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SUMMARY RESULTS OF THE NEPTUN BOIL-OFF EXPERIMENTS TO INVESTIGATE THE ACCURACY AND COOLING INFLUENCE OF LOFT CLADDING-SURFACE THERMOCOUPLES (SYSTEM 00)

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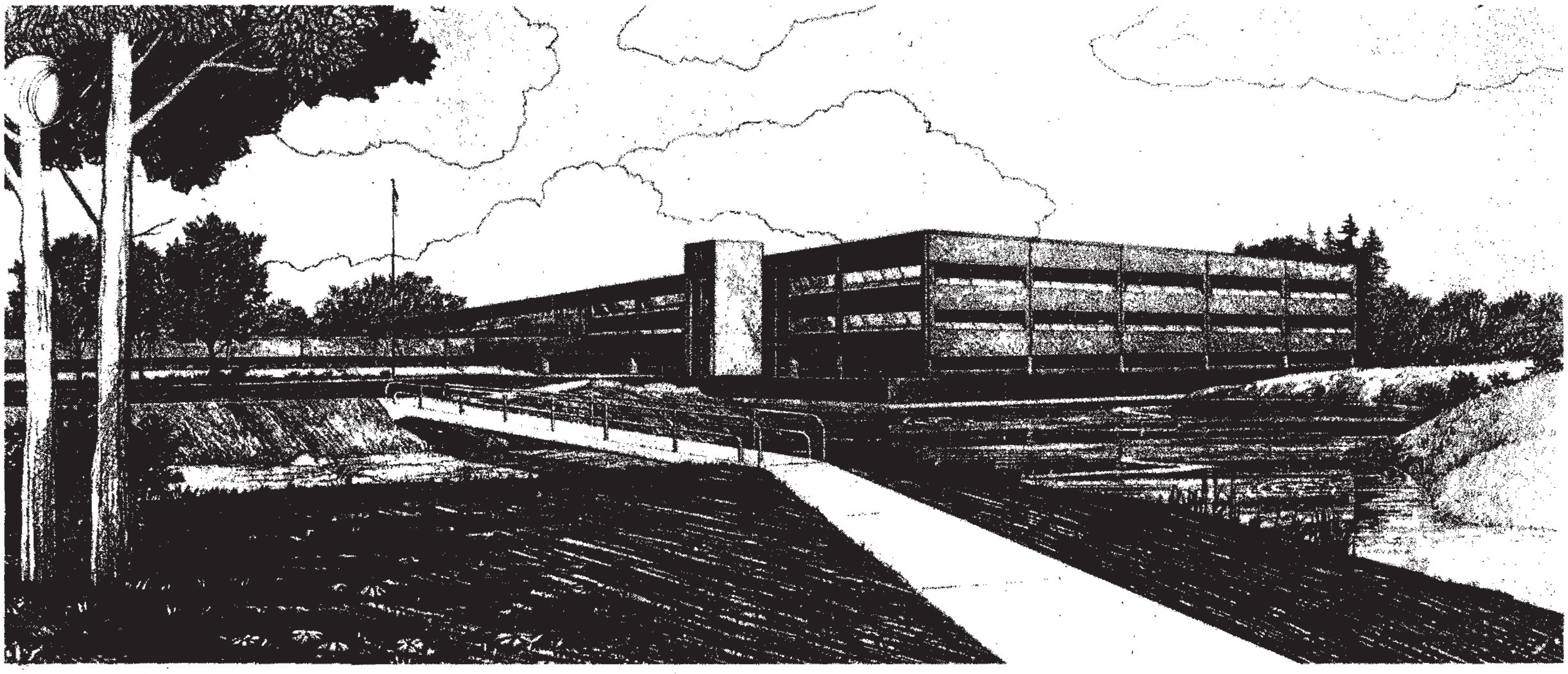

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LOFT TECHNICAL REPORT

Title Summary Results of the NEPTUN Boil-Off Experiments to Investigate the Accuracy and Cooling Influence of LOFT Cladding Surface Thermocouples	LTR No. EGG-LOFT-5554
Author E. L. Tolman, S. N. Aksan	Released By LOFT CDCS
Performing Organization LOFT	Date October 30, 1981
LOFT Review and Approval CW Solbrig LPD Mgr.	Project System Engineer

ABSTRACT

Nine boil-off experiments were conducted in the Swiss NEPTUN Facility primarily to obtain experimental data for assessing the perturbation effects of LOFT thermocouples during simulated small-break core uncovery conditions. The data will also be useful in assessing computer model capability to predict thermal hydraulic response data for this type of experiment. System parameters that were varied for these experiments included heater rod power, system pressure, and initial coolant subcooling.

The experiments showed that the LOFT thermocouples do not cause a significant cooling influence in the rods to which they are attached. Furthermore, the accuracy of the LOFT thermocouples is within 20 K at the peak cladding temperature zone.

DISPOSITION OF RECOMMENDATIONS

No disposition required.

ABSTRACT

Simulated reactor core boil-off experiments were conducted in the Swiss NEPTUN facility to investigate the perturbation effects and accuracy of LOFT-type cladding-surface thermocouples. The NEPTUN facility is briefly described and the boil-off experimental data are discussed and documented.

NRC FIN No. A6053-LOFT Fuel

SUMMARY

Nine boil-off experiments were conducted in the Swiss NEPTUN facility primarily to obtain experimental data for assessing the perturbation effects of LOFT thermocouples during simulated small-break core uncovery conditions. The data will also be useful in assessing computer model capability to predict thermal hydraulic response data for this type of experiment. System parameters that were varied for these experiments included heater rod power, system pressure, and initial coolant subcooling.

The experiments showed that the LOFT thermocouples do not cause a significant cooling influence in the rods to which they are attached. Furthermore, the accuracy of the LOFT thermocouples is within 20 K at the peak cladding temperature zone.

ACKNOWLEDGMENTS

The NEPTUN experiments described in this report were conducted by the staff of Eidg. Institut für Reactorforschung (EIR), Wurenlingen, Switzerland, under the direction of Messrs. G. Varadi and F. Stierli. The NEPTUN system and associated instrumentation worked well and the EIR staff is to be commended for their timely modifications to the NEPTUN bundle configuration (to include LOFT thermocouples) and for the conduct, analysis, and coordination of the experiments. Also, the efforts of Mr. S. N. Aksan of EIR, currently working at EG&G Idaho, are acknowledged for his suggestions and supporting liaison between EG&G Idaho and EIR.

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FIGURES

TABLES

1. INTRODUCTION

During a LOFT small break loss-of-coolant experiment in which the core is uncovered, accurate measurement of the cladding temperature is important to (a) ensure adequate experiment control, and (b) characterize fuel behavior and changing core hydraulics. The accuracy or perturbation influence of the LOFT thermocouples during a core uncovery event, characterized by a slowly decreasing two-phase coolant level and very low rod power levels, have not been previously quantified; however, various cooling mechanisms can be hypothesized to result in cladding surface thermocouple inaccuracy.[1] Experiments have recently been conducted in the Swiss NEPTUN facility to evaluate the accuracy and cooling influence of the LOFT surface thermocouples over a range of power and system pressures representative of a small break loss-of-coolant accident (LOCA).

The NEPTUN facility utilizes a heater rod bundle which duplicates the LOFT fuel rod size (both radially and axially), grid spacer configuration and placement, axial power profile, and is capable of utilizing selected rods instrumented with LOFT-type cladding-surface thermocouples. Thus, the NEPTUN experiment results are expected to be representative of the LOFT core response.

The NEPTUN system configuration and test matrix are discussed in Section 2. Section 3 summarizes the result of the NEPTUN boil-off experiments in terms of the general system response and in regard to LOFT thermocouple accuracy. Section 4 discusses the results and presents conclusions regarding the adequacy of LOFT thermocouples for slow core uncovery experiments.

2. NEPTUN CONFIGURATION AND TEST MATRIX

The Swiss NEPTUN facility configuration is shown in Figure 1 and described in Reference 2. The system was initially designed for low-pressure (<75 psi) reflooding experiments. The heater rod bundle cross-section is shown in Figure 2. Each heater rod has radial and axial dimensions similar to the LOFT fuel rods, and the heater rod bundle uses typical LOFT fuel assembly spacer grids, axially located identically to LOFT. The design of the NEPTUN heater rod allows a continuously variable axial power profile similar to that of LOFT, as shown in Figure 3.

The NEPTUN-LOFT support experiments conducted in the NEPTUN facility are outlined in Reference 2 and include experiments to investigate the effect of LOFT cladding-surface thermocouples during both reflood and core boil-off experiments. The effects of the surface thermocouple are determined by comparing the cladding temperature (as measured by the LOFT thermocouples) to cladding temperature measurements from thermocouples within the cladding of the NEPTUN heater rod, as shown in Figure 4. Figure 5 shows a schematic of both the LOFT-type and NEPTUN embedded thermocouple configuration used for the experiments discussed in this report. Note that there is only one active LOFT thermocouple on each of the five rods with surface thermocouples; the other cladding-surface thermocouples are "dummy" segments. The only difference between NEPTUN and LOFT surface thermocouple placement is a slight adjustment to align the axial elevation of the active LOFT thermocouples with the nearest NEPTUN embedded thermocouple elevation so that direct comparisons can be made.

The nine core boil-off experiments performed are summarized in Table 1. Three parameters were varied--rod power, system pressure, and initial coolant subcooling. Rod power levels were chosen to represent the nuclear decay power over a range of time as shown in Figure 6. System pressure was varied over the 1- to 5-bar (15-70 psi) range possible in the NEPTUN facility.

Experiment number 5007 (see Table 1) was chosen as the "base case" because it was conducted at higher pressure and intermediate power. However, several experiments will be summarized to show the difference in the NEPTUN

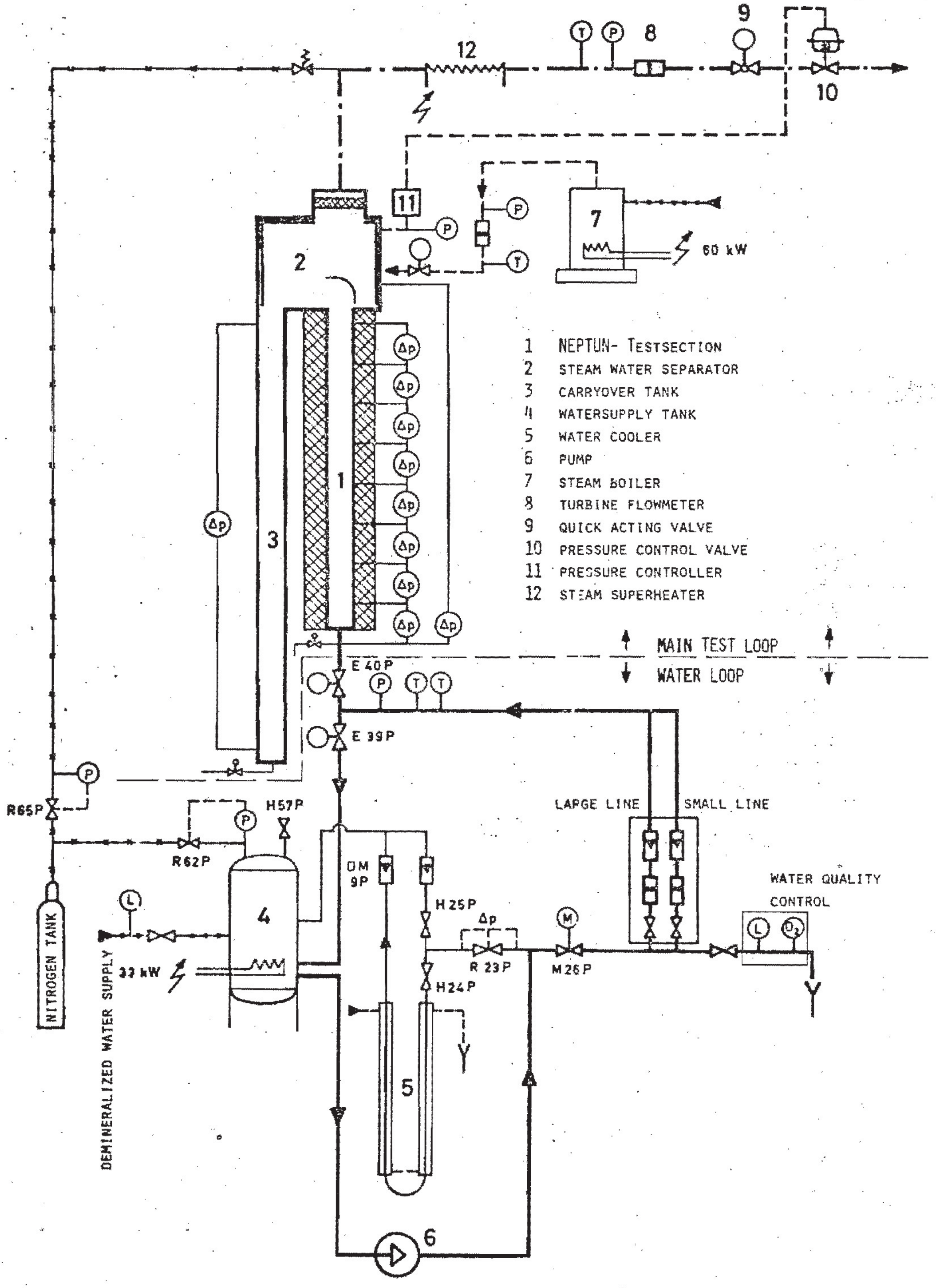


Figure 1. NEPTUN system configuration.

