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February 20, 1981



Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Attention: G. P. Marino, Acting-Chief,
Fuel Behavior Branch
Division of Reactor Safety Research

Dear Sir:

Quick-look Report on MRBT 6 x 6 Bundle Test B-4

Attached is a copy of the Quick-look Report on the 6 x 6 bundle test that was performed January 15. Simultaneously, three copies of the report are being forwarded to the Division of Technical Information and Document Control (NRC-TDIC) for transmittal to the Public Document Room.

The test was planned to be a routine ramp burst test. However, after the onset of deformation, electrical heating of the bundle was terminated by the automatic control system. Further deformation occurred under near-isothermal creep conditions, while hurried attempts were being made to restore electrical power. After 380 s the tubes were depressurized, and the test was terminated; none of the tubes burst. Although the objectives of the test were not realized, the data appear useful for model development and verification, particularly with respect to "flat-topped" transients.

If you require further information on this report, please contact R. H. Chapman or me.

Sincerely,

Herbert E. Trammell, Director
Engineering Technology Division

HET:RHC:nam

NRC Research and Technical
Assistance Report

8108120 761

Mr. G. P. Marino

-2-

February 20, 1981

Attachment

cc: Chief Scientist, Office of Nuclear Regulatory Research, RES/NRC
Director, Division of Reactor Safety Research, RES/NRC
Assistant Director, Water Reactor Safety Research, RES/NRC
Division of Document Control, NRC-TDIC (3 copies)
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NRC Research and Technical
Assistance Report ✓



INTERIM REPORT

Accession No. _____
ORNL/MRBT-6

Contract Program or Project Title: MULTIROD BURST TEST PROGRAM

Subject of this Document: Preliminary Results of B-4 (6 × 6) Bundle Test

Type of Document: Quick-look Report

Author: R. H. Chapman

Date of Document: February 20, 1981

Responsible NRC Individual and NRC Office or Division: M. L. Picklesimer,
Fuel Behavior Branch, Division of Reactor Safety Research, Office of
Nuclear Regulatory Research

This document was prepared primarily for preliminary or internal use. It has not received full review and approval. Since there may be substantive changes, this document should not be considered final.

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Washington, D.C. 20555
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Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
operated by
Union Carbide Corporation
for the
Department of Energy

INTERIM REPORT

NRC Research and Technical
Assistance Report

Summary

An unsuccessful attempt was made on January 15 to perform a burst test on the B-4 (6 x 6) bundle. Consistent with test objectives, initial conditions were established with the expectation that the tubes would burst at $\sim 800^\circ\text{C}$ after ~ 90 s of heating at a rate of ~ 5 K/s. However, after 60 s of heating, electrical power to the bundle was terminated by the automatic control system; the bundle average temperature at the time was $\sim 675^\circ\text{C}$. Hurried attempts to diagnose the cause and to restore power were unsuccessful. The bundle temperature slowly decreased (~ 0.2 K/s), and the tubes deformed under near-isothermal creep conditions during this time. After ~ 380 s the tubes were depressurized to preclude further deformation.

With conditions stabilized after depressurization, quick-look evaluation of the recorded pressure data revealed that none of the tubes had burst but appreciable deformation had occurred. Repressurizing the tubes and continuing the test to burst conditions would only render the data uninterpretable, since the initial conditions (i.e., the extent and distribution of the deformation in each tube at restart) would be unknown. Furthermore, this would prevent realization of a primary objective of the test (i.e., determination of the effect of a relatively cold rod on the deformation behavior of its neighbors). Consequently, a decision was made to terminate the test at this point so that it could be analyzed and interpreted in view of the reasonably well defined test conditions.

Comparison of posttest gas volume measurements with pretest measurements showed heated length volume increases of 8 to 20% and 17 to 48%, respectively, for the exterior and interior rods. These volume increases are equivalent to average strains of about 4 to 22% over the heated length. Visual observations indicate the deformation in each tube is uniformly distributed except for the interior tube (No. 14) with the greatest volume change. This particular tube has a 7-10 cm long balloon that appears to be in contact with its neighbors. The strain in the ballooned region is significantly larger than the average strain ($\sim 22\%$) inferred from the volume increase.

Since the deformation is moderate and uniformly distributed over the heated length, flow tests appear to be of little value and will not be performed. Operations are underway to disassemble the bundle by cutting the grids apart to free the individual tubes to obtain deformation profiles in a manner similar to that used for single rod tests. Blockage data will be generated (mathematically) from the individual tube profiles. These data should be available in late summer.

