AN EVALUATION OF THE INFLUENCE OF CLADDING SURFACE THERMOCOUPLES ON THE THERMAL BEHAVIOR OF NUCLEAR FUEL RODS DURING A LOCA

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SUMMARY

The behavior of light water reactors (LWRs) following a postulated loss-of-coolant accident (LOCA) must conform to criteria specified in the Code of Federal Regulations. To assure that the behavior of both the cooling system and the nuclear core is understood and properly modeled, in-pile experiments are being conducted in the Loss-of-Fluid Test (LOFT) Facility and Power Burst Facility (PBF) at the Idaho National Engineering Laboratory by EG&G Idaho, Inc., for the U.S. Nuclear Regulatory Commission. The LOFT Facility was designed to represent the behavior of an entire large pressurized water reactor (PWR) during a postulated LOCA. The PBF-LOCA program is one of several PBF programs which are providing in-pile information on the behavior of nuclear fuel rods subjected to normal, off-normal, and accident conditions.

The fuel rods in these and similar test programs are instrumented with externally mounted cladding surface thermocouples. The cladding surface thermocouple measurements are used to assess computer calculations of the cladding temperature response and to evaluate and interpret the core thermal-hydraulic behavior. However, these surface thermocouples may act as cooling fins and influence the cladding temperature and fuel rod behavior.

This paper presents an evaluation of the results from a series of special cladding surface thermocouple tests, Tests TC-1A, TC-1B, TC-1C, and TC-1D.[1] The TC-1 tests were performed to specifically evaluate the influence of cladding surface thermocouples on nuclear fuel rods during PBF LOCA conditions. The tests were performed with

four LOFT-type fuel rods contained in individual flow shrouds. The fuel rods were symmetrically placed within a test train in the PBF in-pile tube in an environment with typical PWR coolant pressure, temperature, and flow conditions. Two rods were instrumented with four LOFT cladding surface thermocouples, the junctions of which were located near the high power region of the fuel rods. All four rods were instrumented with internal thermocouples, with junctions at the same axial elevation as the external thermocouples. The internal thermocouples were fitted in slots at the outside surface of the fuel pellets. Some of the thermocouple junctions were welded directly to the inside cladding surface and the remainder were fitted into holes near the surface of the fuel pellets. With this design, the behavior during a LOCA of fuel rods with and without external thermocouples was examined.

The TC-1 Test series consisted of four in-pile LOCA transients. Each test consisted of a power calibration and decay heat buildup phase, blowdown, heatup, and reflood. The system conditions at the initiation of each blowdown were: 600 K inlet temperature, 15.5 MPa system pressure, and 47 kW/m maximum rod power. Each test was designed to simulate the LOFT L2 tests as closely as possible. The system depressurization was similar to LOFT. As in the LOFT tests, the cladding peak temperatures achieved during the TC-1 blowdowns were between 850 and 1000 K, the PBF blowdown system was programmed to force a two-phase liquid slug past each rod early in the blowdowns, and the fuel rods were rapidly rewet during a reflood phase to terminate each test.

On the basis of the TC-1 test results, cladding surface thermocouples accurately measure the cladding temperature response during a LOCA. A comparison of the internal and external cladding thermocouples demonstrates that the surface thermocouples did not respond independently of the fuel rods. After departure from nucleate boiling, momentary rewets of the cladding surface thermocouples were observed to correspond with temperature decreases of the internal thermocouples. During the two-phase slug period, all external and internal thermocouples measured temperatures that reflected the increased heat transfer. During reflood, the external and internal thermcouples measured cladding quench at essentially the same time with a short time delay.

The surface thermocouples, however, influenced the fuel rod thermal performance in the TC-1 tests. As blowdown was initiated, the fuel rods with surface thermocouples cooled for 2 to 4 seconds before critical heat flux (CHF) occurred. The fuel rods without external thermocouples exceeded CHF within 1 second. As a result of the earlier CHF, the cladding peak temperatures achieved during blowdown were as much as 200 K higher for the fuel rods without surface thermocouples. In addition, the surface thermocouples apparently influenced the time of cladding quench during reflood. Fuel rods with surface thermocouples consistently quenched between 5 and 12 seconds before the other rods. Future in-pile programs should consider internal rod temperature measurements in place of surface temperature measurements.

Reference

1. T. R. Yackle, Loss-of-Coolant Accident, Test TC-1, Experiment Operating Specification, EGG-TFBP-5013, September, 1979.

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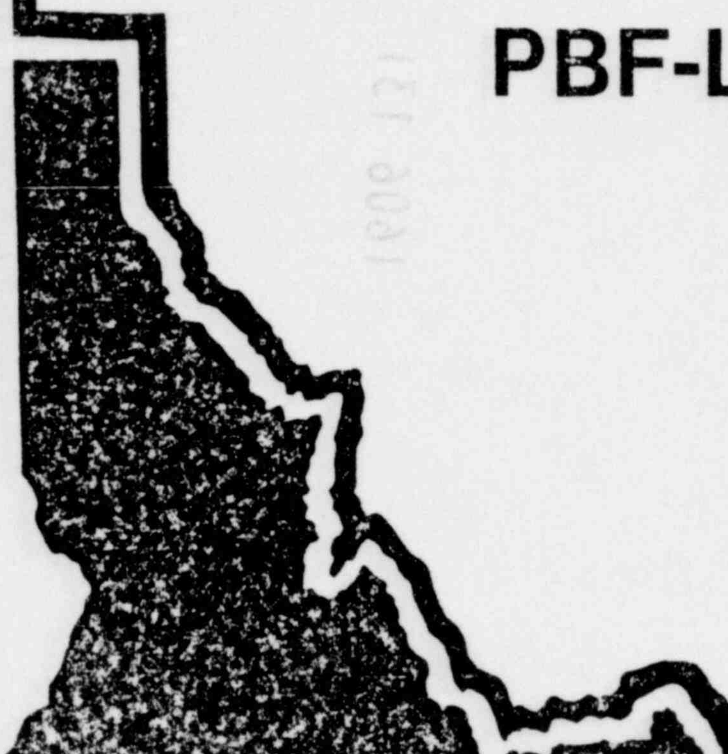
PBF-LOCA Thermocouple Effects Tests

TC-1



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Outline

- Program objectives
- Test design
- Test conduct
- TC-1 thermocouple effects

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TC-1 Test Objectives

- Do cladding surface thermocouples influence fuel rod thermal behavior during a LOCA?

- Do cladding thermocouples accurately measure cladding temperatures?

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Rationale for PBF TC Tests

- LOFT core instrumented with surface TCs
  - Blowdown rewet occurred
  - Reflood

- PBF observed possible surface TC effects

TC-1 Test Philosophy

The TC-1 test series designed to:

- Investigate TC effects on
  - Time to CHF
  - Rod quench during blowdown
  - Rod quench and rewet during reflood
- Compare cladding outside surface thermocouple reponse with cladding inside surface values
- Provide statistical confidence limits

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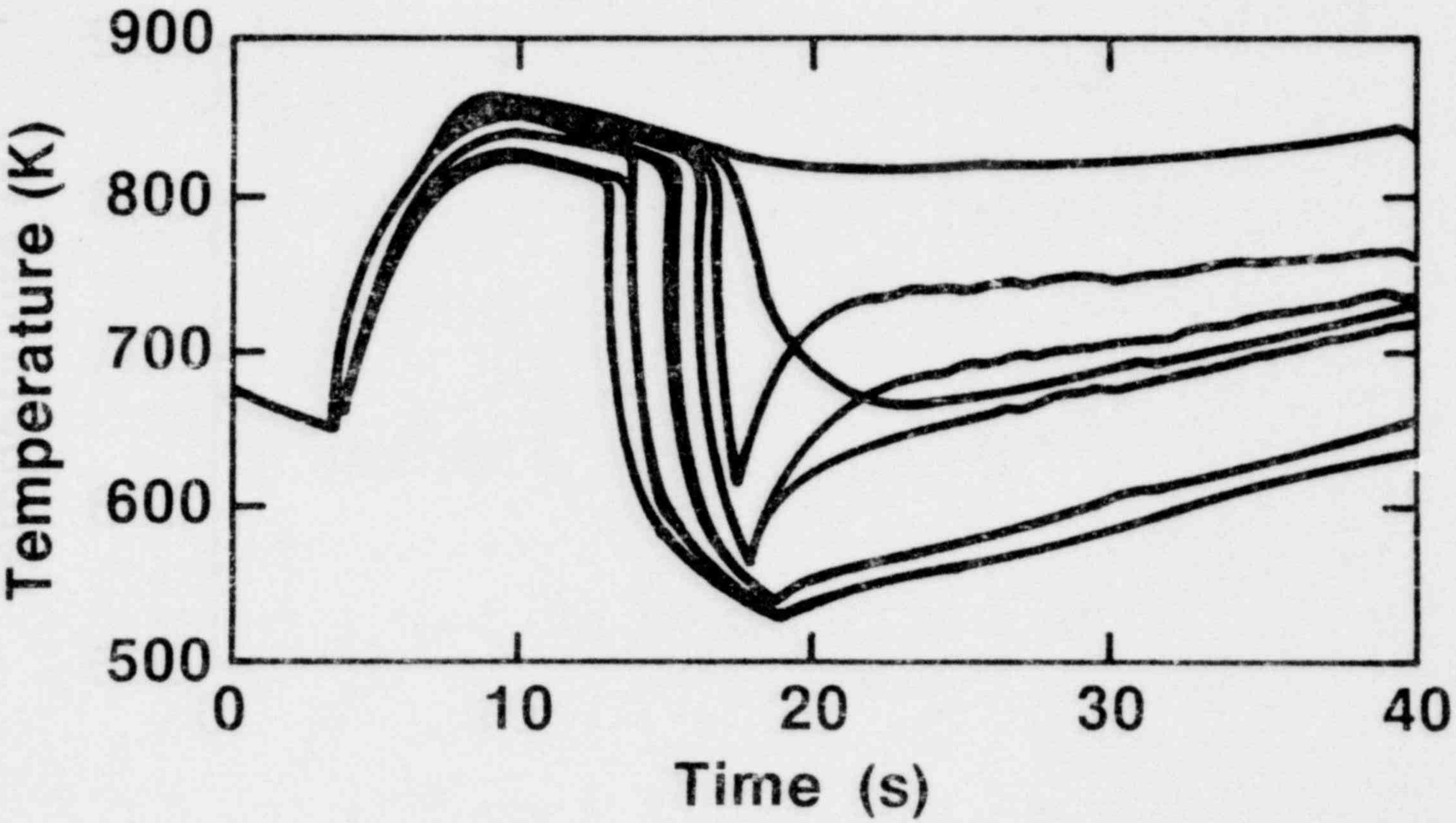
Ten Replications in Semiscale