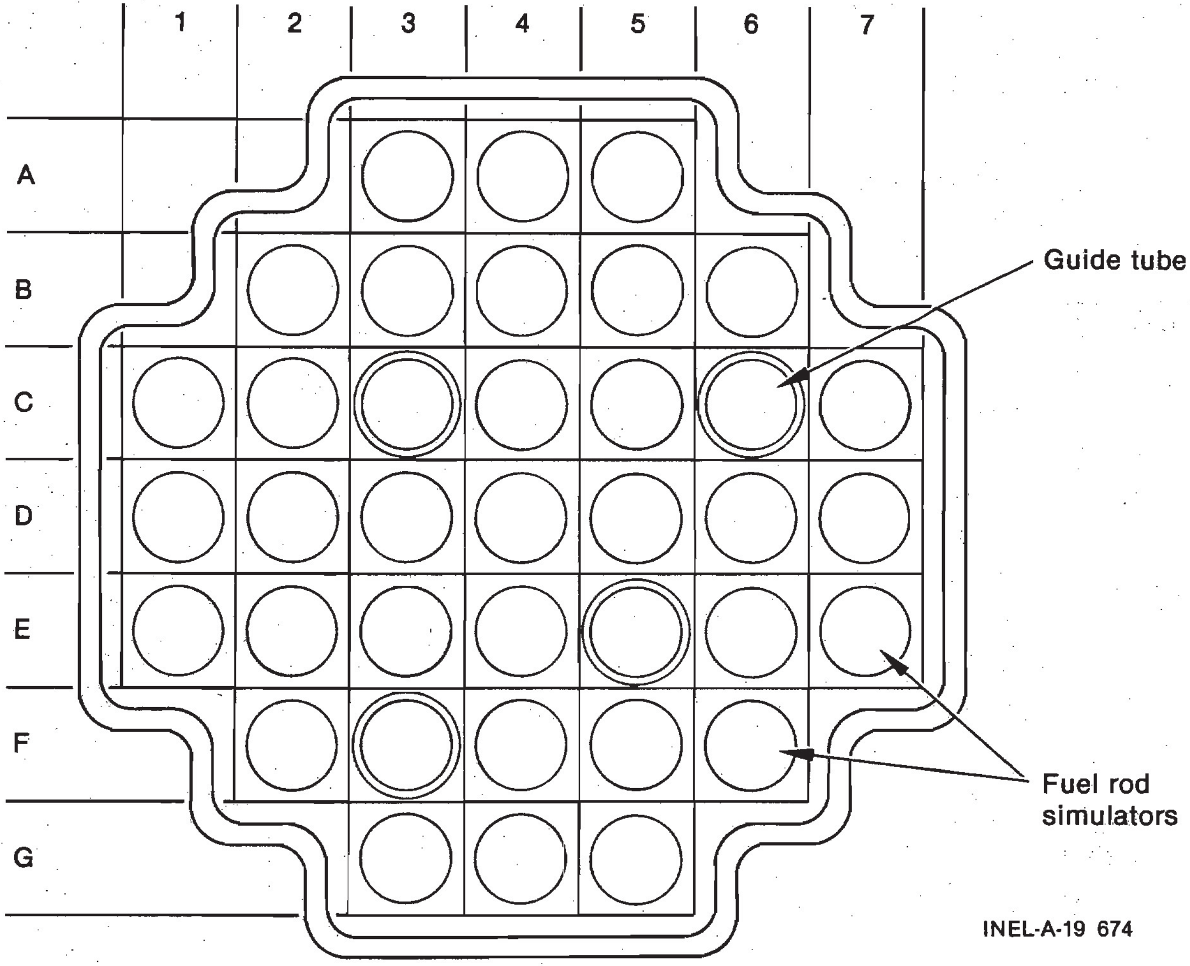


Figure 2. NEPTUN heater rod bundle configuration.

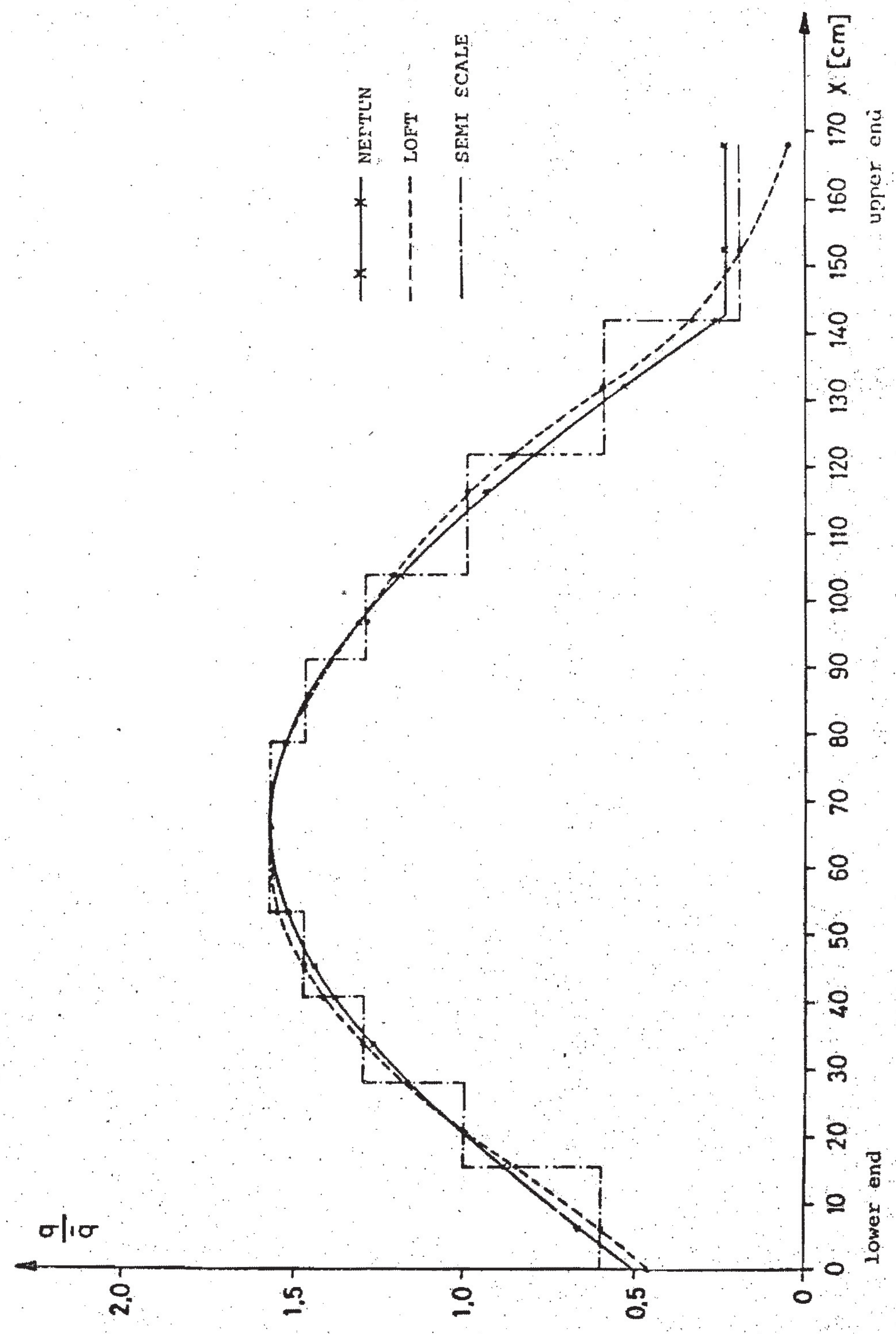
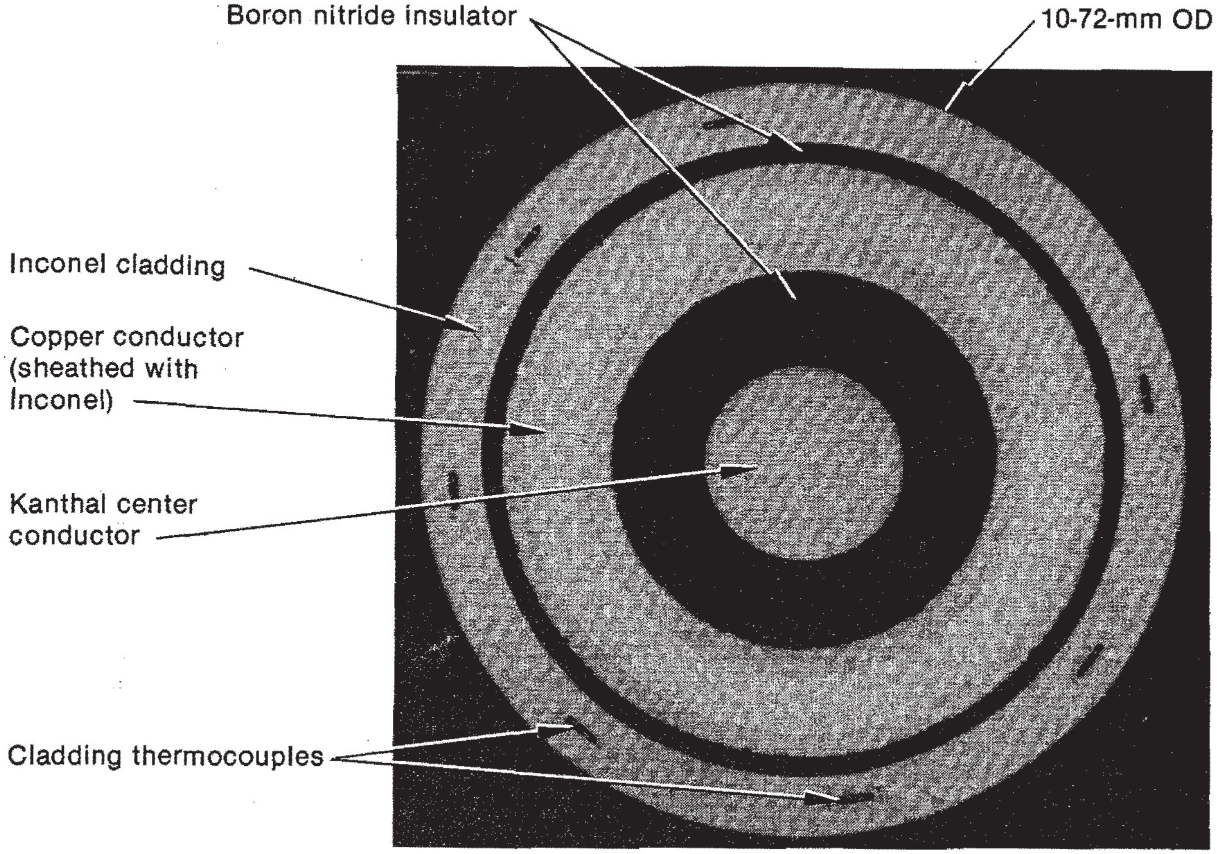


Figure 3. Comparison of NEPTUN and LOFT axial power profile.



NEPTUN Axial Level	Distance from Vessel Inlet Midpoint (mm)	Distance from Bottom of Active Heater Rod (mm)	Distance from Bottom of Active Heater Rod (inches)
1	250	50	1.9
2	482	282	11.1
3	714	514	20.2
4	946	746	29.3
5	1178	978	38.5
6	1410	1210	47.6
7	1642	1442	56.7
8	1874	1674	65.9

Figure 4. NEPTUN heater rod cross-section and axial thermocouple elevations.

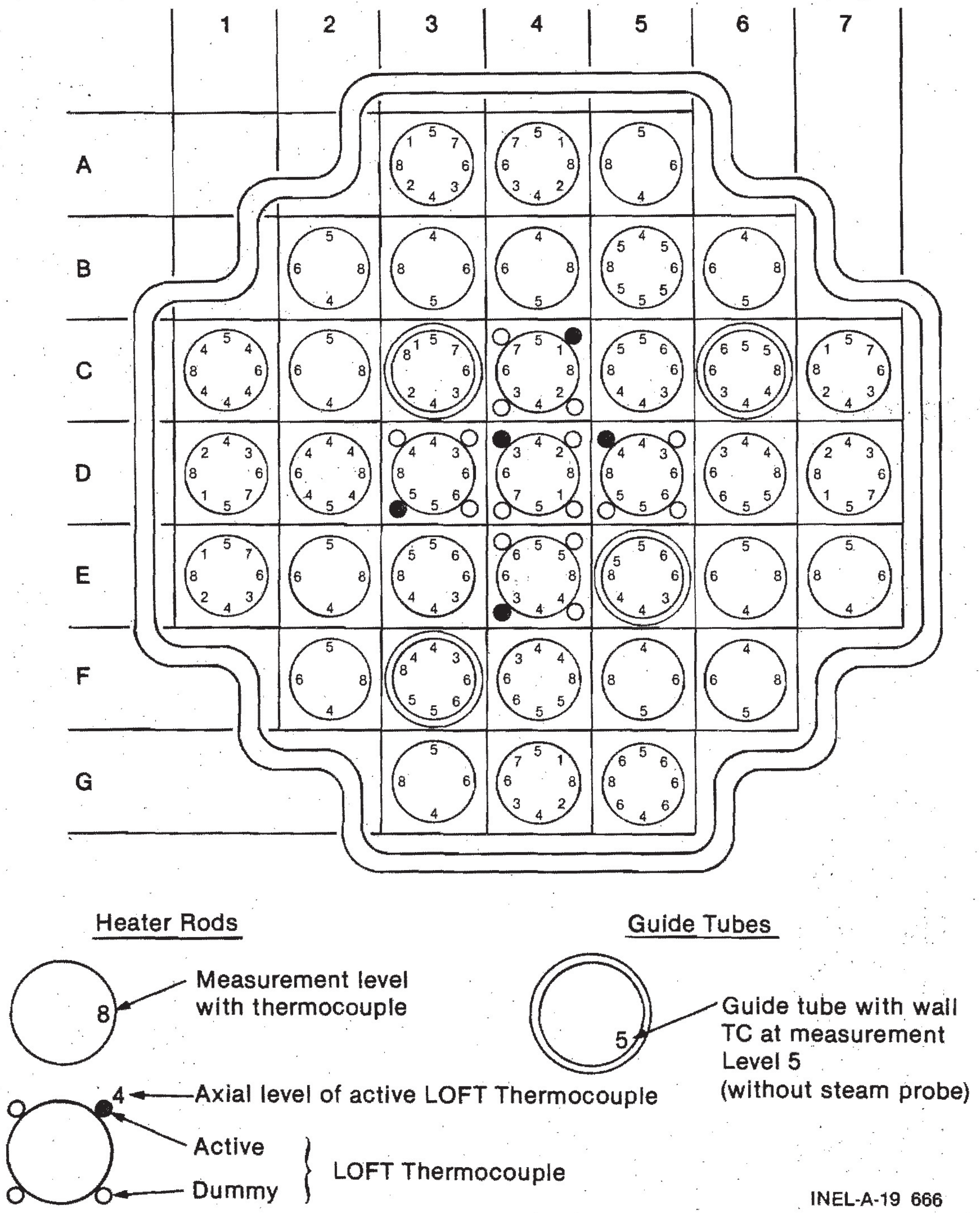


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Figure 5. NEPTUN bundle thermocouple configuration for boil-off experiments.