Although objectives of the test were not realized, the data appear useful for model development and verification, particularly with respect to "flat-topped transients". However, because the transient was not allowed to proceed to failure conditions, the blockage data cannot be used to establish bounds on the blockage expected for LOCA transients.

Introduction

An unsuccessful attempt was made on January 15 to perform a burst test on the B-4 (6 x 6) bundle. Initial conditions were established to

cause the tubes to burst at $\sim 800^{\circ}\text{C}$ after ~ 90 s of heating at a rate of ~ 5 K/s, and the test was initiated. However, after 60 s of heating electrical power to the bundle was terminated by the automatic control system; the bundle average temperature at this time was $\sim 675^{\circ}\text{C}$. Hurried attempts to diagnose the cause and restore power were unsuccessful. The bundle temperature slowly decreased (~ 0.2 K/s) and the tubes deformed (by creep) during this time period. After ~ 380 s the pressure was vented from the tubes to stop deformation, and the test was terminated.

The loss of power was caused by a 0-to-60 s backup timer that was inadequately bypassed after it was used to terminate the short (15 s) power-bump checkout transient. Although an electrical bypass circuit was installed around the timer contacts in the primary shutdown circuit, a redundant shutdown circuit was not bypassed, and this caused termination of the transient after 60 s. Although primary objectives of the test were not realized, useful data will be obtained.

The objectives of the test were to investigate axial propagation of ballooning as the result of rod-to-rod contact and to determine the effect of a relatively cold fuel pin simulator on the deformation behavior of its hotter neighbors under test conditions known to produce large deformation. One of the central four simulators (No. 16) was selected as the unheated simulator. Other than omitting the fuse from its electrical circuit and setting its initial pressure level at 500 kPa (to preclude deformation), this simulator was identical to the others. It was originally intended that the No. 27 simulator would be unheated but a leak developed in No. 16 after the power-bump transient, and a decision was made to change the selection to No. 16.

Figure 1 shows a simplified drawing of the B-4 test assembly. As indicated in Section B-B of the figure, the shroud was constructed of thin (0.13-mm-thickness) stainless steel, with a highly reflective gold plating, and was backed by insulating material and a strong structure to withstand radial forces during the test transient. The shroud was spaced one-half of a coolant-channel-distance away from the outer surface of the guard heaters. This would permit some deformation of these simulators before contact with the shroud, but would prevent outward movement of the simulators. This design concept was also used in the B-5 (8×8) test. The inlet steam arrangement was modified from a single nozzle on the north side as used in the B-5 test to diametrically opposed nozzles on the east and west sides of the bundle (see Section A-A in the figure) to obtain a more uniform inlet temperature distribution than existed in B-5. As will be discussed later, this (and other) improvements were effective.

Figure 2 gives pertinent details of the fuel pin simulators. The fuel simulators (internal heaters) included those used in the B-2 and B-3 tests (16 heaters each) plus an additional four from the original lot of simulators purchased from SEMCO for the 4×4 tests. The axial heat generation profiles of the simulators were characterized by pretest infrared scans. The highest quality simulators were selected for the bundle interior positions.

Each fuel pin simulator was instrumented with a fast response, strain-gage-type, pressure transducer and four Inconel sheathed (0.71-mm-diam), type K thermocouples with ungrounded junctions. The thermocouples were spot-welded to the inside of the Zircaloy-4 tubes (10.2-mm O.D. \times 0.635-mm wall thickness) at axial and azimuthal positions shown in Fig. 3.

The figure also gives thermocouple identifications for use in subsequent figures in which TE 10-4 identifies the No. 4 thermocouple in the No. 10 simulator. One thermocouple (TE 26-3) read $\sim 20^{\circ}\text{C}$ low throughout the transient, and its reading is suspect.

Eight, 0.13-mm-diam, bare wire, type S thermocouples were spot-welded on the outside surface of the thin shroud surrounding the rod array. Two thermocouples were attached to each side at positions shown in Fig. 3 in an attempt to obtain information on both the axial and circumferential temperature distributions. The shroud thermocouple identifications are also given in the figure for use in subsequent temperature plots.

