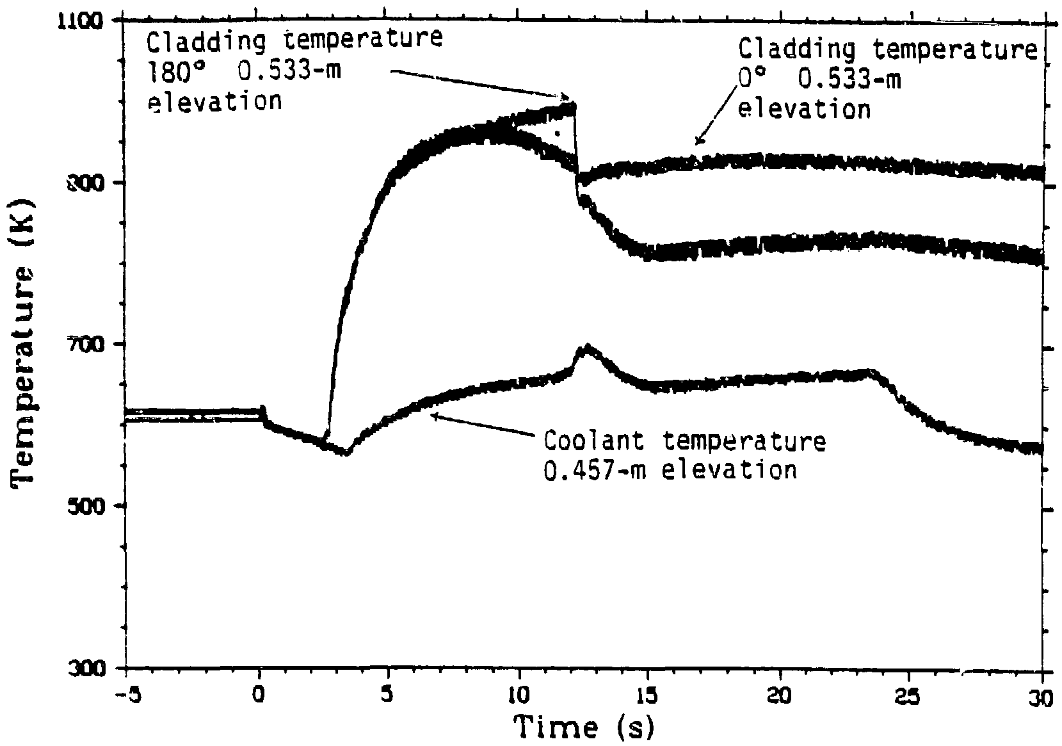

Fig. 7 Thermal behavior of Rod 312-3 during Test LLR-3.