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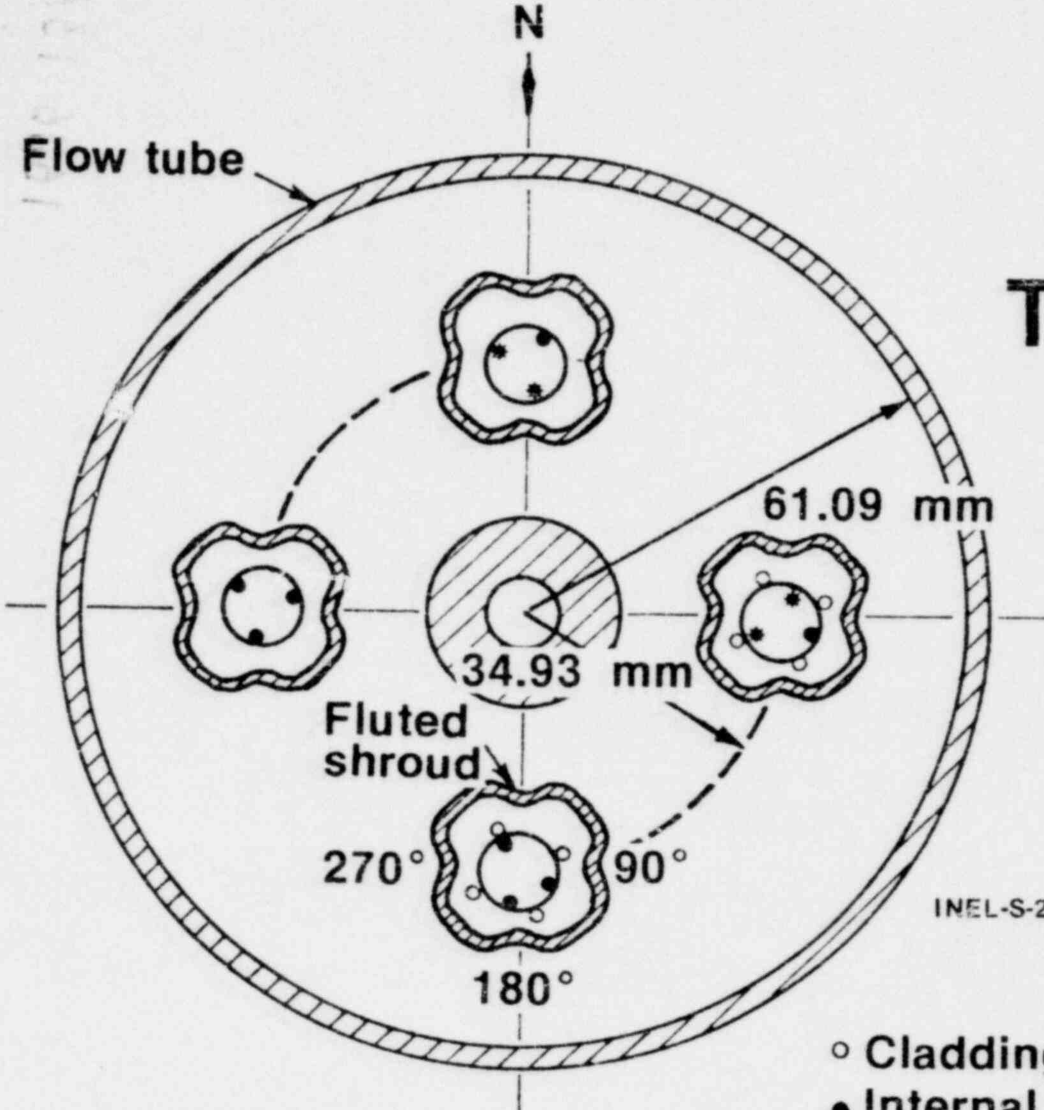
TC-1 Geometry



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- ○ Cladding thermocouples
- • Internal fuel thermocouples (not welded)
- * Internal thermocouple (welded)

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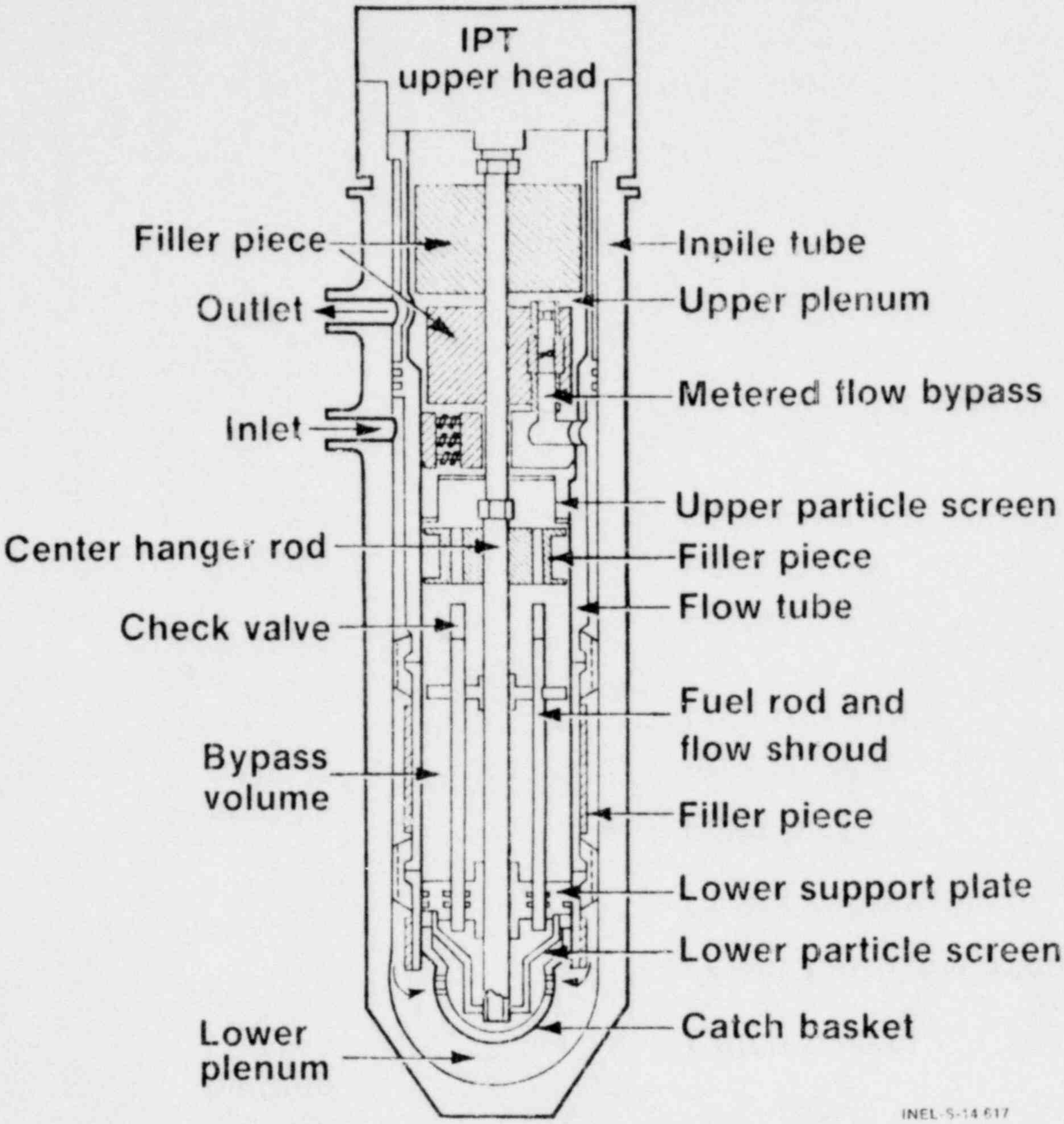
PBF Inpile Tube and LOCA Test Train



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TC-1 Test Series

Test	Blowdown System Operation	Reflood Rate cm/s
1	2 second slug	4
2	4 second slug	4
3	6 second slug	4
4	6 second slug	4

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TC Initial Conditions

Power	47 kW/m
Inlet temperature	600 K
System pressure	15.5 MPa
Coolant flow	0.8 ℓ/s

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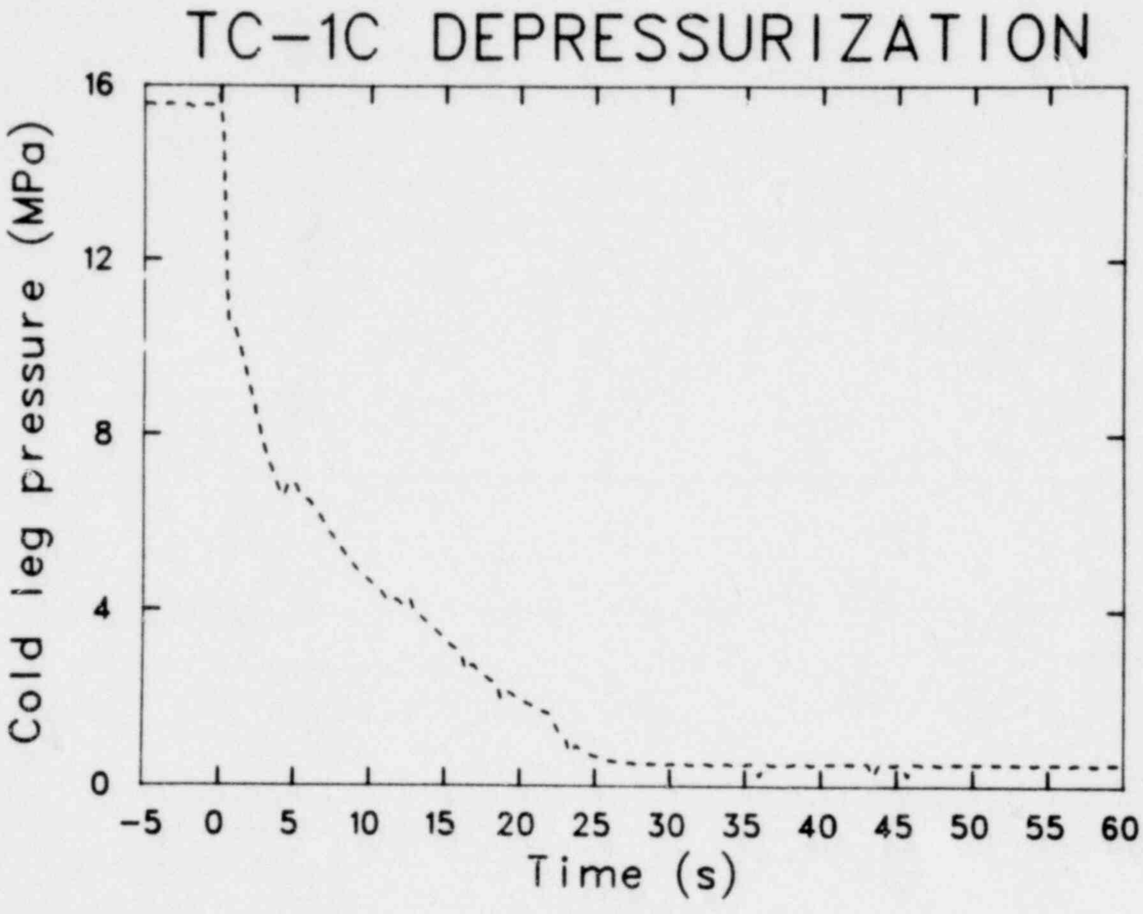