TABLE 1. SUMMARY OF NEPTUN BOIL-OFF EXPERIMENTS

Experiment Number	Rod Peak Power (kW/rod)	System Pressure (bar)	Initial Coolant Temperature (°C)	Comments
5000	0.744-4.6	1	100	Powers were too high for the first test; the data were not evaluated from this experiment
5001	0.744	1	100	Repeat experiment at low pressure
5002	0.744	1	100	Repeat experiment at low pressure
5004	0.744	5	120	Effects of changing rod power and initial coolant subcooling
5005	1.276	5	120	Effects of changing rod power and initial coolant subcooling
5006	1.276	5	140	Effects of changing rod power at high system pressure
5007[a]	0.744	5	140	Effects of changing rod power at high system pressure
5008	0.319	5	140	Effects of changing rod power at high system pressure
5009	1.276	5	140	Repeat of high-power, high-pressure experiment 5006 with higher data-scanning rate

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a. Base case

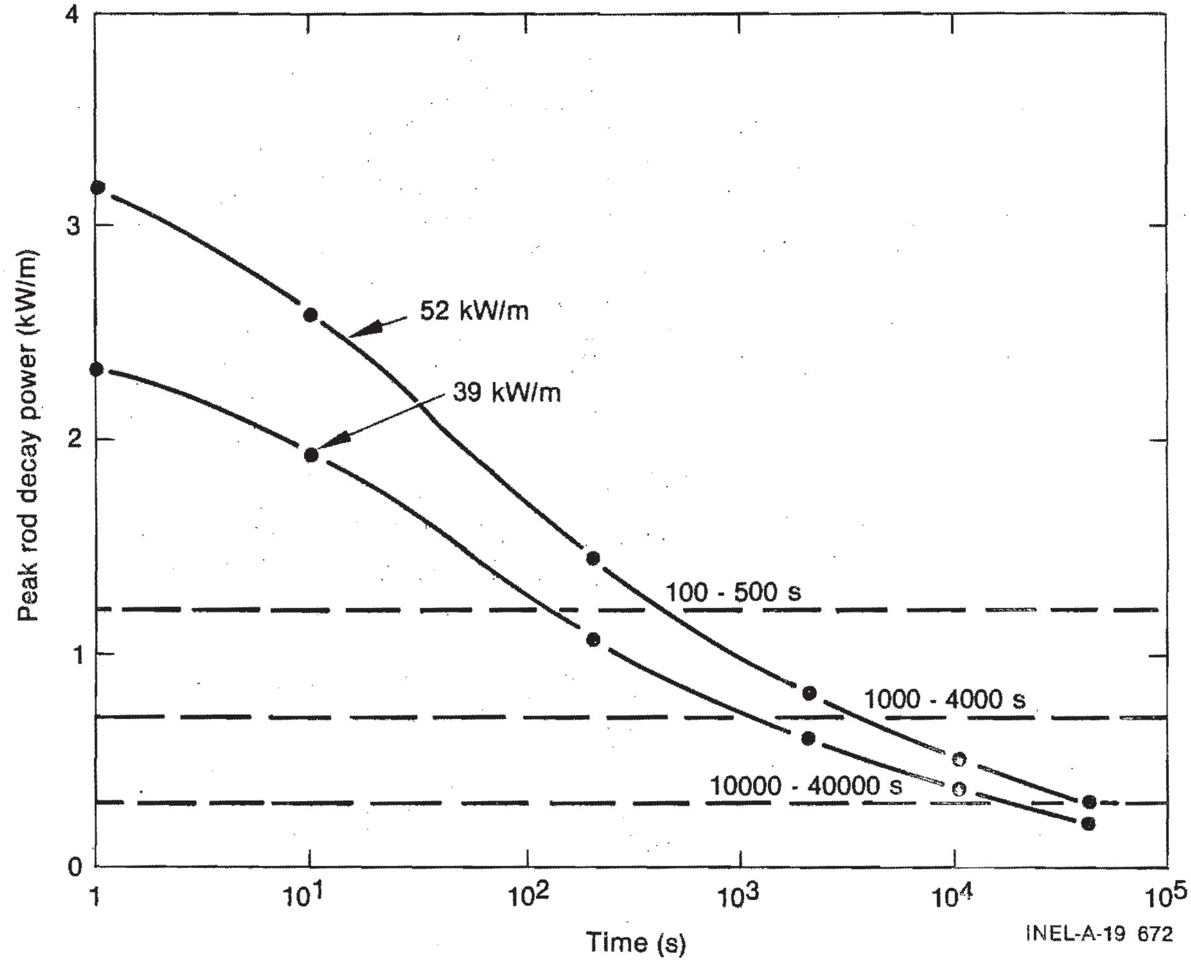

Figure 6. LOFT decay power curves showing power range for NEPTUN boil-off experiments.

system response due to varying rod power, system pressure, initial water subcooling, and finally, to demonstrate experiment repeatability.

2.1 System Response--Base Case, Experiment 5007

Figure 7 presents an overlay[a] of the core power history, core fluid level as measured by the core total Δp measurement, and typical responses of the heater rod thermocouples for the base case. Notice that the power is increased at about 50 s, and that a rapid drop in the core fluid level occurs at about 100 s. This delay time between initial power and the rapid initial liquid level decrease is a result of heating the subcooled water to the saturation temperature. Shortly after the water reaches the saturation temperature (between 100 and 110 s), large voids are formed due to vapor generation, expelling the liquid in the core. After this initial liquid swell, the core liquid continues to be slowly boiled off as shown by the decreasing core Δp in Figure 7. The cladding thermocouples dry out and heat up with differing heat-up rates for each axial elevation. At ∿800 s the power is shut off and the rods are allowed to cool down before the system is reflooded.

2.2 System Response--Effect of Core Power

The effects of increasing the core power (experiment 5006) and decreasing core power (experiment 5008) on the core boil-off response are presented in Figures 8 and 9, respectively, which can be compared directly to the base case (5007) response shown in Figure 7. The system responded as expected in each case; increased core power resulted in more rapid boil-off and cladding heatup, and decreased power resulted in the opposite trends.

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[a] The system response overlays are presented to compare selected general system response data. All measured data for each experiment (with the exception of 5000) are presented in Appendices B-I on microfiche.

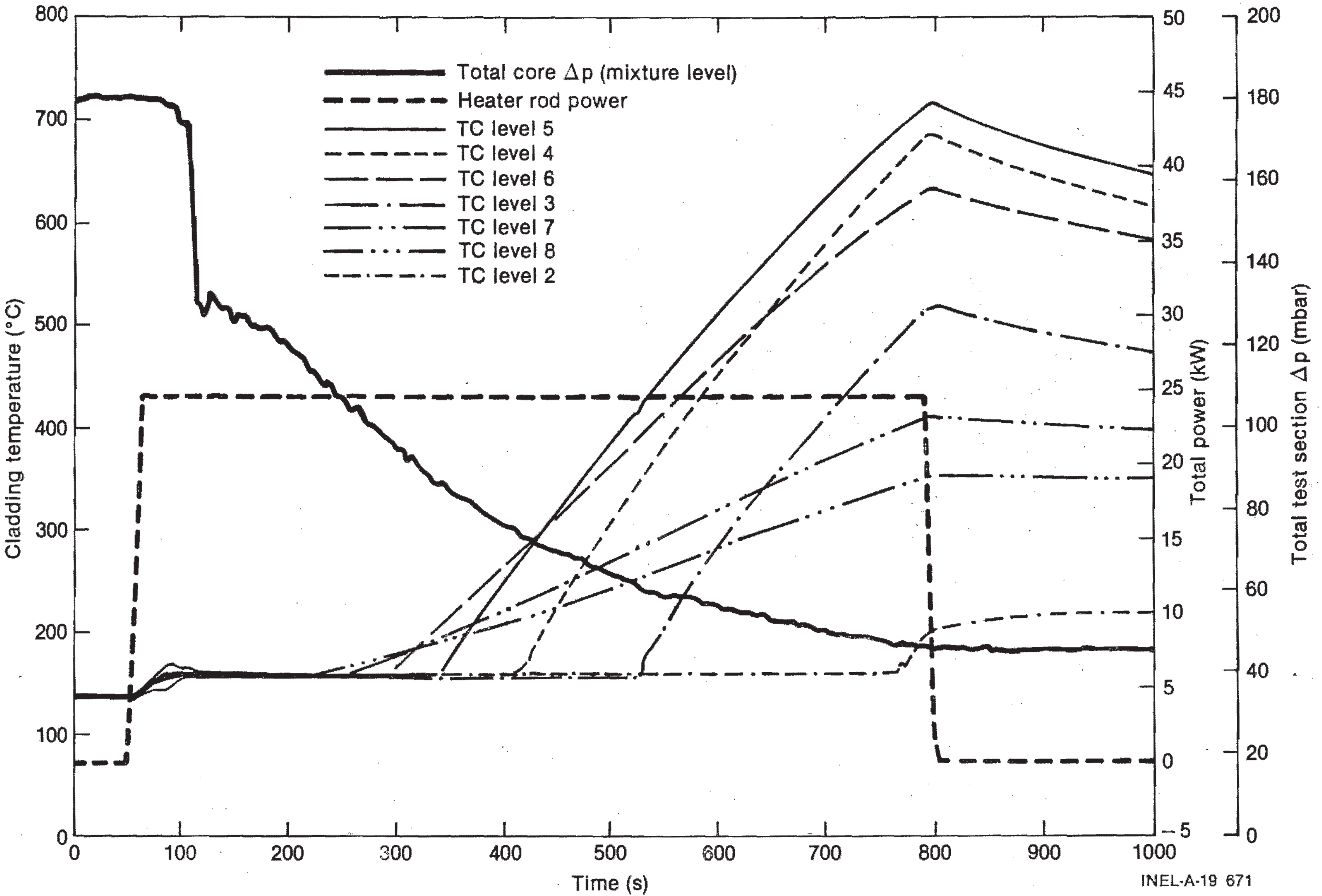

Figure 7. NEPTUN system response--base case (test 5007--high system pressure, intermediate rod power).

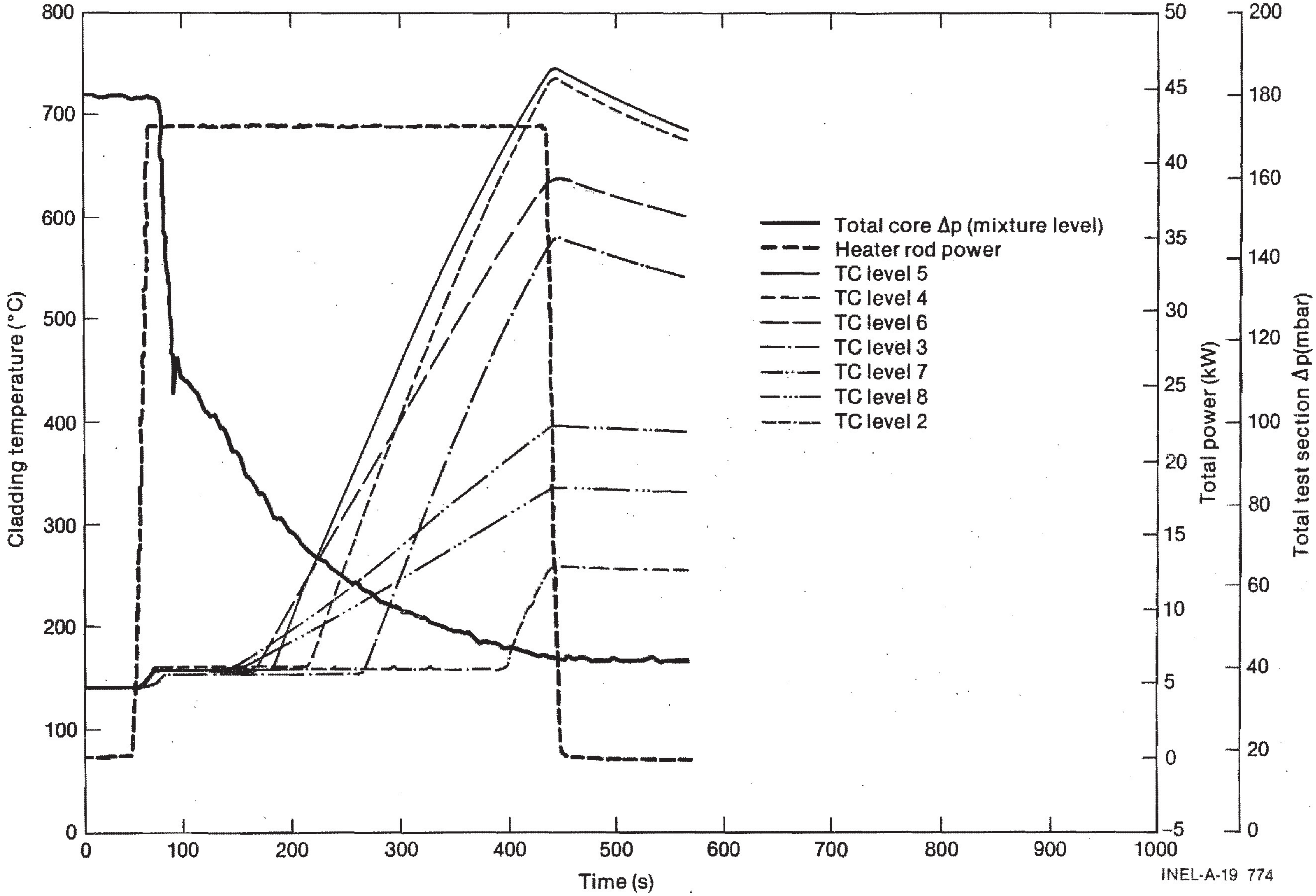

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Figure 8. NEPTUN system response--test 5006--high system pressure, high rod power.