Five thermocouples (TE-320 through TE-324) were located in the tube matrix at the 107-cm elevation (centerline elevation of the steam inlet nozzles) to obtain inlet steam temperature measurements. Five thermocouples (TE-325 through TE-329) were dispersed in the tube matrix near the bottom of the heated zone (at the 3-cm elevation) to obtain outlet steam temperature measurements in the bundle at this elevation. Figure 4 shows the identifications and locations. The thermocouples were 0.71-mm-diam, stainless steel sheathed, type K with ungrounded junctions.

Millivolt signals from the pressure transducers, thermocouples, and electrical power measuring instruments were recorded on magnetic tape by a computer controlled data acquisition system (CCDAS) for subsequent analysis. This report summarizes some of the quick-look data obtained immediately after the test and presents a selection of photographs of the bundle.

Test Operations

Heatup of the test assembly was initiated early in the afternoon of January 14; the temperature was near 200°C at the end of the work shift. Power adjustments to the vessel heaters were made to maintain the temperature near this value during the next 12 hours to avoid temperature cycling the test assembly. About 0400 h on January 15, power to the vessel heaters was increased and superheated steam was admitted to the vessel in the approach to the initial test temperature. Throughout this phase of operation, periodic leak checks indicated the simulator seals were performing very well, (i.e., less than 10 kPa pressure loss per min at 8,600 kPa and $\sim 330^{\circ}\text{C}$).

After thermal equilibration ($\sim 330^{\circ}\text{C}$) of the test assembly was attained, the simulators were pressurized to approximately 5,300 kPa (simulator 27 was only pressurized to 670 kPa since it was earmarked at this time to be the unheated one), and a short powered run (~ 15.0 s transient) was conducted at 1230 h to ascertain that the data acquisition system and all the instrumentation were functioning properly and that the performance of the test components was as expected. Examination and evaluation of the quick-look data from this short transient (the temperature of the simulators increased to about 410°C) indicated voltage adjustments were not needed to achieve the desired heating rate of 5 to 6 K/s.

During the time (~ 5 h) between the pretest power-bump and the test, the lower seal (see Fig. 2) on simulator 16 developed a severe leak. The magnitude of the leak was such that for deformation to be comparable to

the other simulators it would be necessary to test the simulator at constant pressure by inflow of helium at a rate equal to the leak. Rather than degrade the quality of the deformation data by this expediency, a decision was made to select No. 16 as the unpressurized (actual pressure of 560 kPa) and unheated simulator. All the remaining simulators were leaktight (leak rates of <10 kPa/min at 9,300 kPa and 332°C) and were tested in the usual manner, i.e., with the individual isolation valves to the supply header closed to provide a constant gas mass inventory in each simulator during the transient.

Superheated steam entered the array on the east and west sides at the 107-cm elevation (Fig. 1) and flowed downward through the bundle during the test at a mass flux of ~ 279 g/s $\cdot\text{m}^2$ (compared to 288 g/s $\cdot\text{m}^2$ in B-5). Inlet steam conditions of $\sim 327^{\circ}\text{C}$ and ~ 305 kPa (absolute) resulted in a Reynolds number of ~ 132 at the inlet end of the bundle. This Re can be compared to 143 in B-5 and 263 in B-3. These inlet conditions remained essentially constant throughout the transient, although a small perturbation (lasting 10 to 15 s) occurred about 140 s after power-off, as will be discussed later.

Following stabilization of the bundle temperature at $\sim 332^{\circ}\text{C}$, all the fuel simulators except No. 16 were pressurized simultaneously to $\sim 9,100$ kPa (differential above the external simulator pressure) and isolated from the supply header. Pressure in the unheated simulator (No. 16) was set at ~ 560 kPa (differential) to preclude deformation. With these initial conditions established, the test transient was initiated.

It was planned that the powered portion of the test would be terminated by any of three actions: (a) CCDAS action resulting from a signal that 32 of the 36 simulators had burst, (b) CCDAS action that 75 simulator thermocouples had exceeded the upper temperature limit (50°C above the anticipated burst temperature) on each of three successive data scans, or (c) operator override. The test was terminated before any tube bursts by a timer circuit that was not effectively bypassed as discussed earlier.

Quick-look Results

Quick-look data of interest are extensive and inconvenient to present in concise tabular format. Therefore, we have elected to display the data in a series of bundle schematic layout diagrams and quick-look plots to facilitate visualization. It should be noted that these data are very preliminary and subject to change as detailed data tabulations and plots are generated from the magnetic data tape recorded during the test.