TC-1C DEPRESSURIZATION
Cold leg pressure (MPa)
16
12
8
4
0
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
Time (s)

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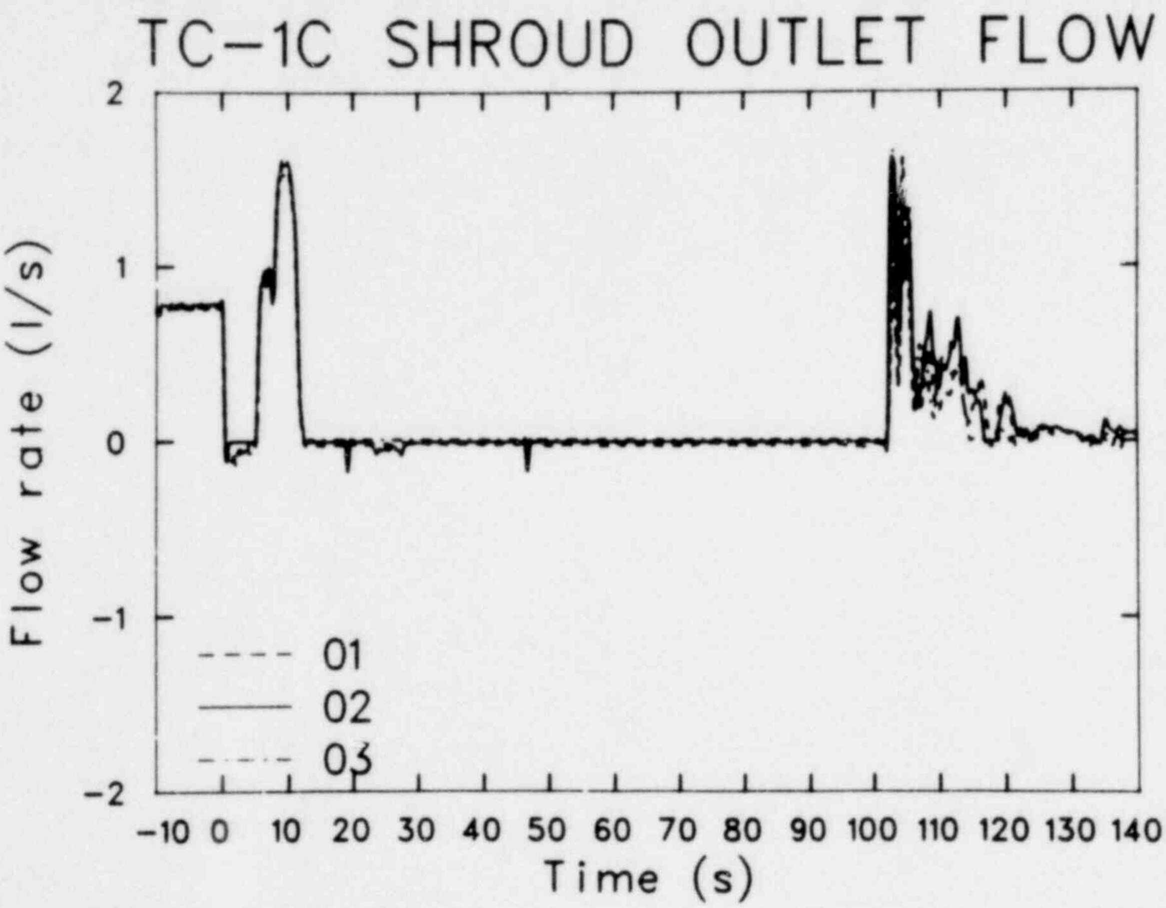
TC-1C SHROUD OUTLET FLOW
Flow rate (l/s)
Time (s)
01
02
03
2
1
0
-1
-2
-10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140

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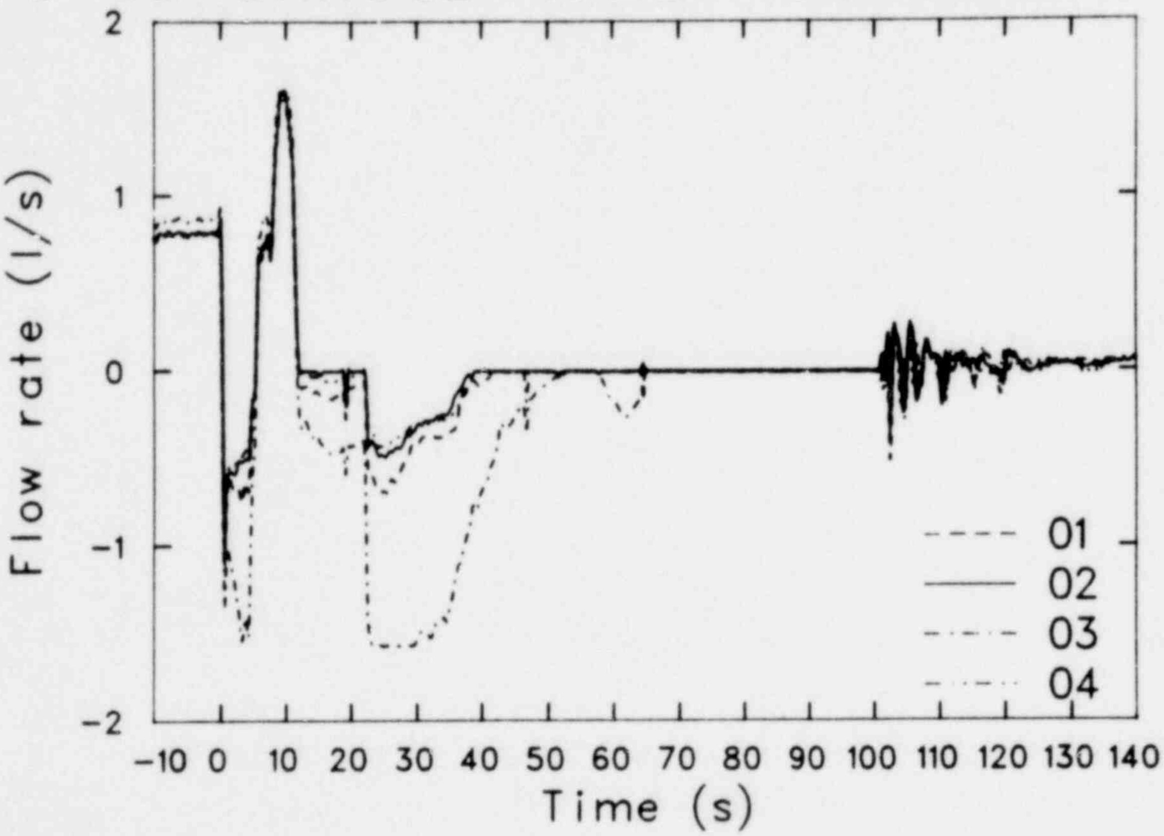
TC-1C SHROUD INLET COOLANT FLOW



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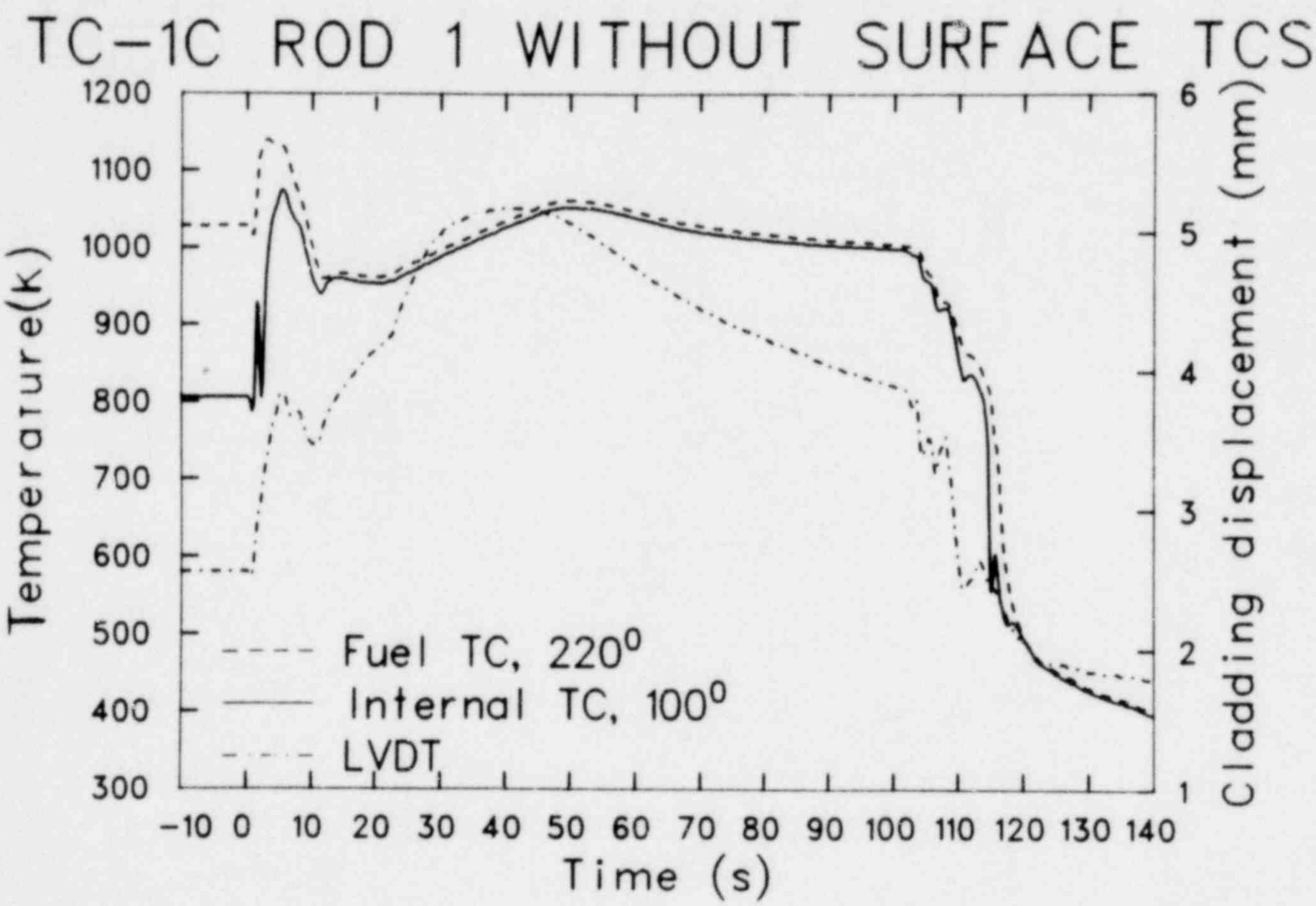
TC-1C ROD 1 WITHOUT SURFACE TCS
Temperature(K)
Cladding displacement (mm)
Time (s)
Fuel TC, 220°
Internal TC, 100°
LVDT
1200
1100
1000
900
800
700
600
500
400
300
6
5
4
3
2
1
-10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140