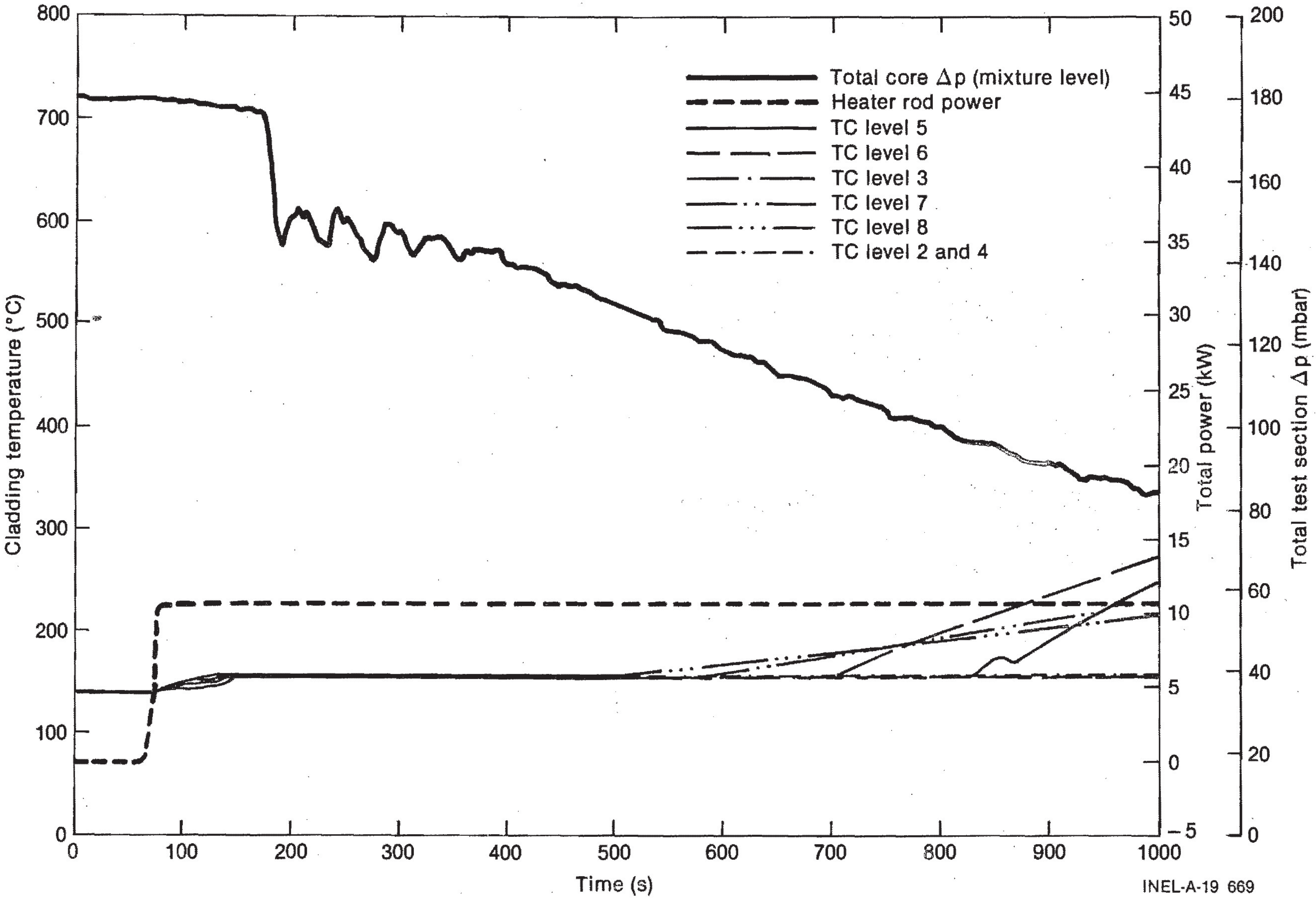

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Figure 9. NEPTUN system response--test 5008--high system pressure.
power. (Note: Time scale has been extended for clarit

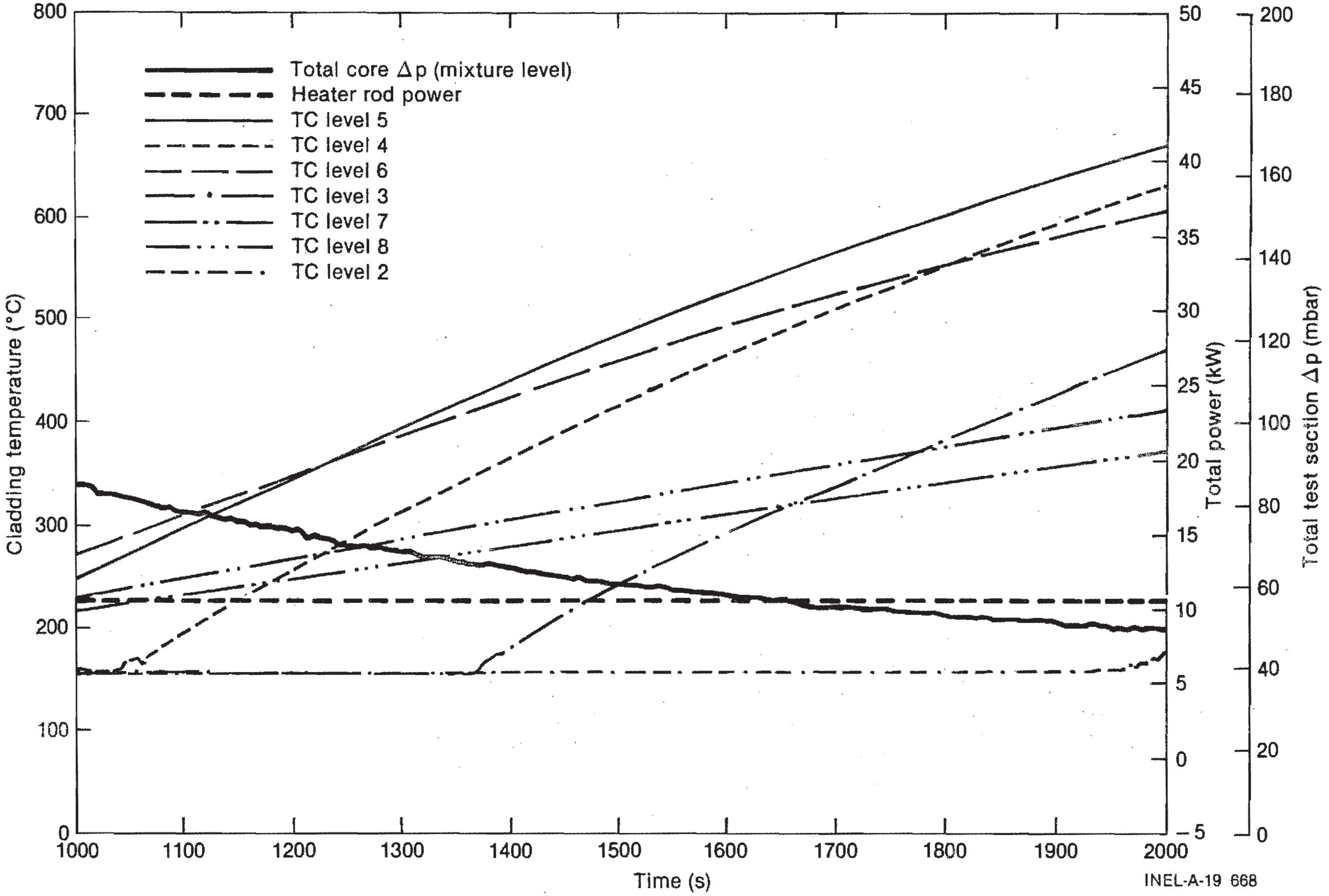

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Figure 9. (continued).

2.3 System Response--Effect of System Pressure

The effect of lowering the system pressure from 5 to 1 bar (experiment 5002) on the core liquid level and cladding temperatures is shown in Figure 10. The lower system pressures result in more rapidly decreasing liquid levels and rod dryouts ranging from 100-200 s earlier than experienced for the base case (Figure 7).

2.4 System Response--Experiment Repeatability

The system was found to be very repeatable for both high- and low-pressure conditions. Experiments 5001 and 5002 were repeat experiments at low pressures. Figure 11 shows the system response for the repeat conditions (experiment 5001) for comparison to Figure 10, discussed in the previous section. Experiments 5006 and 5009 are repeat experiments at high pressure. For comparison of these experiments refer to the appropriate appendices.

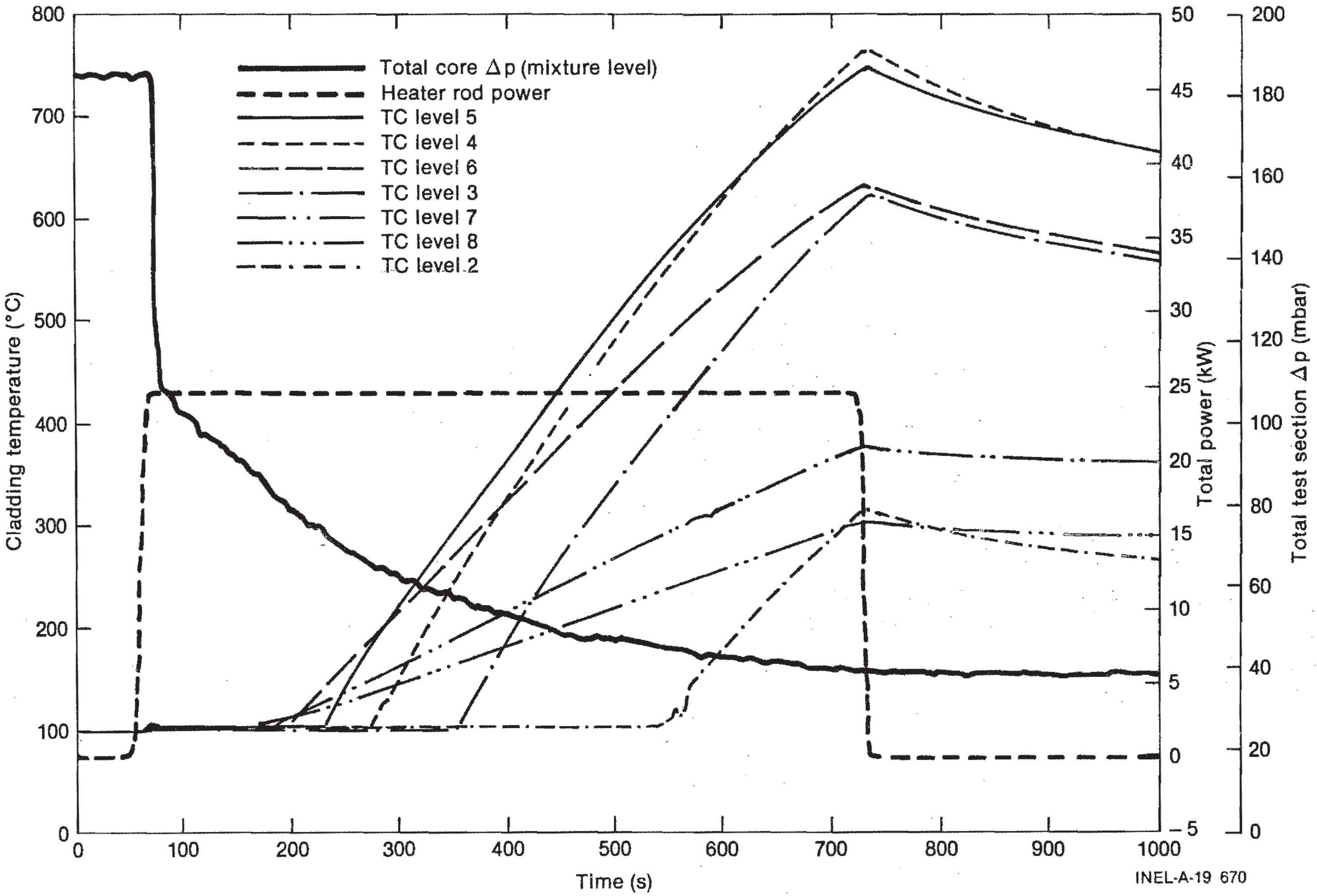


Figure 10. NEPTUN system response--test 5002--low system pressure, intermediate rod power.