Superheated steam entered the array through two inlet nozzles located on the east and west sides of the bundle (see Fig. 1) at the 107-cm elevation and flowed downward through the bundle at a mass flux of 279 g/s $\cdot\text{m}^2$, equivalent to an inlet Re of ~ 132 at the top of the heated zone (91.5-cm elevation). Apparently the nozzle arrangement and other modifications made since the B-5 test, such as a steam distribution baffle just below the inlet (see Fig. 1) to minimize flow channeling and additional heaters on the vessel closure flange to minimize heat losses from the flange via axial conduction along the simulators, were effective in producing a fairly uniform inlet steam temperature distribution in the matrix. This is illustrated in Fig. 4, which shows a schematic of the

array with the locations, identifications, and temperature readings of the steam inlet and outlet thermocouples about 1 s before power-on. The measurements indicate the temperature distribution at the inlet was fairly uniform and very uniform at the outlet. Also, the steam average temperature increased about 9°C while passing through the bundle.

Figures 5-14 present temperatures measured 1 s before power-on in the format of a schematic layout of the bundle at each of the instrumented sections. The layout represents the tube by eight dots, positioned at possible thermocouple azimuthal angles (see Fig. 3), centered about the rod position number. An asterisk replaces a dot, indicating the azimuthal position of a thermocouple, if the junction is in the plane for which the particular map applies; the temperature measured by the thermocouple at that time is printed below the schematic representation of the tube. The respective row and column average temperatures are printed on the right and at the bottom of the layout. The cross section and bundle average temperatures, the elevation of the section, and other pertinent information are also included in the format. The thermocouples in simulator 16 (unheated) and those located at the grid elevations are excluded from the bundle average temperature. Also, if a particular thermocouple indicates a temperature 25°C greater or less than the section average, that reading is excluded (and noted in the format) from the averages.

The maps provide considerable data and greatly facilitate interpretation and quick-look evaluation of local and overall temperature distributions. As evident, the initial radial and axial temperature distributions were very uniform, indicating uniform distribution of the steam. Compare, for example, data in Fig. 5 for the 84-cm elevation with the inlet steam temperatures (at the 107-cm elevation) in Fig. 4. Also, compare Fig. 14 with Fig. 4 for the radial distributions at the lower end of the heated zone.

The overall radial temperature distribution may be visualized somewhat easier in the temperature map depicted in Fig. 15. The temperature given in the map for each simulator is the average of the thermocouple measurements for that simulator without regard to elevation, excluding measurements obtained from thermocouples at the grid elevations. Asterisk locations (and number) in the schematic representation of the simulators denote the azimuthal position of the thermocouples whose measurements comprise the average. Row and column averages are printed, respectively, on the right side and at the bottom of the map to facilitate visualization of uniformity.

Initial pressures are presented in a similar format in Fig. 16. Again the column of numbers on the right and the row of numbers at the bottom of the figure represent, respectively, the row and column average pressures.

With these initial conditions established, the transient was initiated. A number of quick-look plots and data maps will be presented to illustrate the significant features of the test as it progressed and to provide an indication of the general conditions prevailing at the times of important events. A parameter, TAV-10, will be plotted in a number of these figures to represent the bundle average temperature. This parameter is in reality the average of six thermocouples (TE 9-3, TE 14-2, TE 15-1, TE 21-3, TE 23-1, and TE 26-1) at the 38-cm elevation (see Fig. 3 for

relative positions) and was electronically averaged and recorded during the test to facilitate visualization of the bundle temperature as a function of time. Because this average temperature was derived electronically from uncorrected thermocouple output signals, it differs slightly ($\sim 10^\circ\text{C}$) from the average calculated posttest from corrected values. This small discrepancy is unimportant for quick-look characterization.

Figure 17 shows TAV-10 and the applied voltage plotted as a function of scan time during the powered portion of the transient; the average heating rate during this time was $\sim 5.7\text{ K/s}$. The temperature measured by TE 16-3 on the unpressurized and unpowered simulator (at the same elevation as the thermocouples used to obtain TAV-10) is also shown for reference. Internal pressure measured on a corner (No. 1) and a central (No. 21) simulator are included to illustrate pressure behavior, respectively, of exterior and interior simulators. Maximum pressure was encountered in all the pressurized simulators 5 to 10 s before power-off, indicating the onset of deformation. Pressure (Fig. 18) and temperature (Figs. 19-29) measurements made $\sim 0.2\text{ s}$ before power-off show conditions were very uniform at the time power was terminated; the effect of the unpowered simulator (No. 16) appears negligible up to this time.