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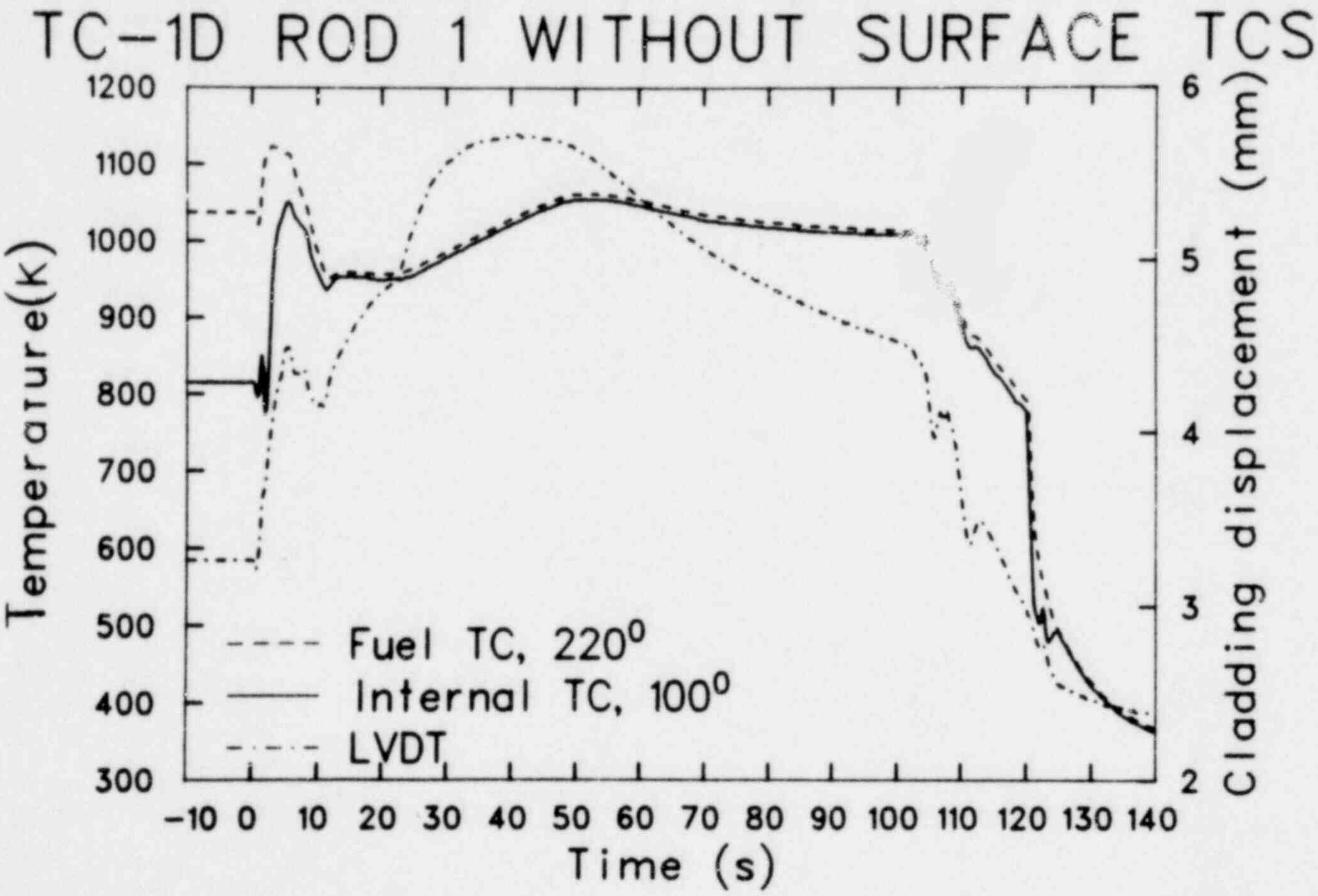
TC–1D ROD 1 WITHOUT SURFACE TCS
Temperature(K)
Cladding displacement (mm)
Time (s)
1200
1100
1000
900
800
700
600
500
400
300
6
5
4
3
2
–10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Fuel TC, 220°
Internal TC, 100°
LVDT

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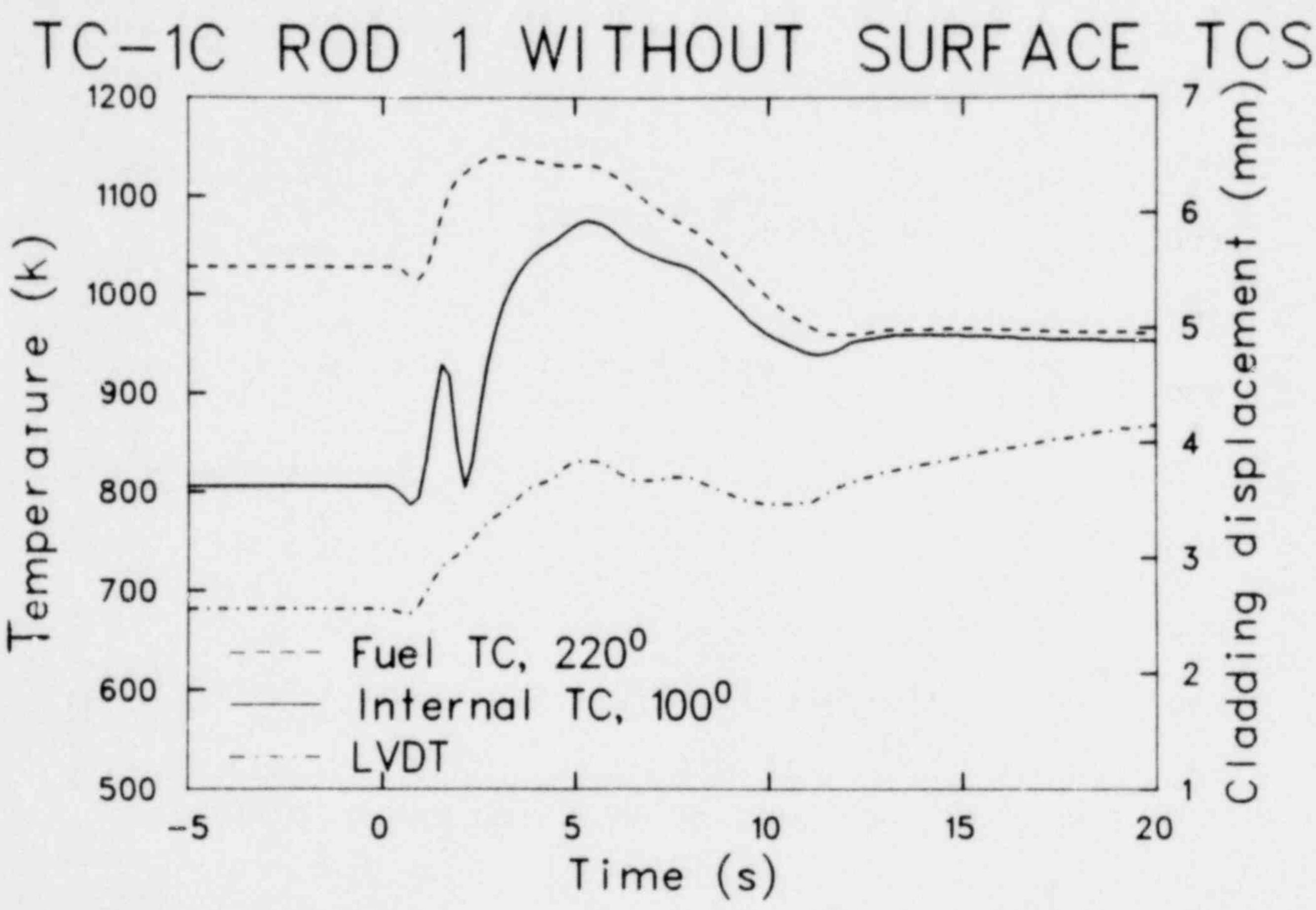
TC-1C ROD 1 WITHOUT SURFACE TCS
Temperature (K)
Cladding displacement (mm)
Time (s)
Fuel TC, 220°
Internal TC, 100°
LVDT
1200
1100
1000
900
800
700
600
500
-5
0
5
10
15
20
7
6
5
4
3
2
1