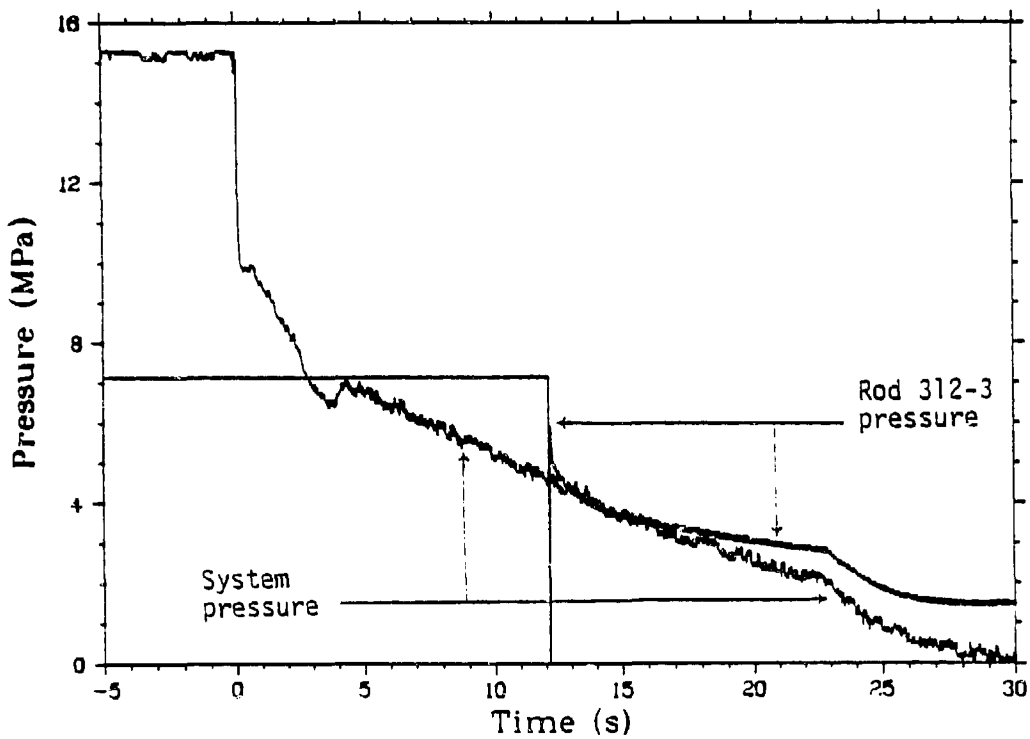

Fig. 8 Comparison of Rod 312-3 internal pressure with system pressure during Test LLR-3.

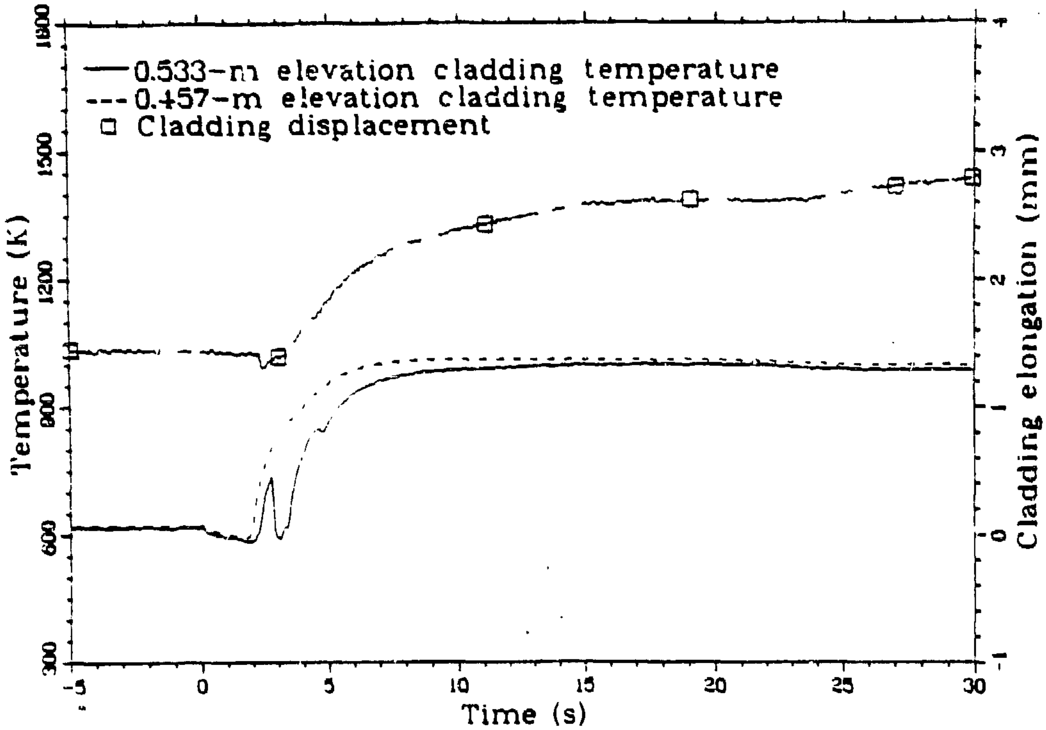

Fig. 9 Rod elongation (cladding displacement) and cladding temperature for Rod 312-2 (zircaloy shrouded) during Test LLR-5.