Figure 30 shows the temperature behavior, as characterized by TAV-10 and TE 16-3, during the time attempts were being made to restore electrical power to the bundle. As evident the temperature reached a maximum $\sim 3\text{ s}$ after power-off (see Fig. 17) and decreased steadily thereafter ($\sim 0.15\text{ K/s}$ based on TAV-10 and $\sim 0.23\text{ K/s}$ based on overall bundle average temperature, with the latter value reflecting development of an axial temperature gradient during this time). The temperature of the unpowered rod increased at a rate of $\sim 1.7\text{ K/s}$ during the first 100 s of unpowered time and at a reduced rate thereafter until it reached essential equilibrium with TAV-10 $\sim 300\text{ s}$ after power-off.

The figure also shows the pressure behavior of the first (No. 1) and last (No. 25) simulators to be depressurized and of the simulator (No. 14) that exhibited the greatest pressure decrease before depressurization. Since the temperature decrease before venting was moderate, the predominant cause of the observed pressure decrease was creep deformation.

The first simulator (No. 1) was vented to be supply header at $\sim 41.7\text{ s}$ scan time and the last (No. 25) at $\sim 491.7\text{ s}$, creating conditions that precluded further deformation. About 30 s after venting the simulators to the header and each other (at a common pressure of $\sim 3,620\text{ kPa}$), the header was vented to $\sim 800\text{ kPa}$ and the bundle was allowed to continue cooling without disturbing the inlet steam conditions.

Discussion of the short temperature perturbation evident at $\sim 240\text{ s}$ scan time in Fig. 30 will be deferred to later point.

Pressures measured $\sim 0.7\text{ s}$ before the first simulator was vented are shown in Fig. 31. Since the pressure changed very little from the time of these measurements to that of venting the individual simulators, the pressures are very good estimates of those existing at the time of venting. Since the final pressure can be correlated with deformation, the map provides an indication of how the deformation is distributed with respect to simulator position. As would be expected, the exterior simulators have less deformation than the interior ones, with the corner simulators having the least deformation.

Also, deformation is greater in the lower left triangular half of the bundle formed by simulators at the No. 1, No. 31, and No. 36 positions than in the upper right half. This may be an effect of the unpowered simulator (No. 16) in the upper right half.

Temperature measurements made at the same time (i.e., ~ 0.7 s before venting of the No. 1 tube) are shown in Figs. 32-41. The axial and radial temperature distributions were highly nonuniform as may be deduced by comparison of the individual measurements and averages within a section, by comparison of the various section averages to the bundle average, and by comparison of the simulator averages in the radial temperature map given in Fig. 42.

Thermocouples were attached to the outside surface of the (electrically) unheated shroud to obtain information about shroud axial and azimuthal temperature variations. As indicated in Fig. 3, two thermocouples were located at each of four elevations, with one of the two thermocouples being positioned directly opposite a simulator and the other being positioned between two simulators. Since the shroud was very thin (~ 0.13 mm thick), significant variations might be expected from the thermocouple measurements. Figure 43, which compares shroud temperature measurements at the 76-cm elevation during the powered portion of the transient to cladding temperature measurements obtained from simulators in the vicinity of the shroud thermocouples (see Fig. 3), confirms this expectation. The figure shows that the thermocouple (TE 91-2) located opposite simulator thermocouple (TE 32-3) indicated a much higher temperature than that indicated by the thermocouple midway between two simulators. In fact, at about 65 s scan time, the shroud thermocouple reading indicated an increased heating rate as if the simulator and shroud were in contact. The matched simulator thermocouple showed a decreased heating rate at the same time, as if local cooling conditions had changed. Posttest visual examination of the shroud panel showed significant temperature variations existed during the transient as revealed by the degree of oxidation evident on the unplated back side of the stainless steel surface.

The shroud thermocouples at three of the four instrumented elevations showed this general behavior. This should not be taken as positive evidence that the simulators bowed outward to contact the closely spaced shroud during the test because it may be possible that the thin shroud panel buckled inward and touched the simulators.

Figure 44 shows measurements obtained from the same sensors over a much longer time span. The perturbation at ~ 240 s scan time was very pronounced on the shroud and simulator thermocouples at this elevation. The perturbation was caused by partial opening of steam valves upstream and downstream of the test vessel by action of interlocks during an attempt to restore power to the bundle; Fig. 45 will facilitate explanation of the event.