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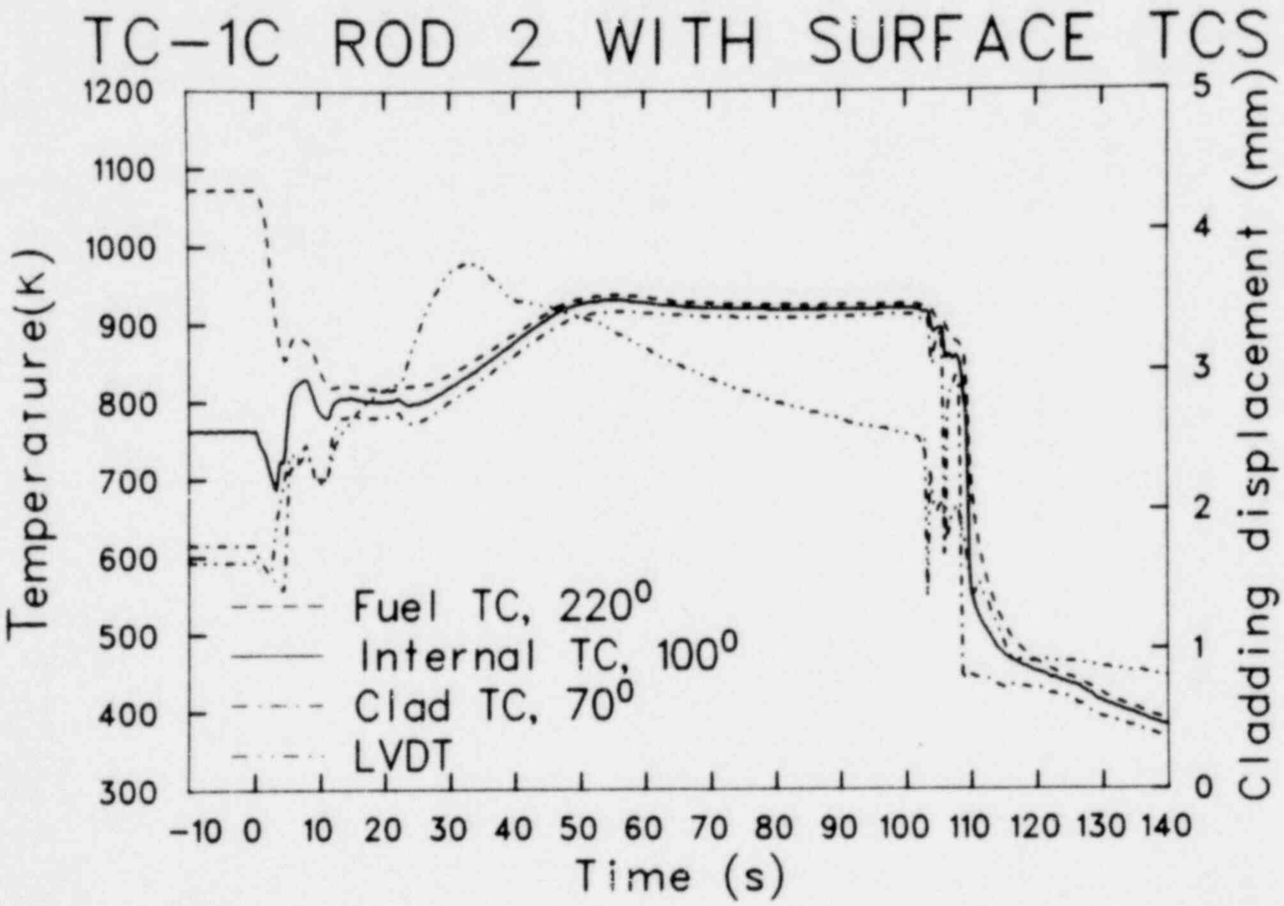
TC-1C ROD 2 WITH SURFACE TCS
Temperature(K)
Cladding displacement (mm)
Time (s)
Fuel TC, 220°
Internal TC, 100°
Clad TC, 70°
LVDT
1200
1100
1000
900
800
700
600
500
400
300
5
4
3
2
1
0
-10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140

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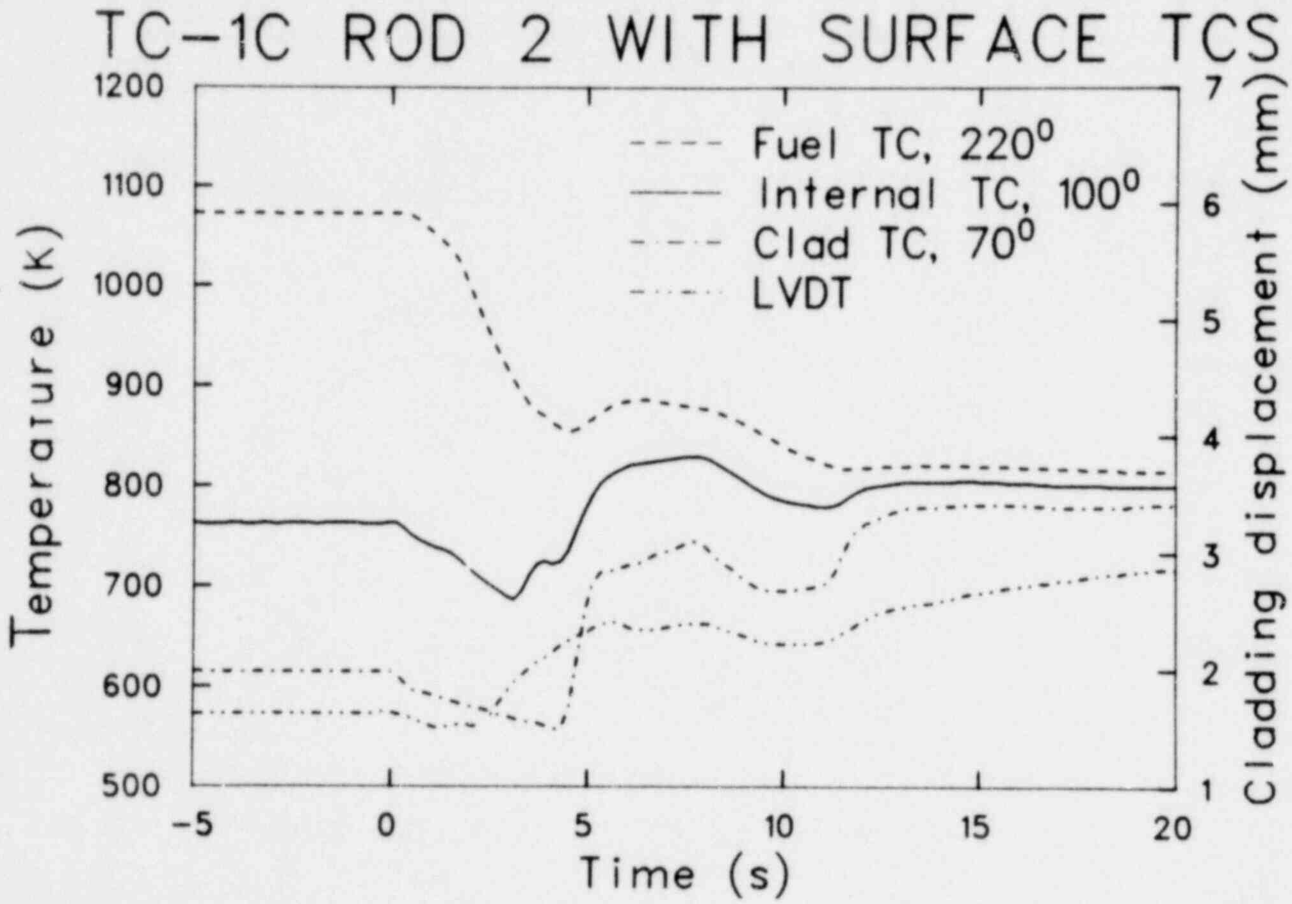

TC-1C ROD 2 WITH SURFACE TCS
Fuel TC, 220°
Internal TC, 100°
Clad TC, 70°
LVDT
Temperature (K)
Cladding displacement (mm)
Time (s)
1200
1100
1000
900
800
700
600
500
7
6
5
4
3
2
1
-5
0
5
10
15
20

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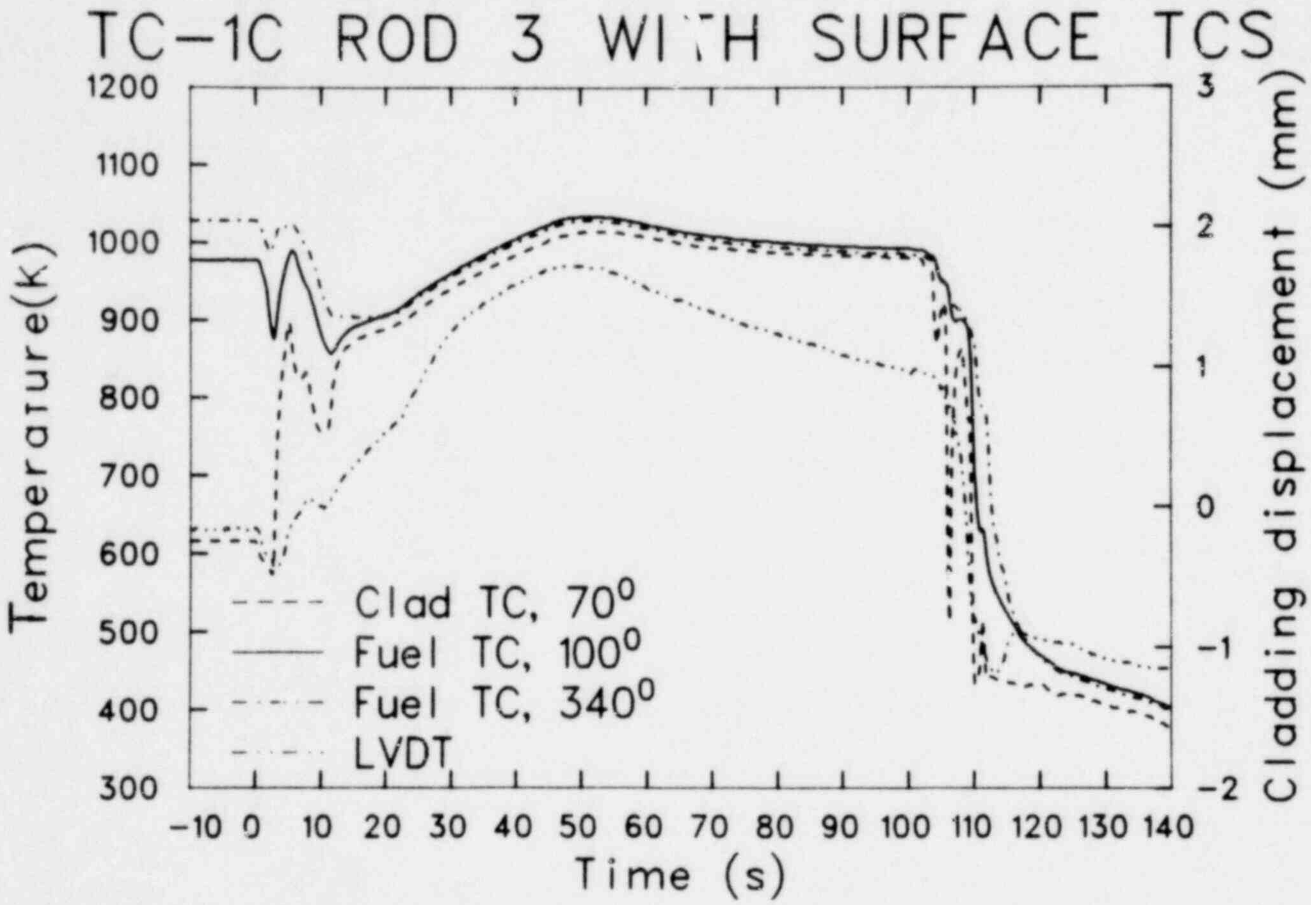
TC-1C ROD 3 WITH SURFACE TCS
Temperature(K)
Cladding displacement (mm)
Time (s)
Clad TC, 70°
Fuel TC, 100°
Fuel TC, 340°
LVDT
1200
1100
1000
900
800
700
600
500
400
300
3
2
1
0
-1
-2
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