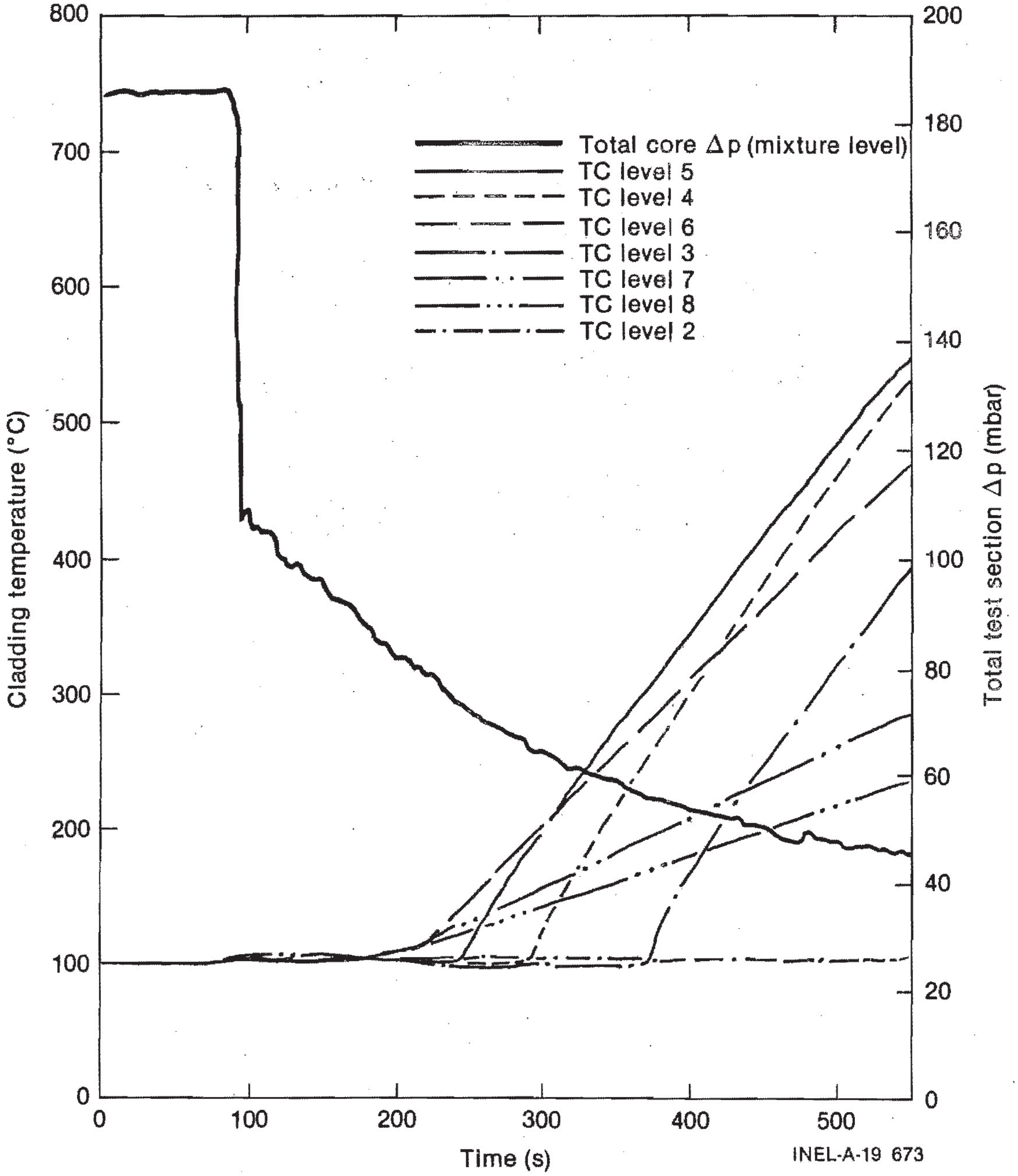


Figure 11. NEPTUN system response--test 5001--low system pressure, intermediate rod power.

3. EVALUATION OF LOFT THERMOCOUPLE RESPONSE

Prior to the NEPTUN experiments, it was hypothesized that the LOFT thermocouples might cause additional selective cooling of the rods, which would result in delayed dryout for a slow core uncovery experiment in LOFT. Also, the added increase in surface area for heat transfer (fin effect) might result in accuracy problems. It was found from the NEPTUN experiments that delayed dryout was less than 10 s and fin cooling was less than 20 K.

Overlay plots of the thermocouple responses for many different thermocouples at each axial elevation are contained in the appendices for each experiment. Examples of these plots are shown in Figures 12 through 16, corresponding to axial elevations of the LOFT thermocouples for the base case (experiment 5007). Notice that in each of these plots the LOFT thermocouple is well within the response spread of the internal thermocouples.

To better understand the relative heater rod responses within the NEPTUN bundle, the rods were grouped and compared according to their locations within the test bundle. Figure 17 shows a schematic of the various rod thermocouple groups, categorized as:

1. Peripheral rods (thermocouples facing shroud)
2. Peripheral rods (thermocouples facing other rods)
3. Intermediate rods
4. Center bare rods (no LOFT thermocouples)
5. Center LOFT rods (with LOFT thermocouples)
6. LOFT thermocouples

Grouping the rods in this manner provided a more consistent view of thermocouple response, allowing an estimation of LOFT thermocouple accuracy, as shown below.

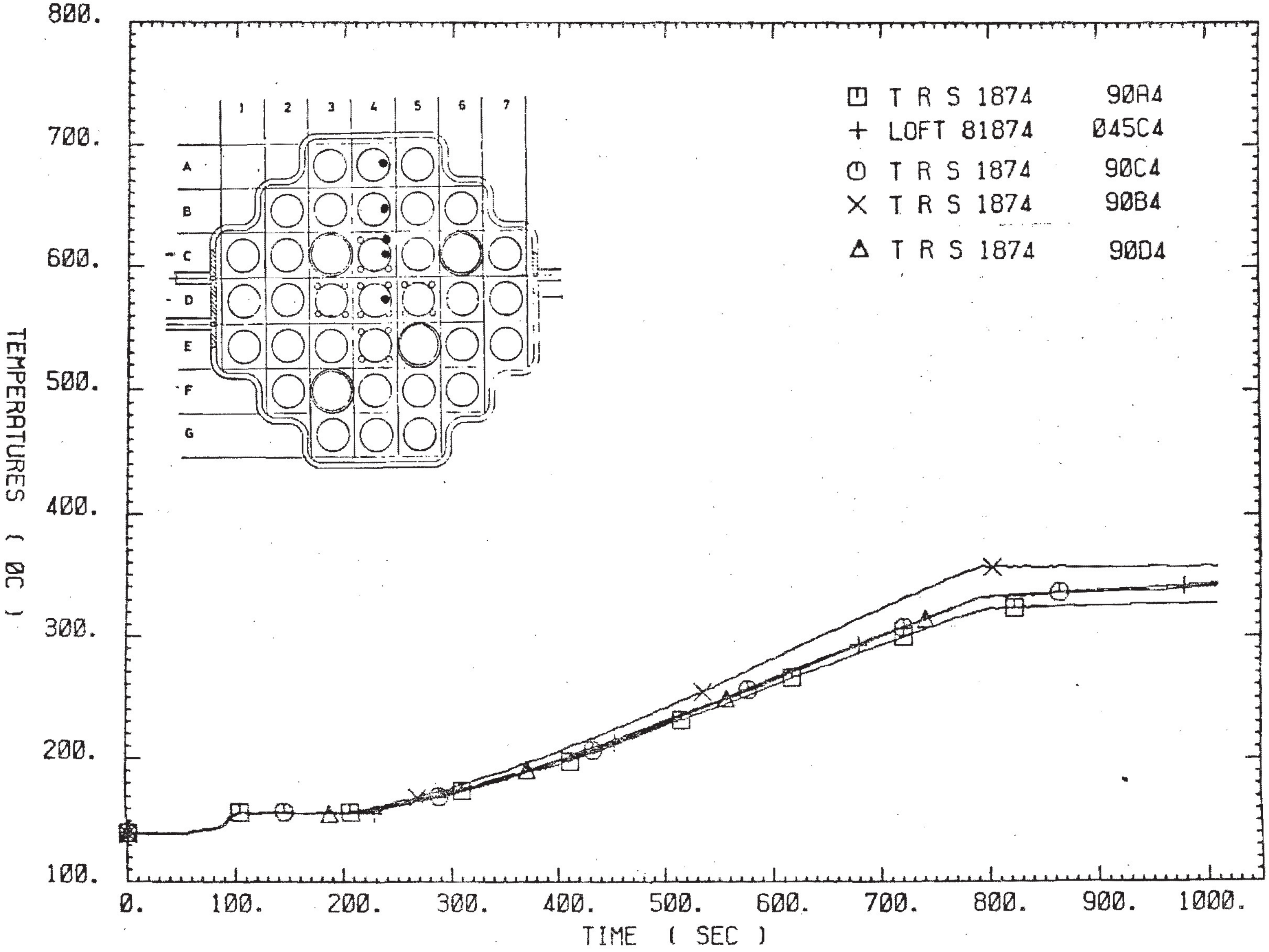


Figure 12. Overlay comparisons of selected NEPTUN thermocouples--axial elevation 8, base case experiment 5007.

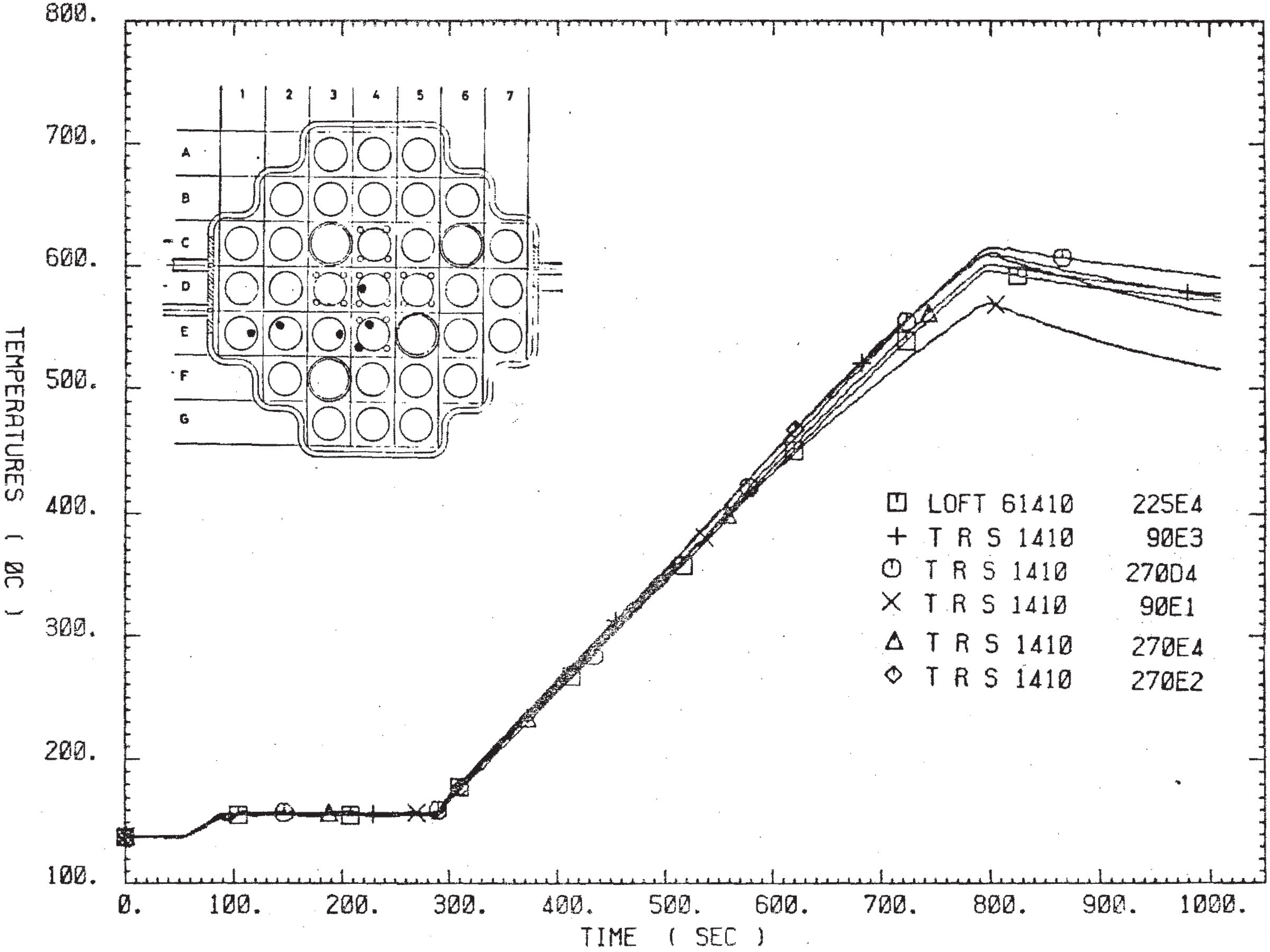


Figure 13. Overlay comparisons of selected NEPTUN thermocouples--axial elevation 6, base case experiment 5007.