The steam flow rate is controlled by a small valve downstream of the vessel, and the steam pressure in the vessel, indicated by PE 301 in the figure, is controlled by a pressure regulator upstream of the vessel. After the tubes burst (in a normal burst test), a large downstream valve opens to relieve the vessel pressure, and a large upstream valve opens simultaneously to admit a large flow of steam from the building supply to cool the bundle. Actuation of these valves is controlled through

interlock circuits that require the proper sequence of events. In an attempt to reinitialize the sequence for startup of the electrical power generator, the valves were opened partially as indicated in Fig. 45 by the sharp decrease in vessel pressure (PE 301) at ~225 s scan time and closed 12 to 15 s later.

Measurements by the inlet and outlet steam thermocouples, of which an example of each (see Fig. 4 for locations) is plotted in the figure, indicated significant temperature changes as a result of the sudden increase in steam flow. The first response was an increase in temperature caused by a reduction in residence time in the steam inlet line (i.e., less sensible heat loss from the highly superheated steam as it passed through the line. Shortly thereafter the superheated steam was displaced by a larger flow of saturated (or only slightly superheated) steam, causing the inlet steam temperature to decrease to ~125°C. This relatively cold steam provided good cooling conditions throughout the bundle for a few seconds. Shortly thereafter, the vessel pressure, steam flow rate, and inlet temperature returned to their original values and were maintained at these values until the bundle average temperature reached a value of ~300°C.

The short period of rapid cooling caused a significant axial temperature gradient to develop within the bundle. This, in turn, decreased the rate of deformation on the interior simulators as indicated by the change in the rate of pressure decrease noted on the pressure plots in Fig. 30 at the time of the perturbation.

Posttest Examination

Following cooldown, the assembly was removed from the test vessel and partially disassembled to facilitate photography, dimensional measurements, etc., for documentation.

Since none of the tubes burst, posttest volume measurements were made on all the simulators except two that developed leaks. One of these (No. 16) developed a leak prior to the test, and the other (No. 22) developed a leak during posttest cooldown. The No. 16 simulator was unpressurized and was not electrically heated, so deformation is not expected. The difference between the posttest and pretest volume measurements represents the volume increase over the heated length and can be used to estimate the average strain over the same length. Comparison of these data (Fig. 46) with the pressure and the radial temperature distributions (Figs. 31 and 42, respectively) shows a definite correlation in that the higher temperature (lower pressure) interior simulators deformed more than the lower temperature (higher pressure) exterior simulators.

Visual observations (and micrometer measurements on the corner simulators) confirmed that the deformation is uniformly distributed over the heated length as expected from the test conditions. Figure 47 shows an overall view of the west face of the test array after removal of the shroud and internal heaters. The west face of the shroud, shown below the bundle, is axially located in its correct position relative to the bundle. One of the steam inlet nozzles is visible in the shroud near the upper end of the bundle.

Posttest views of the four faces of the bundle are shown in Fig. 48; the meter scale is positioned so that 0-cm is at the bottom and the 91.5-cm mark is at the top of the heated length. Deformation uniformity is evident in the photographs. However, localized ballooning of the No. 14 (an interior simulator) is obvious, particularly in the east and west face views at the 49-cm mark. It will be recalled that this is the simulator with the greatest volume increase (Fig. 46). Two closeup views of this region of the bundle are shown in Fig. 49 as viewed from the west face at slightly different camera angles. These views indicate the ballooned region is symmetrical and not in contact with the No. 8 simulator. However, one cannot see through the bundle from the north face in this region, indicating that the ballooned portion is perhaps in contact with the neighboring simulators (Nos. 13 and 15).

While the posttest volume measurements indicate an average strain of ~22% for the No. 14 simulator (Fig. 46), clearly the strain in the ballooned region is significantly greater.

Axial shrinkage is also an indicator of circumferential strain in tests, such as this one, conducted in the alpha temperature region. Axial shrinkage data (Fig. 50) are consistent with the other data, indicating greater shrinkage (and greater circumferential strain) on the interior simulators compared to the exterior ones.

Since deformation is modest and uniformly distributed in the B-4 test array, flow tests will not yield meaningful data. Consequently, a decision was made to omit the flow characterization tests and proceed directly with destructive examination for strain determination. This will be accomplished by complete disassembly of the array to free the individual tubes so that each can be measured to obtain axial profiles of the circumferential strain, using available single rod examination equipment. The individual profiles will be used to generate (mathematically) blockage data as a function of axial position.