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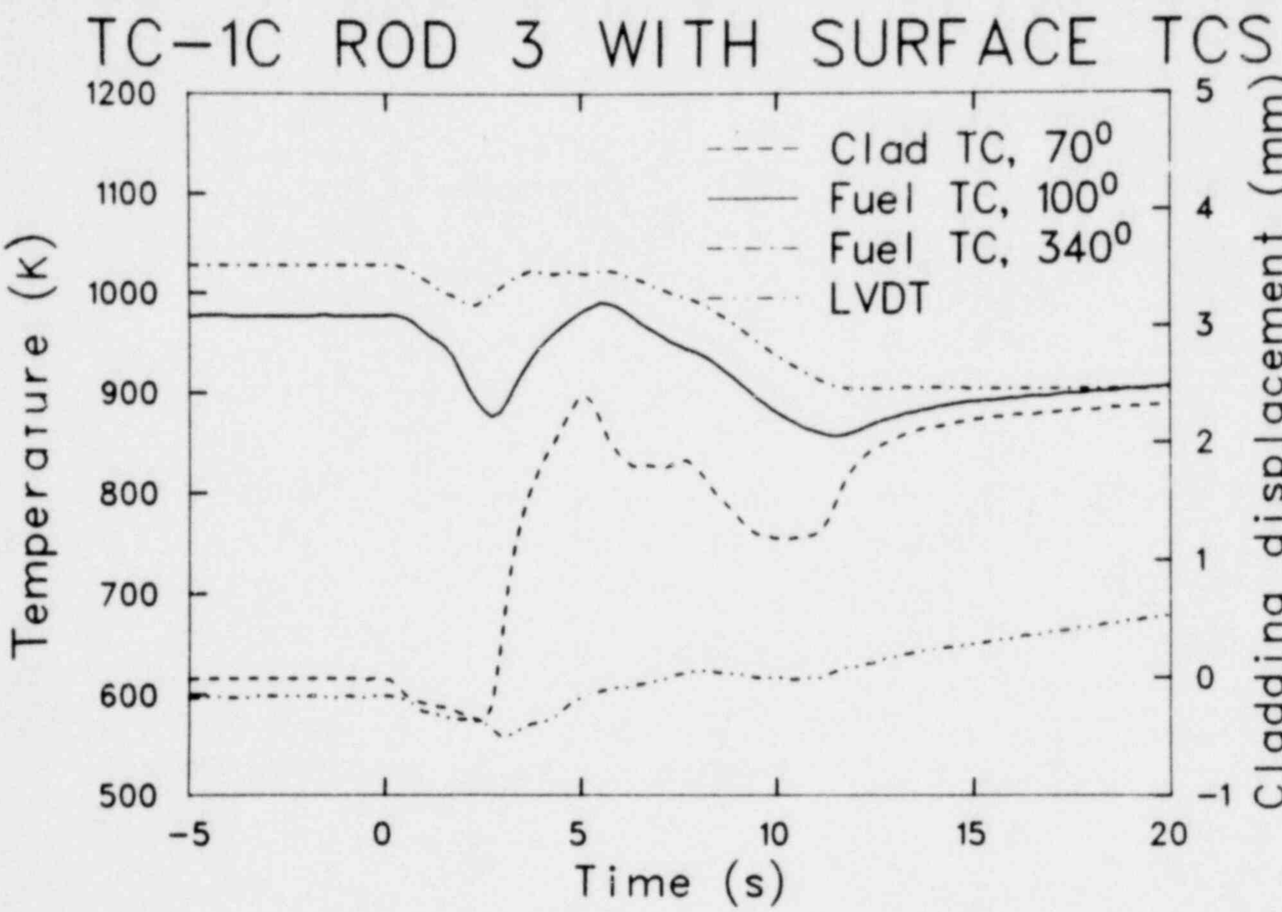

TC–1C ROD 3 WITH SURFACE TCS
Clad TC, 70°
Fuel TC, 100°
Fuel TC, 340°
LVDT
Temperature (K)
Cladding displacement (mm)
Time (s)
1200
1100
1000
900
800
700
600
500
5
4
3
2
1
0
−1
−5
0
5
10
15
20

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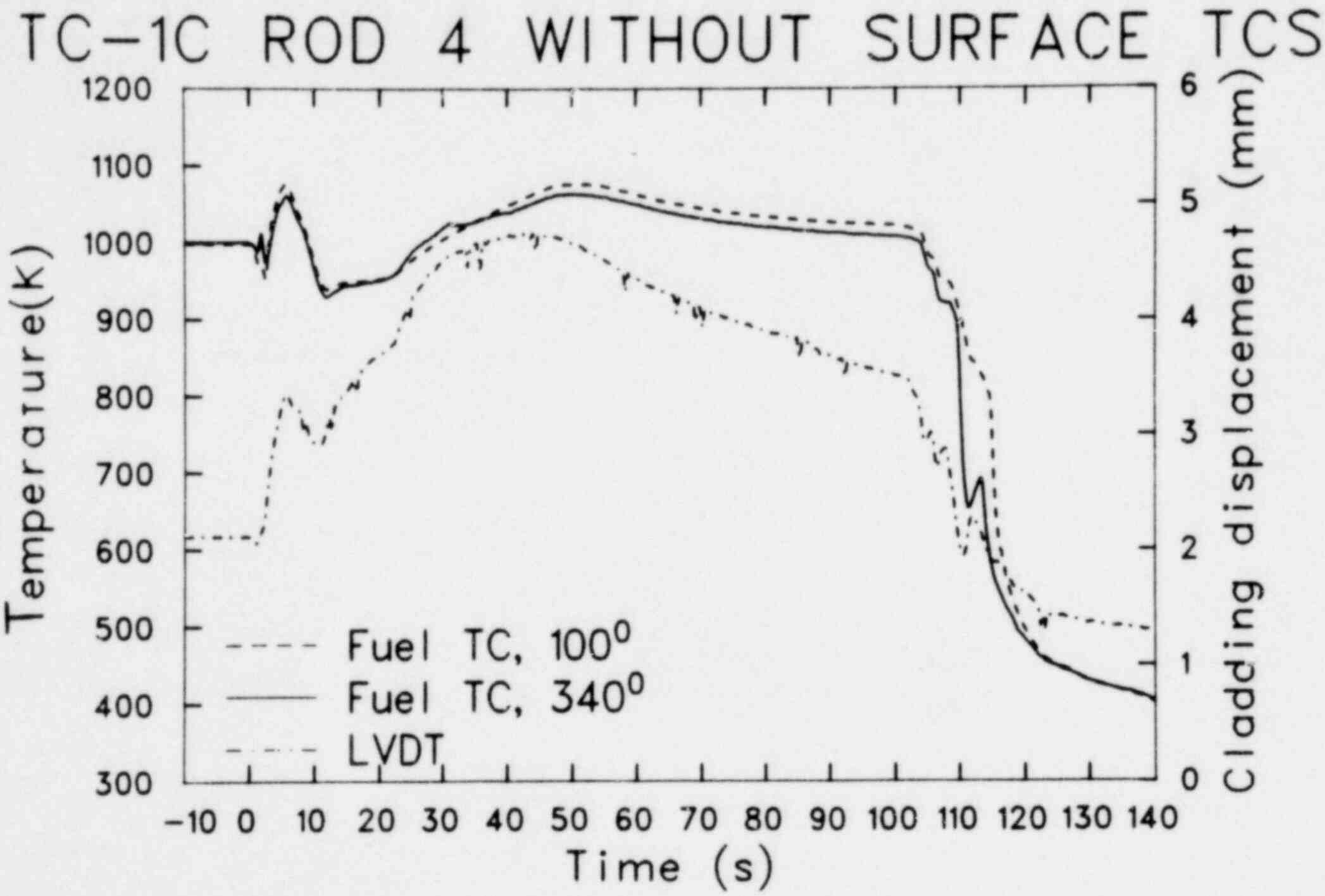
TC–1C ROD 4 WITHOUT SURFACE TCS
Temperature(K)
Cladding displacement (mm)
Time (s)
Fuel TC, 100°
Fuel TC, 340°
LVDT
1200
1100
1000
900
800
700
600
500
400
300
6
5
4
3
2
1
0
–10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140