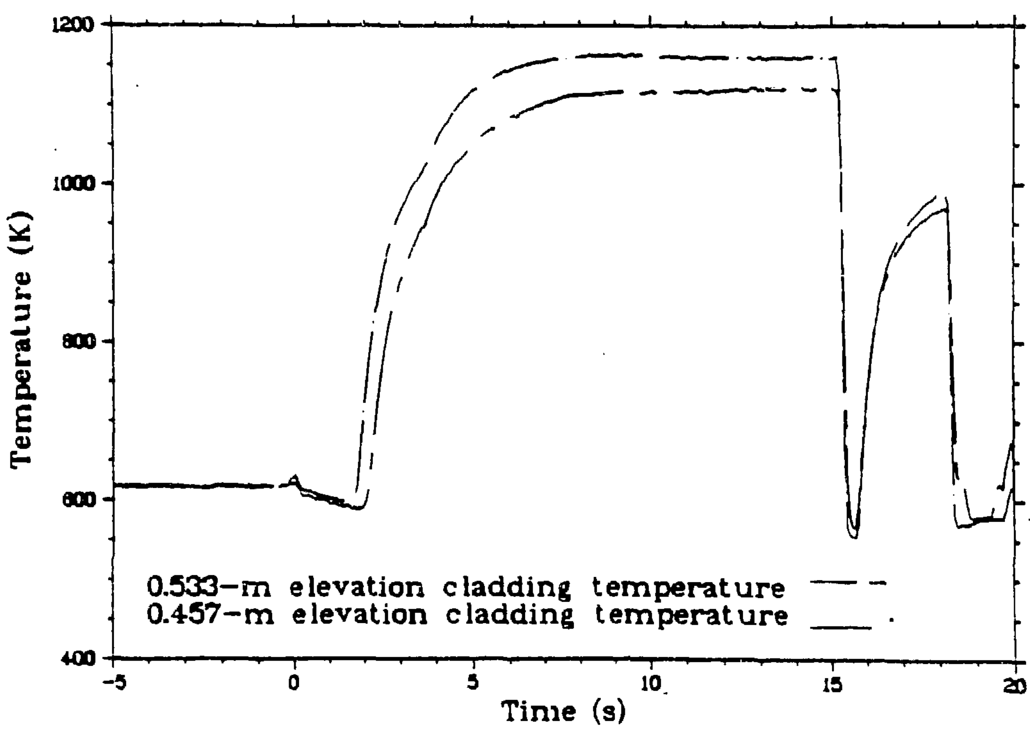

Fig. 10 Thermal behavior of Rod 312-2 during Test LLR-4.