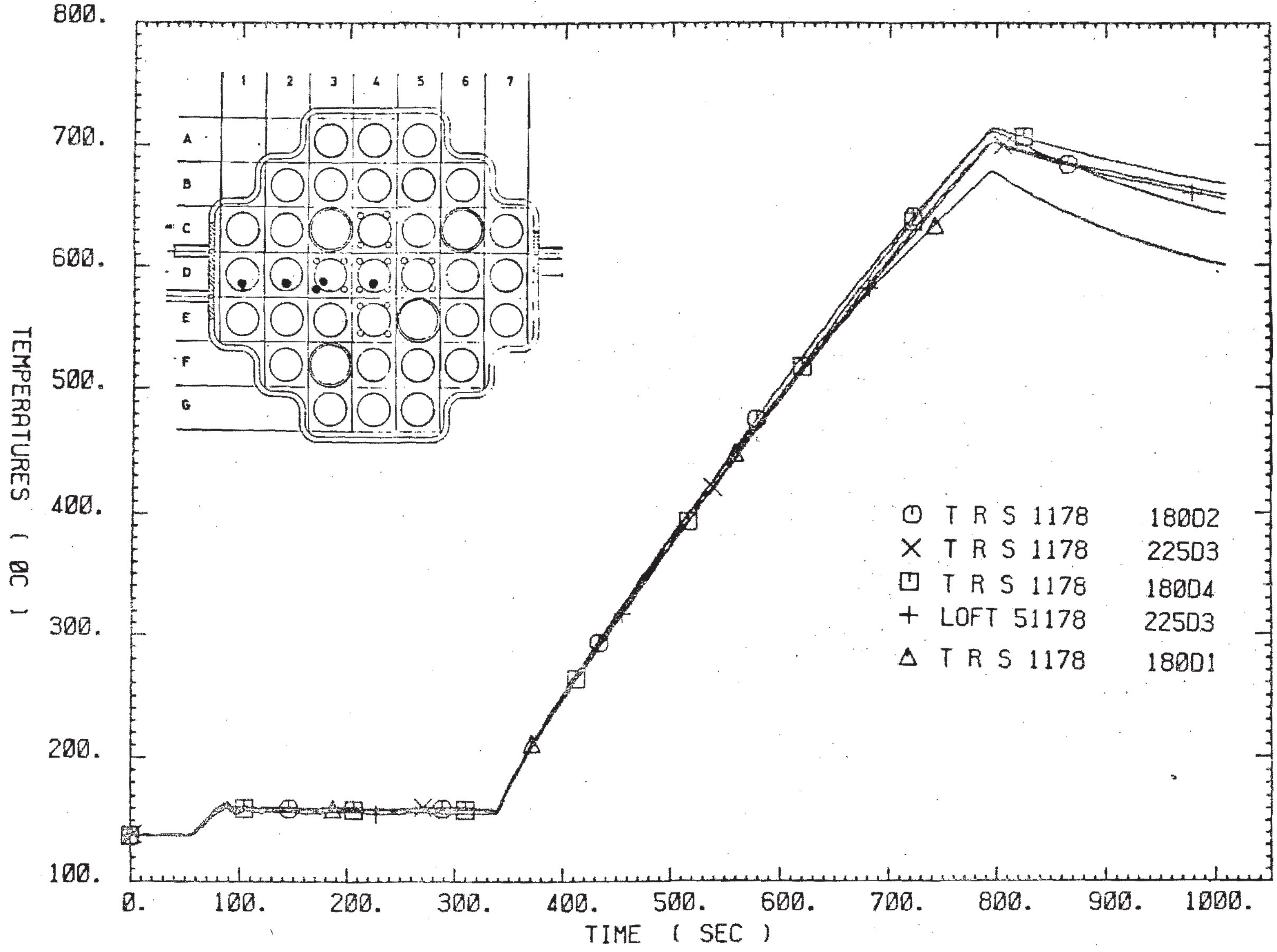


Figure 14. Overlay comparisons of selected NEPTUN thermocouples--axial elevation 5.

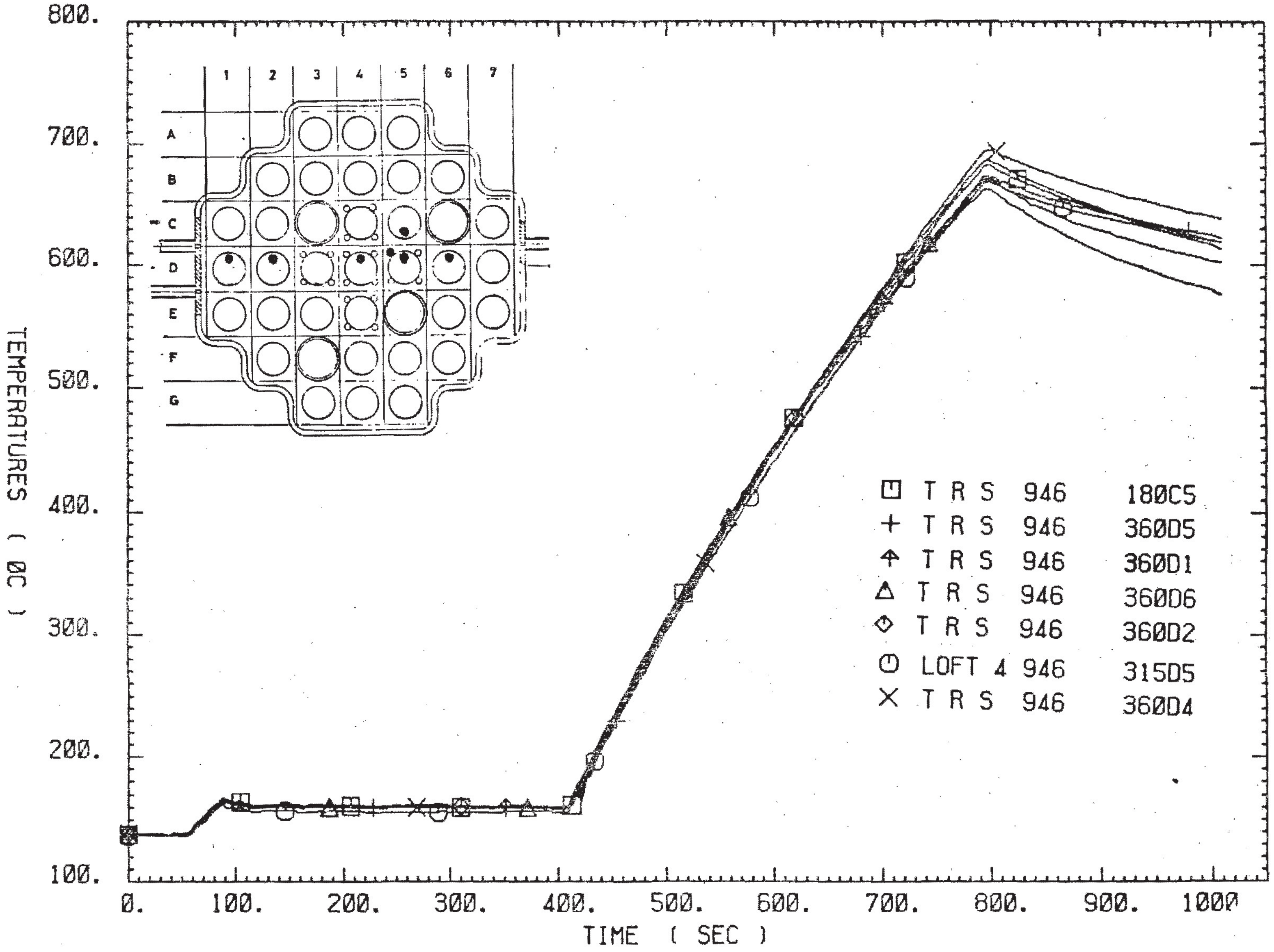


Figure 15. Overlay comparisons of selected NEPTUN thermocouples--axial elevation 4.

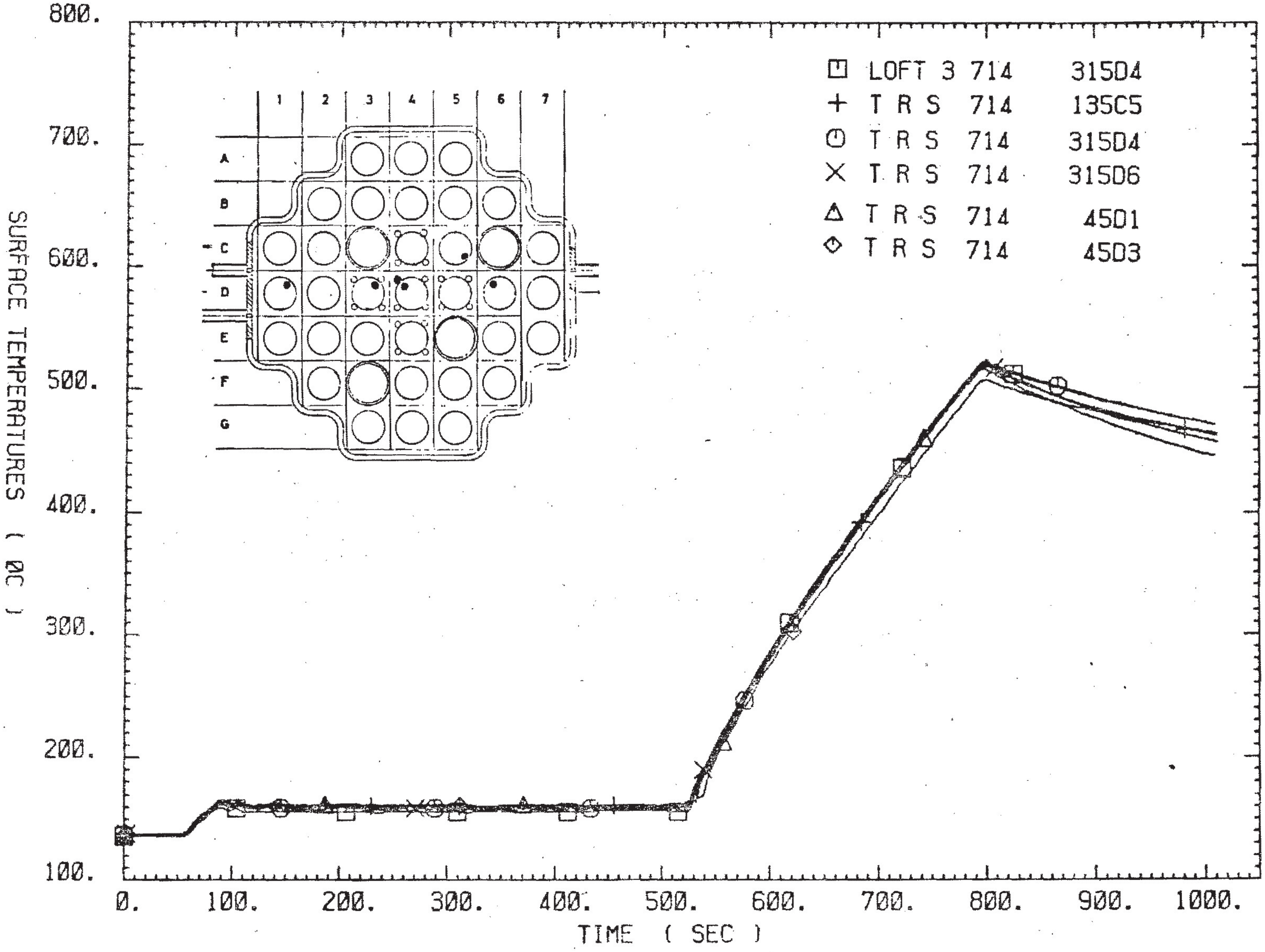
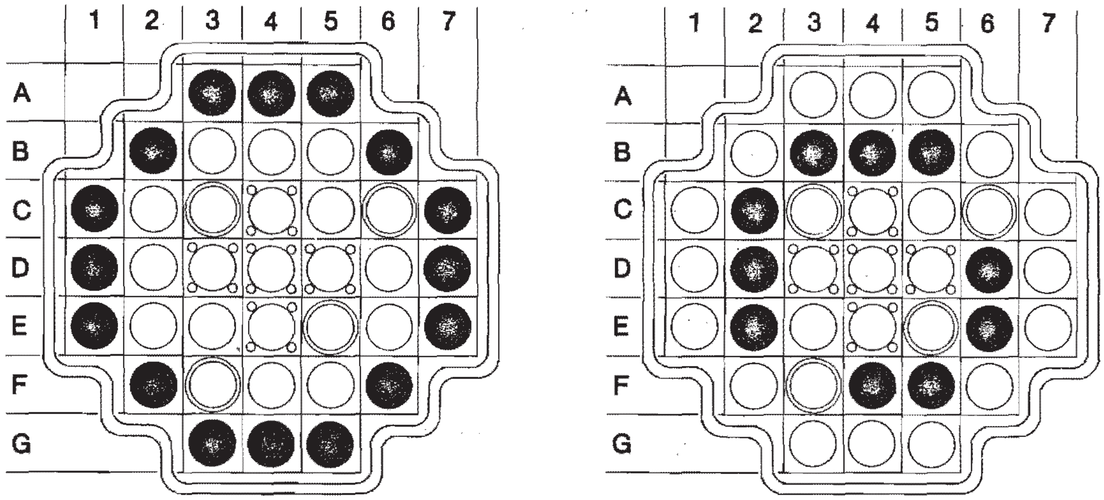
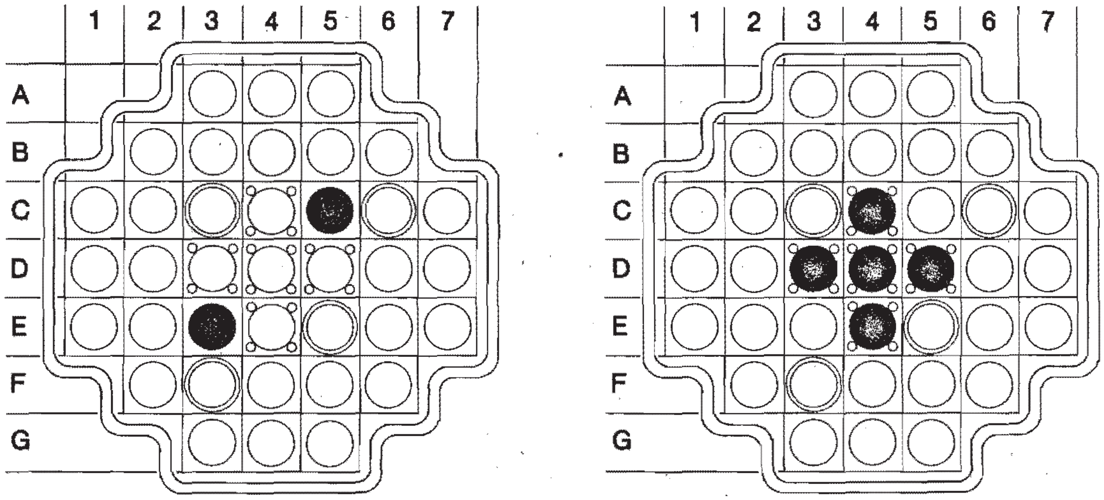


Figure 16. Overlay comparisons of selected NEPTUN thermocouples--axial elevation 3.