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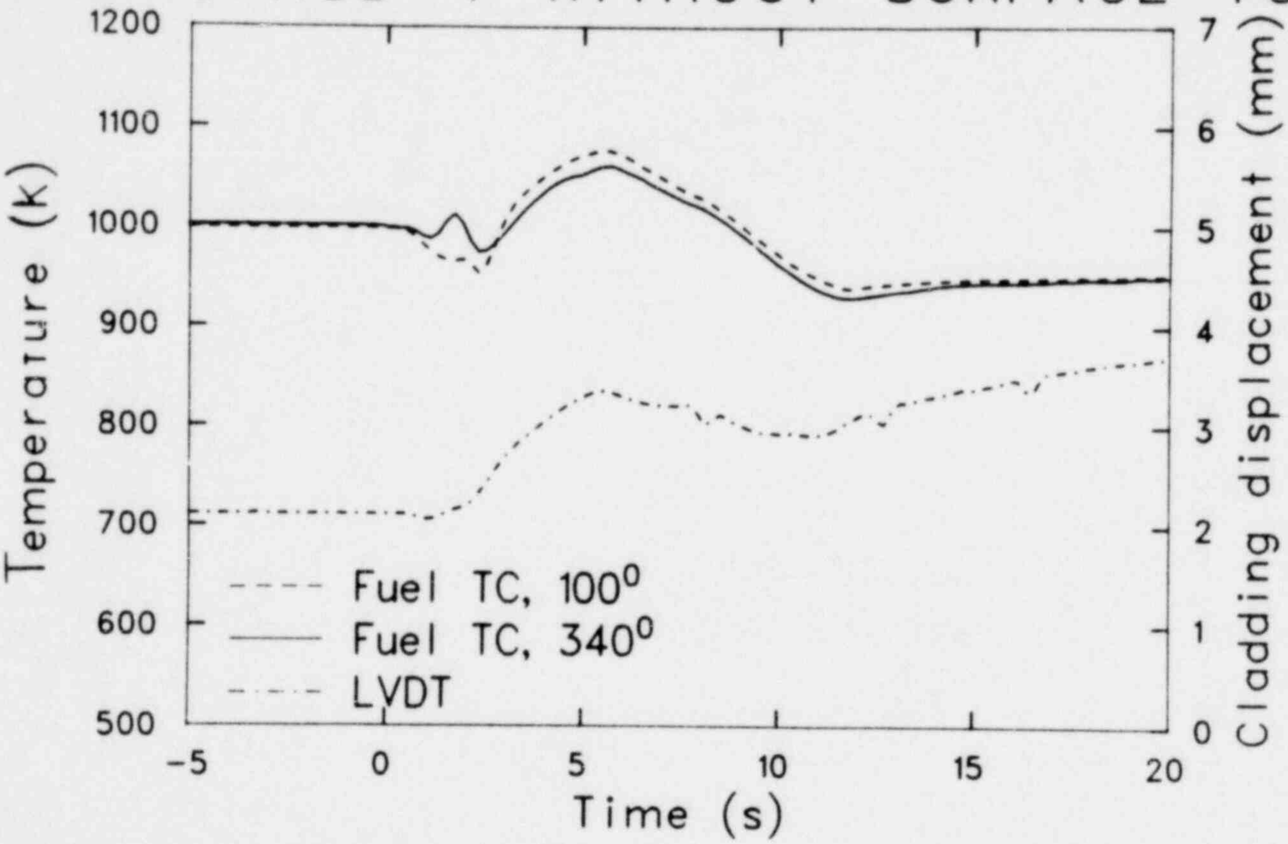
TC-1C ROD 4 WITHOUT SURFACE TCS



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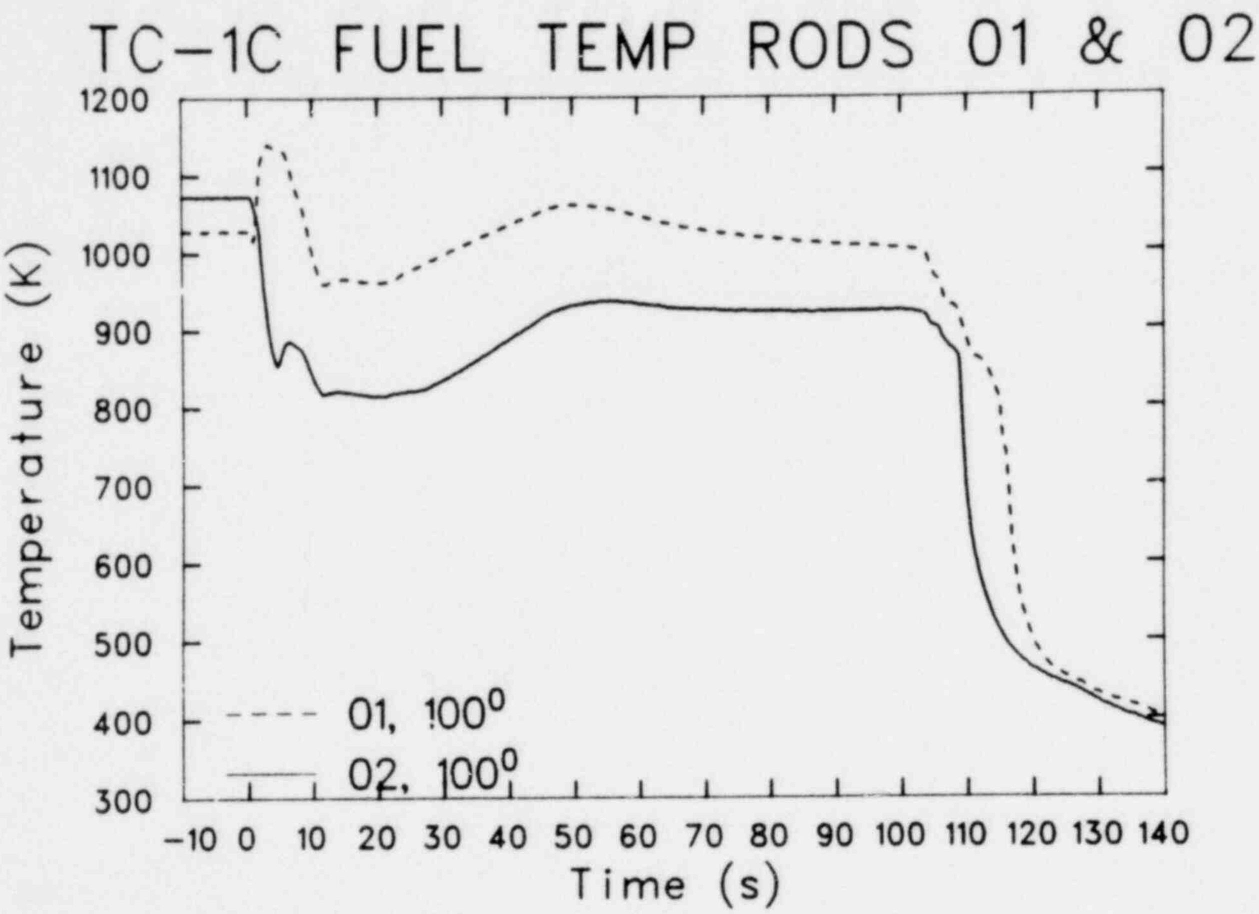

TC–1C FUEL TEMP RODS 01 & 02
1200
1100
1000
900
800
700
600
500
400
300
Temperature (K)
01, 100°
02, 100°
–10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Time (s)

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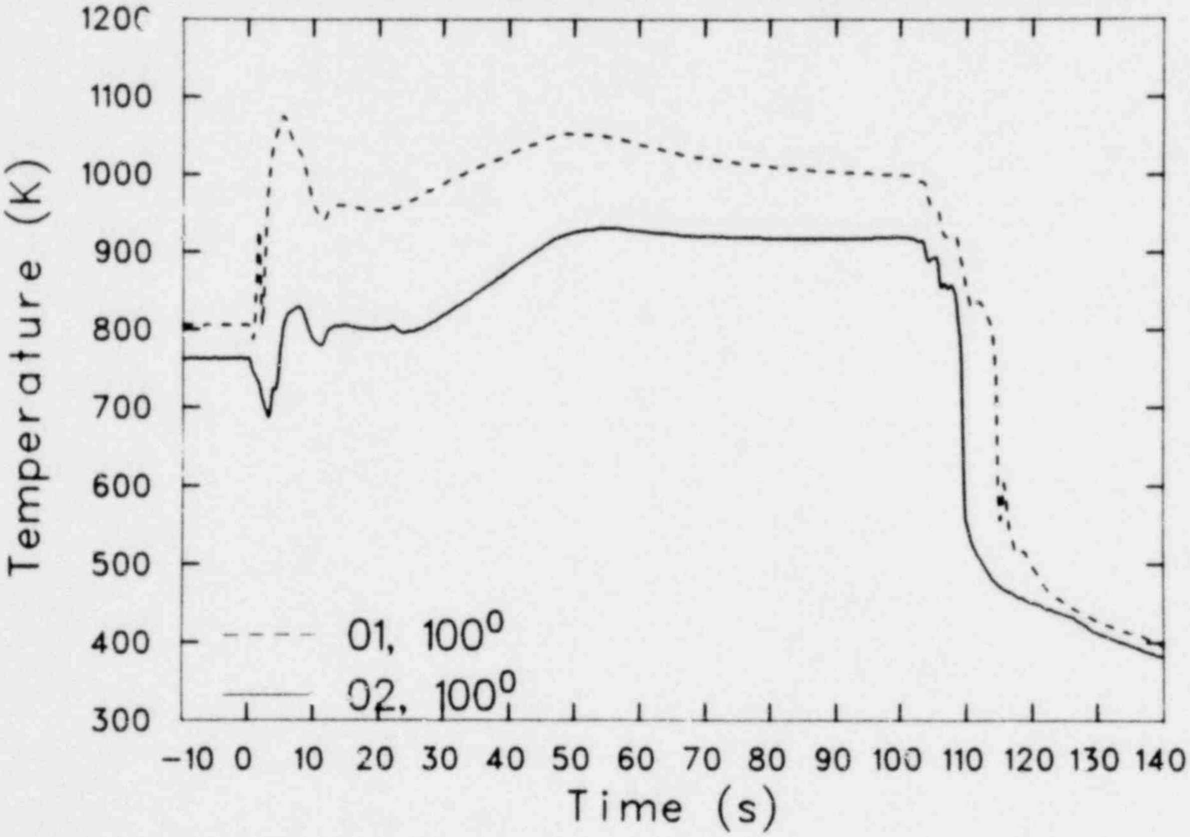
TC-1C INNER CLAD TEMP RODS 1 & 2