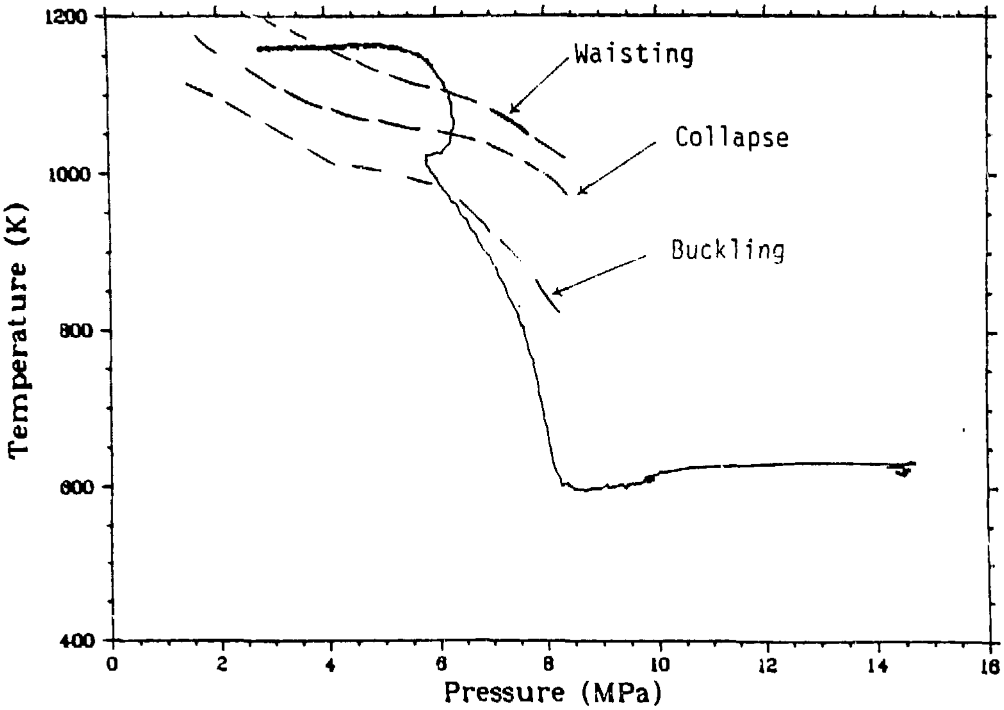

Fig. 11 Temperature versus pressure response of Rod 312-2 during Test LLR-4 compared with rod cladding deformation thresholds developed by Olsen.

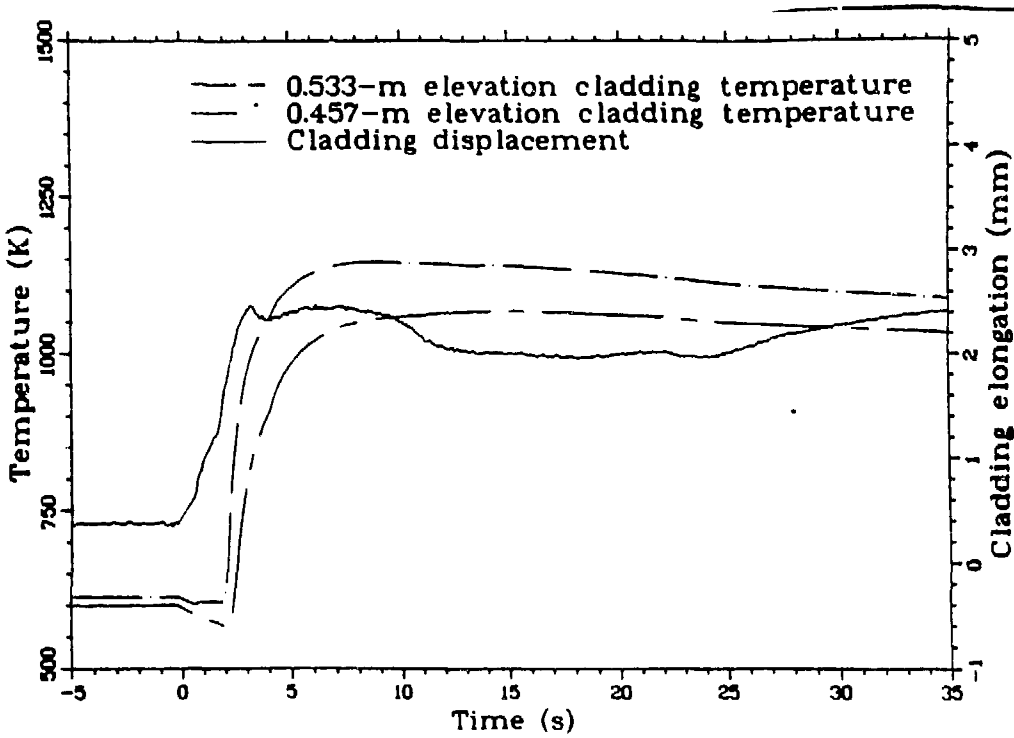

Fig. 12 Rod cladding displacement and temperature for Rod 312-2 during Test LLR-4A.