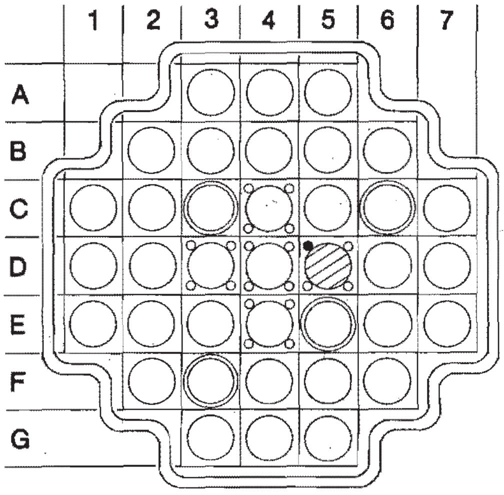
Peripheral rods

Intermediate rods



Center bare rods

Center LOFT rods



LOFT thermocouple

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Figure 17. Schematic of rod groups chosen to compare thermocouple response.

For example, considering the base case (experiment 5007), Figure 18 shows the relative response of the peripheral rods with thermocouples facing the outer shroud and those thermocouples facing other rods, i.e., towards the bundle. The outer facing thermocouples are cooler, in some cases, by approximately 10 K. The next overlay, shown in Figure 19, compares the peripheral rod thermocouples to the intermediate rod thermocouples, and again the intermediate, or innermost rods, read consistently higher by ∿20-30 K. Figure 20, which compares the intermediate rod thermocouples with the center bare rods (no LOFT thermocouples), shows that at the time of peak cladding temperature the center bare rods are only slightly higher (0-10 K) than the intermediate rod thermocouples.

At this point, a quantification of the perturbation influences of the LOFT thermocouples can be made. To evaluate the selective cooling effects of the surface thermocouples, Figure 21 presents the response of the center rods with and without LOFT thermocouples; only the embedded cladding thermocouples are shown. It is clear that the rods with LOFT thermocouples experience dryout 0-10 s later than bare rods; however, the heatup rates of the two types of rods are nearly identical. When the center rods (LOFT thermocouples) are compared with the intermediate position rods (see Figure 19), it is evident the center rods, even with external thermocouples, are measuring higher temperatures than the intermediate row of rods--indicating that the bundle size has a stronger cooling effect on the rods than do the external thermocouples. The final comparison, Figure 22, compares LOFT thermocouple response with that of internal thermocouples on the center bare rods. Notice that a systematic lower temperature is measured by the LOFT thermocouple. This temperature difference can be taken as an estimate of the measurement error of the LOFT thermocouples, i.e., less than 20 K.

Notice also in Figures 19 through 22 there is less than 5-10 s difference in the initial dryout times for all level 5 thermocouples, both embedded and external.

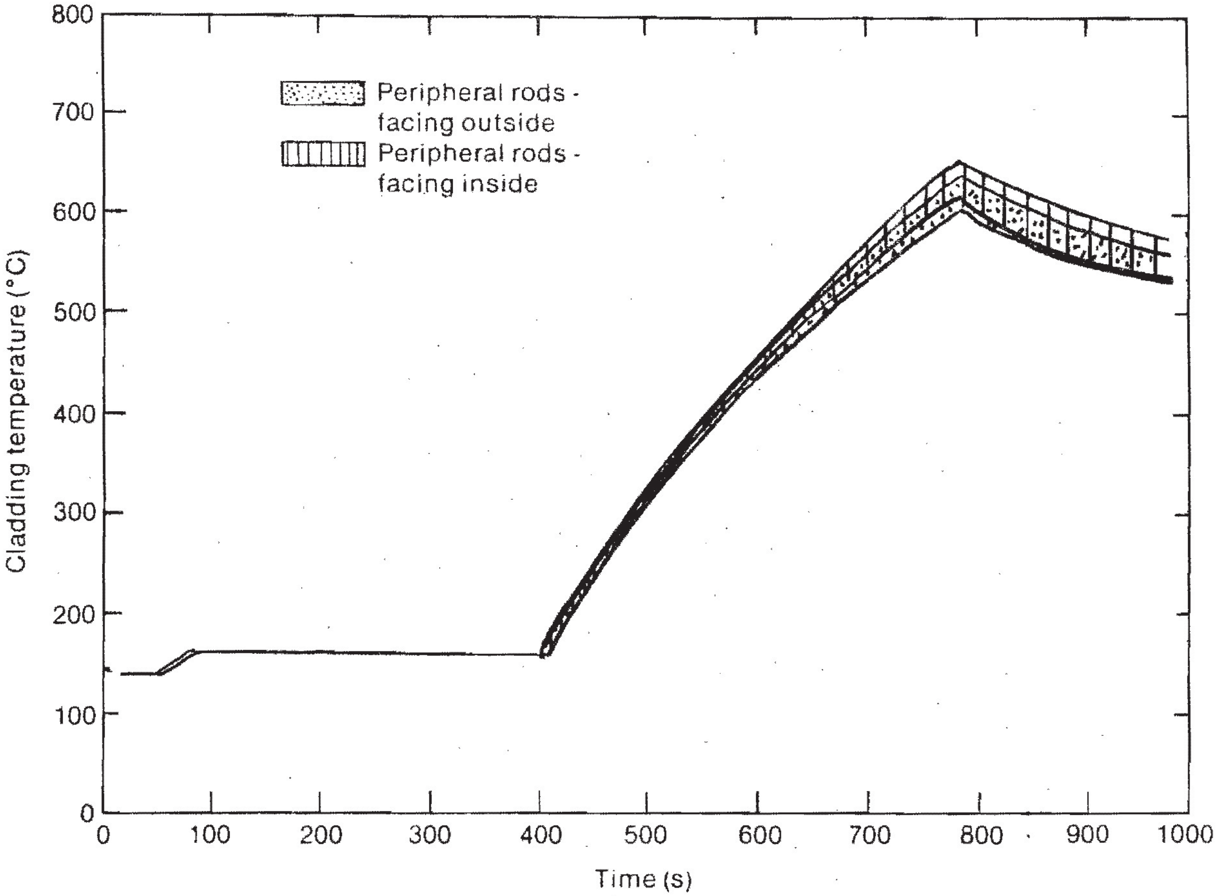

Figure 18. Comparison of peripheral rod internal thermocouple on rods facing the bundle housing and those facing other rods (test 5007, axial elevation, 29.3 in.-level 4).

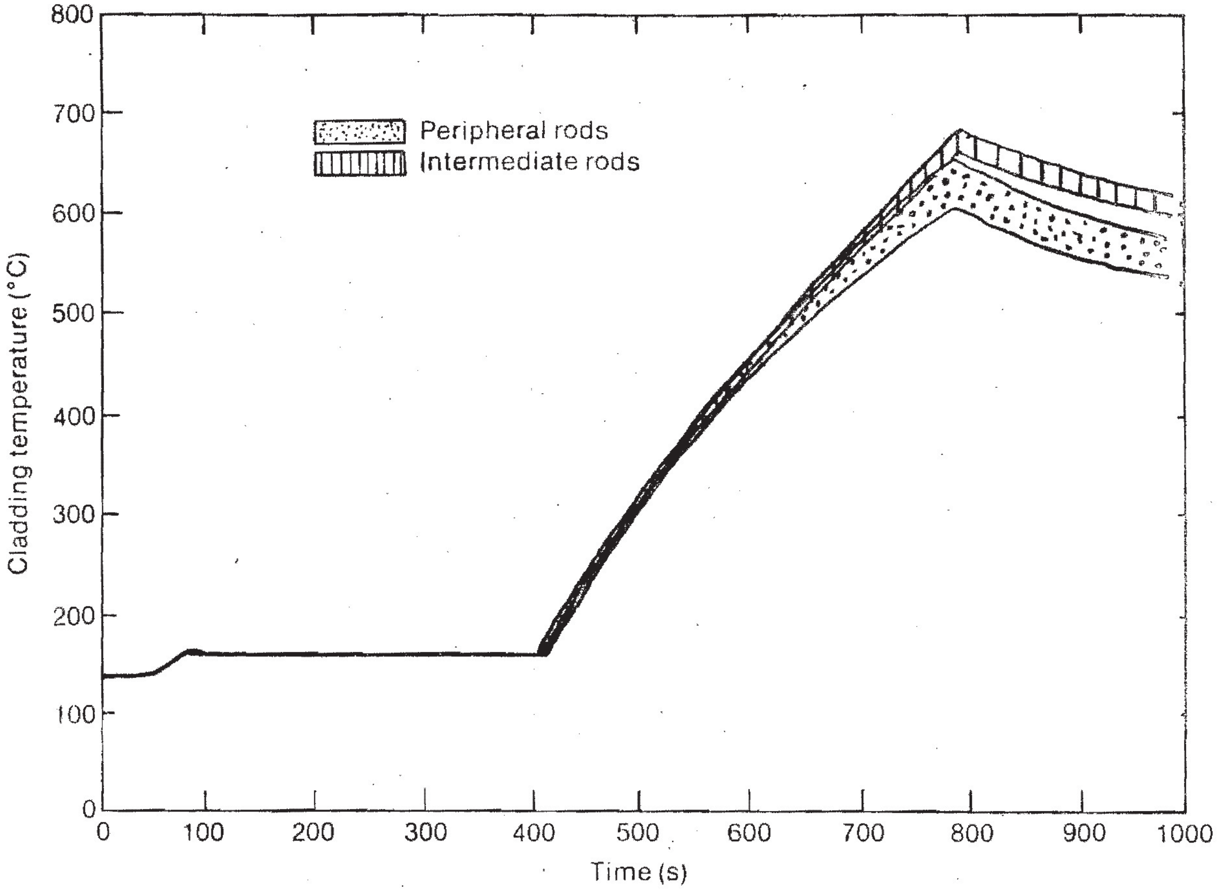

Figure 19. Comparison of peripheral rod and intermediate rod internal thermocouples (test 5007, axial elevation, 29.3 in.-level 4).

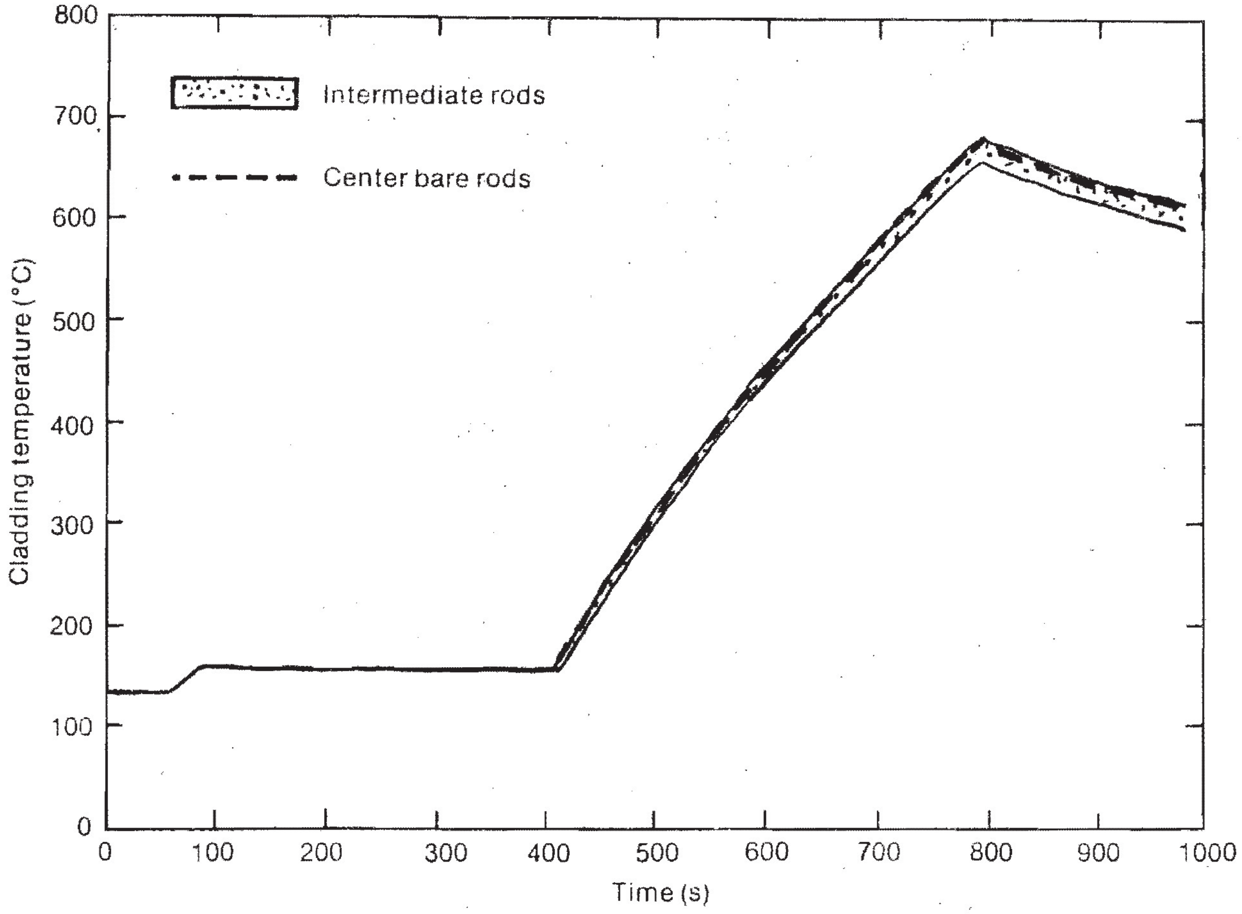

Figure 20. Comparison of intermediate rod and center rods (no LOFT thermocouples) internal thermocouples (test 5007, axial elevation, 29.3 in.-level 4).