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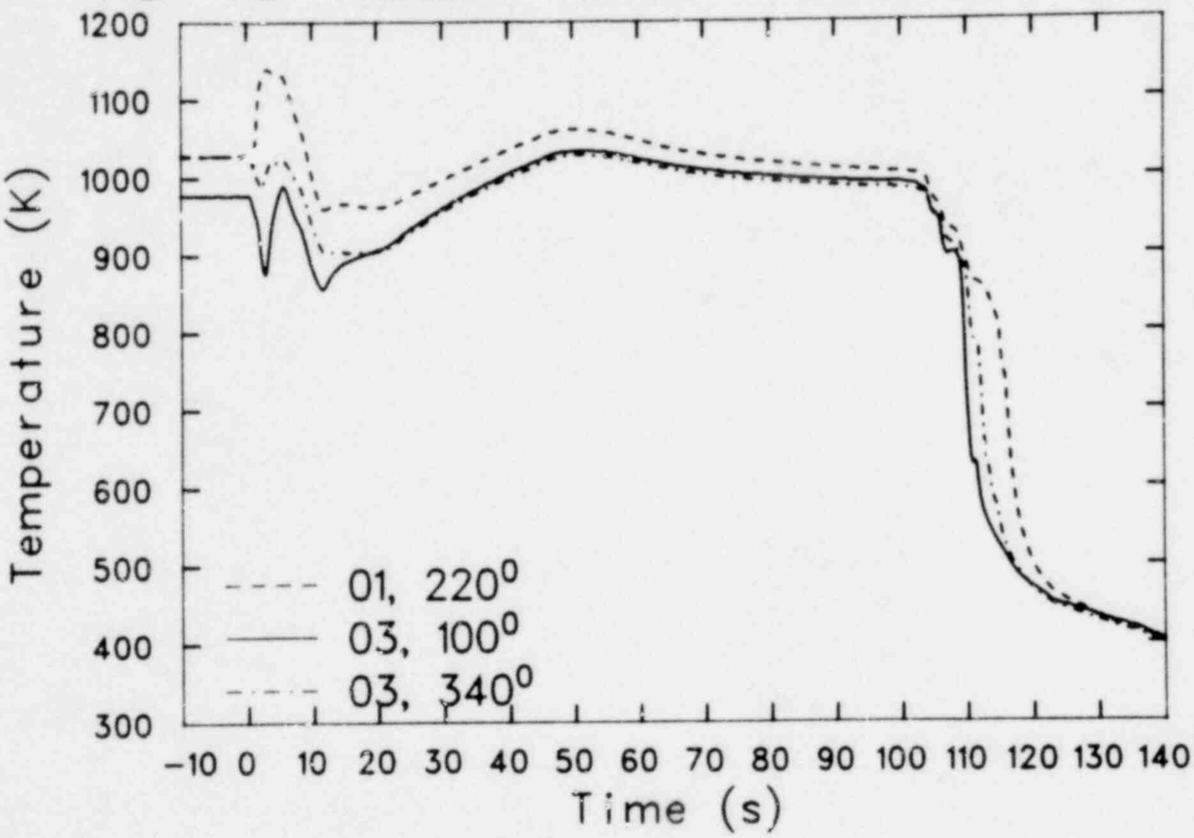
TC-1C FUEL TEMP RODS 01 & 03



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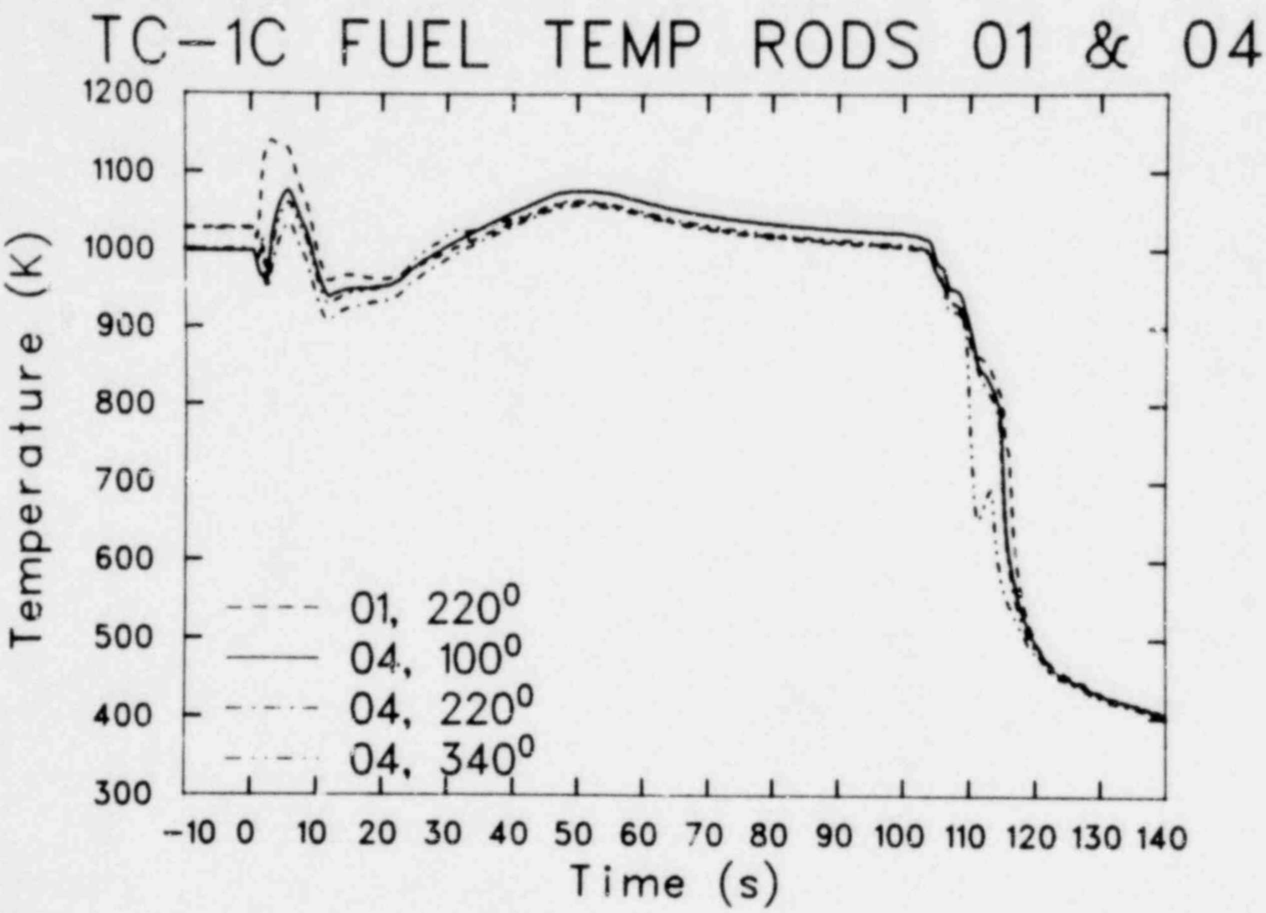

TC-1C FUEL TEMP RODS 01 & 04
Temperature (K)
1200
1100
1000
900
800
700
600
500
400
300
01, 220°
04, 100°
04, 220°
04, 340°
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (s)

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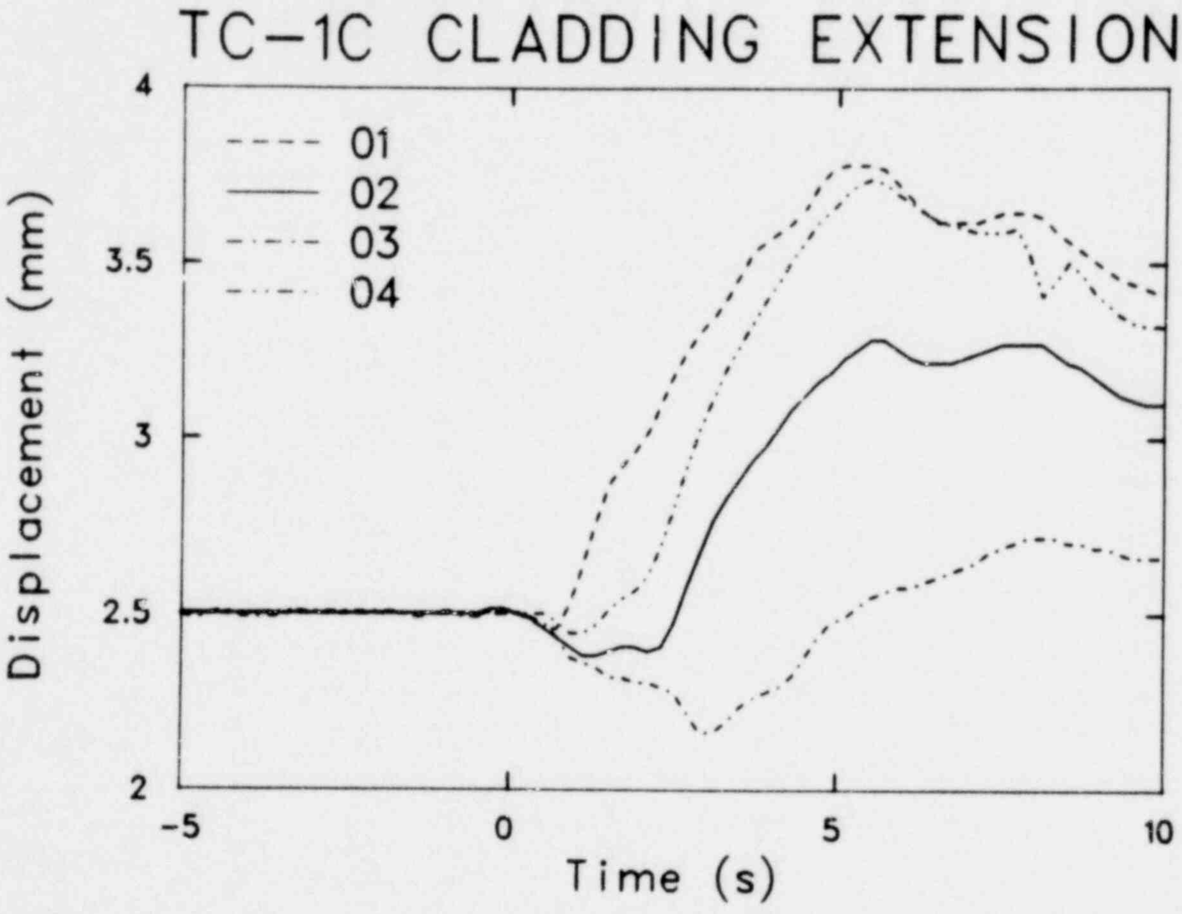
TC-1C CLADDING EXTENSION
Displacement (mm)
Time (s)
01
02
03
04
4
3.5
3
2.5
2
-5
0
5
10

Conclusions

- Surface thermocouples accurately measure local rod behavior

- All rods responded to the two-phase slug

- Surface thermocouples did influence the rod thermal behavior by:

    - Delaying CHF

    - Inducing early rewet during reflood

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