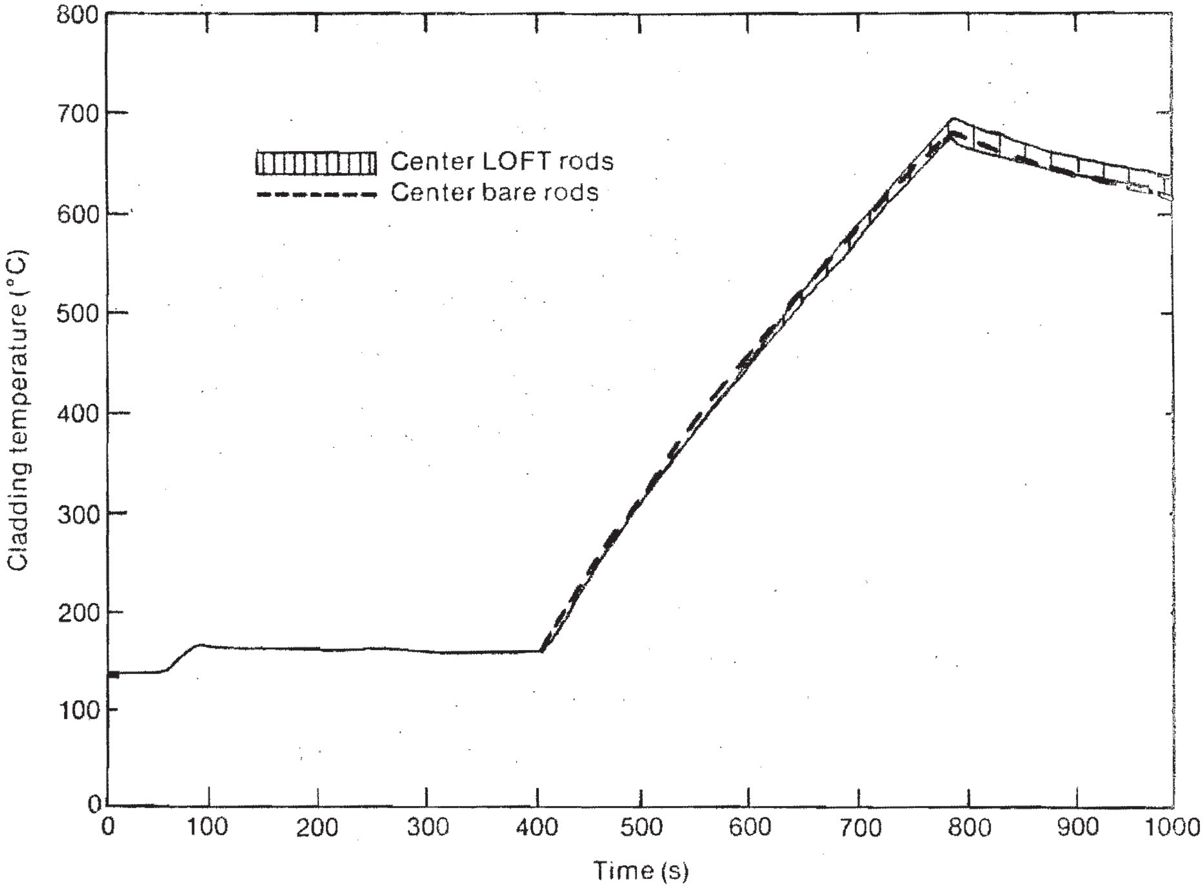

Figure 21. Comparison of center rod (no LOFT thermocouples) and center rod (with LOFT thermocouples) internal thermocouples (test 5007, axial elevation, 29.3 in.-level 4).

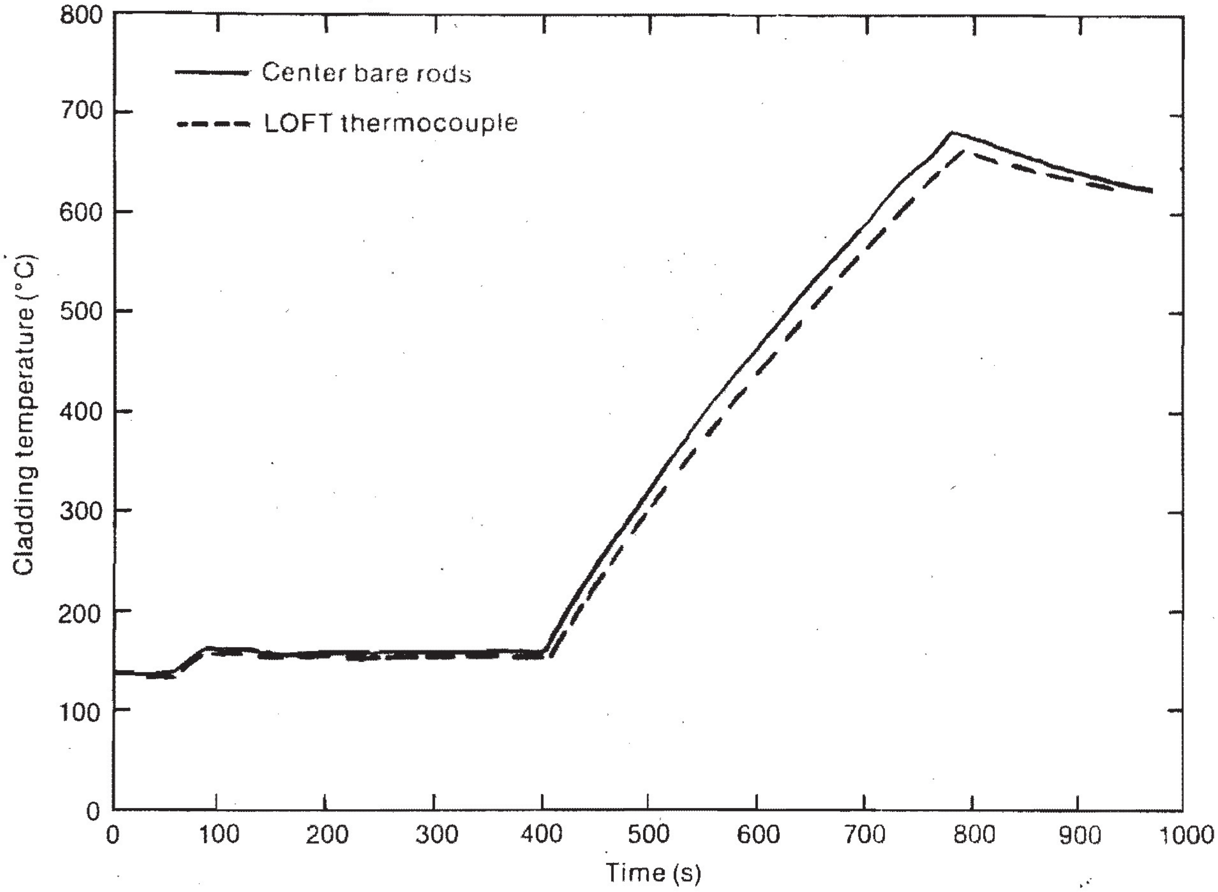

Figure 22. Comparison of center rod internal and LOFT thermocouples (test 5007, axial elevation, 29.3 in.-level 4).

4. DISCUSSION AND RECOMMENDATIONS

The NEPTUN experiments have provided thermal-hydraulic data simulating LOFT core boil-off conditions. The NEPTUN system responded generally as expected. Dryout times of the internal and external thermocouples were consistent (within 10 s) at any given axial elevation for all rods in the bundle. The cladding surface thermocouples measure the true cladding temperatures to within 0 to -20 K for the NEPTUN experiments. Based on the NEPTUN data, it is recommended that the best-estimate thermocouple error be taken as -20 K for future LOFT boil-off experiments.

5. REFERENCES

1. E. L. Tolman, LOFT Cladding Thermocouple Accuracy During Core Boil-Off Experiments, EGG Idaho Internal Letter, ELT-05-81, March 1981.

2. H. Grutter, F. Stierli, S. Aksan and G. Varadi, NEPTUN Bundle Reflooding Experiments: Test Facility Description, Eidg. Institute für Reacktorforschung Report EIR-Bericht Nr. 386., March 1980.

APPENDIX A
NEPTUN INSTRUMENTATION

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APPENDIX A

NEPTUN INSTRUMENTATION

The purpose of this appendix is to provide a reference description of the NEPTUN instrumentation. Each instrument is designated by a nineteen-digit identifier as described in Table A-1.

TABLE A-1. NEPTUN INSTRUMENTATION DESIGNATION

		Identity Code Digits			
Channel Designations	Units	1-6	7-10	15-17	18-19
Temperatures					
Heater rod surface temperature	°C	T-R-S-	level (in mm)	azimuth (in degrees)	core position
Guide tube wall temperature	°C	T-G-W-	level (in mm)	azimuth (in degrees)	core position
LOFT thermocouples:					
-Measurement level (ML) 8	°C	LOFT-8	level (in mm)	azimuth (in degrees)	core position
6		6	level (in mm)	azimuth (in degrees)	core position
5		5	level (in mm)	azimuth (in degrees)	core position
4		4	level (in mm)	azimuth (in degrees)	core position
3		3	level (in mm)	azimuth (in degrees)	core position
Test section fluid temperature	°C	T-T-F-	level (in mm)	azimuth (in degrees)	core position
Flooding water temperatures	°C	TM-21 TM-22	level (in mm)	azimuth (in degrees)	core position
Housing temperatures	°C	TM-60	level (in mm)	azimuth (in degrees)	core position
Insulation temperatures	°C	TM-61			
		TM-98			
Exhaust steam line:					
-steam temp. before super heater	°C	TM-105	level (in mm)	azimuth (in degrees)	core position
-steam temp. after steam turbine					
r/R=0	°C	TM-108	level (in mm)	azimuth (in degrees)	core position
r/R=0.34	°C	TM-109	level (in mm)	azimuth (in degrees)	core position
r/R=0.68	°C	TM-110	level (in mm)	azimuth (in degrees)	core position
Fresh steam temperature	°C	TM-118	level (in mm)	azimuth (in degrees)	core position
Steam-water separator temperatures:					
-connection bellows-lower end plate	°C	TM-168	level (in mm)	azimuth (in degrees)	core position
-connection bellows-housing	°C	TM-169	level (in mm)	azimuth (in degrees)	core position
-lining	°C	TM-172	level (in mm)	azimuth (in degrees)	core position
-steam temp. at test section outlet	°C	TM-171	level (in mm)	azimuth (in degrees)	core position
-steam temp. before wire mesh separator	°C	TM-173	level (in mm)	azimuth (in degrees)	core position
Flow rates (turbines):					
Flooding water:					
-small flow rate	gr/s	DM-19	level (in mm)	azimuth (in degrees)	core position
-medium flow rate	kg/s	DM-17	level (in mm)	azimuth (in degrees)	core position
-large flow rate	kg/s	DM-15	level (in mm)	azimuth (in degrees)	core position
Fresh steam	Hz	DM-123	level (in mm)	azimuth (in degrees)	core position
Exhaust steam	Hz	DM-107	level (in mm)	azimuth (in degrees)	core position

TABLE A-1. (continued)

Channel Designations	Units	Identity Code Digits 1-6	7-10	15-17	18-19
Absolute pressures:					
Flooding water pressure (near test section inlet valve)	bar	PAM-23	level (in mm)	azimuth (in degrees)	core position
Exhaust steam pressure (before turbine)	bar	PAM-106	level (in mm)	azimuth (in degrees)	core position
Fresh-steam generator pressure	bar	PAM-112	level (in mm)	azimuth (in degrees)	core position
Fresh-steam pressure before turbine	bar	PAM-115	level (in mm)	azimuth (in degrees)	core position
Pressure in space between housing and pressure vessel	bar	PAM-124	level (in mm)	azimuth (in degrees)	core position
Test-section pressure (tap at steam-water separator)	bar	PAM-126	level (in mm)	azimuth (in degrees)	core position
Pressure differences:					
Pressure difference between:					
-flooding water distributing pipe and measuring level (ML) 8	mb	PDM-51	level (in mm)	azimuth (in degrees)	core position
-flooding water distributing pipe and ML 1	mb	PDM-52	level (in mm)	azimuth (in degrees)	core position
-ML1 and ML2	mb	PDM-53	level (in mm)	azimuth (in degrees)	core position
-ML2 and ML3	mb	PDM-54	level (in mm)	azimuth (in degrees)	core position
-ML3 and ML4	mb	PDM-55	level (in mm)	azimuth (in degrees)	core position
-ML4 and ML5	mb	PDM-56	level (in mm)	azimuth (in degrees)	core position
-ML5 and ML6	mb	PDM-57	level (in mm)	azimuth (in degrees)	core position
-ML6 and ML7	mb	PDM-58	level (in mm)	azimuth (in degrees)	core position
-ML7 and ML8	mb	PDM-59	level (in mm)	azimuth (in degrees)	core position
Content of tanks:					
Entrainment tank	kg	PDM-34	level (in mm)	azimuth (in degrees)	core position
Valve position:					
Test section flooding valve[a]	mV	VM-200			
Control valve-test bundle press[b]	mV	VM-135			
Heater rod power:					
Total bundle power	kW	KWM-TOT	level (in mm)	azimuth (in degrees)	core position

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[a] Only two positions possible: 0 ± 5 mV = closed; 100 ± 5 mV = open.

[b] Variable position: 3 mV = closed; 104 mV = open; linear interpolation within this range.

The appendices listed below are reproduced on microfiche attached to the inside rear cover of this report.[a]

APPENDIX B--DATA FROM EXPERIMENT 5001

APPENDIX C--DATA FROM EXPERIMENT 5002

APPENDIX D--DATA FROM EXPERIMENT 5004

APPENDIX E--DATA FROM EXPERIMENT 5005

APPENDIX F--DATA FROM EXPERIMENT 5006

APPENDIX G--DATA FROM EXPERIMENT 5007

APPENDIX H--DATA FROM EXPERIMENT 5008

APPENDIX I--DATA FROM EXPERIMENT 5009

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a. Data from experiment 5003 unavailable.