Although objectives of the B-4 test were not realized, the data appear useful for model development and verification, particularly with respect to the class of transients referred to as "flat-topped transients". However, because the transient was not allowed to proceed to failure conditions, the blockage data cannot be used to establish bounds on the blockage expected for LOCA transients.

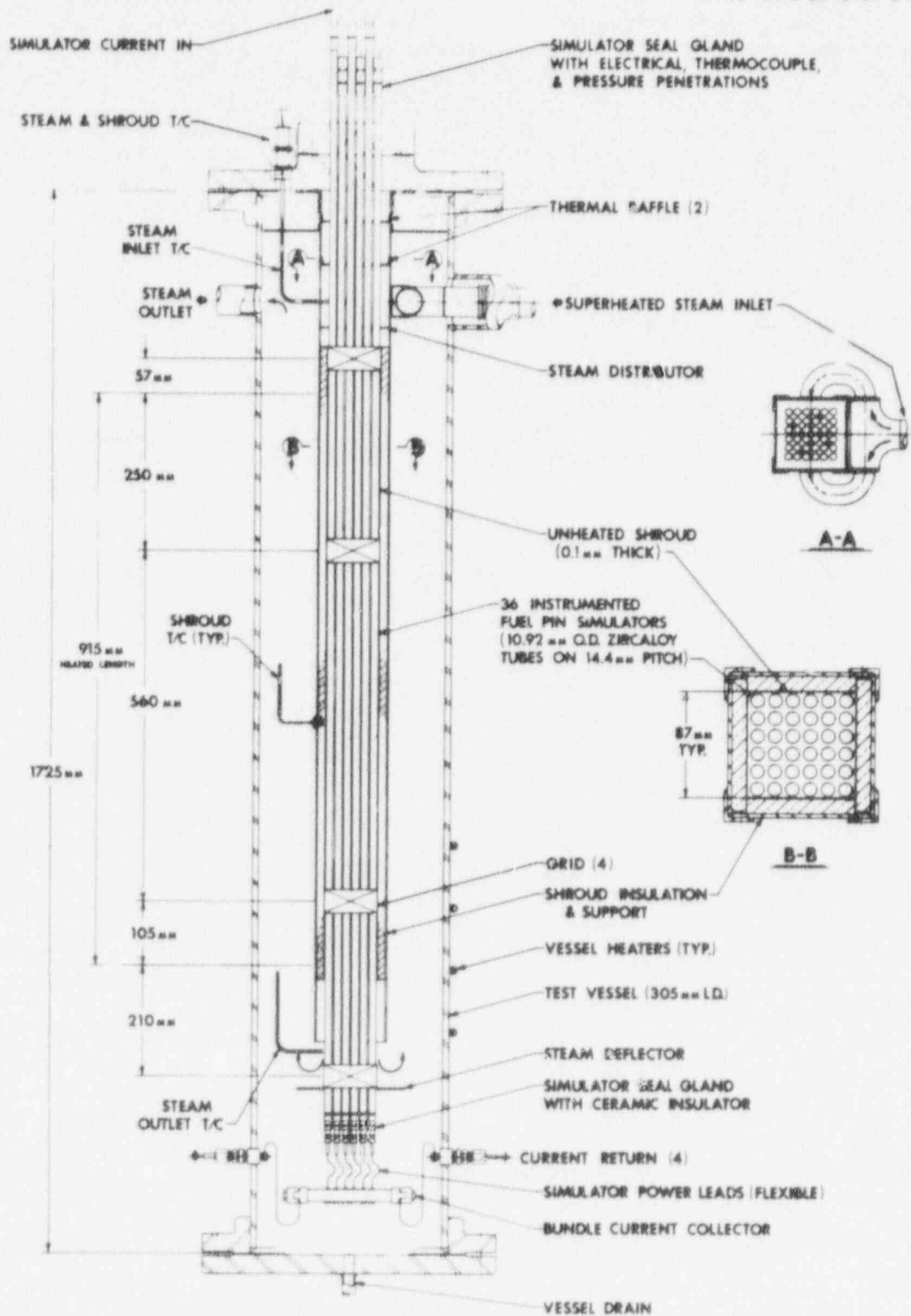


Fig. 1. Schematic of B-4 test.

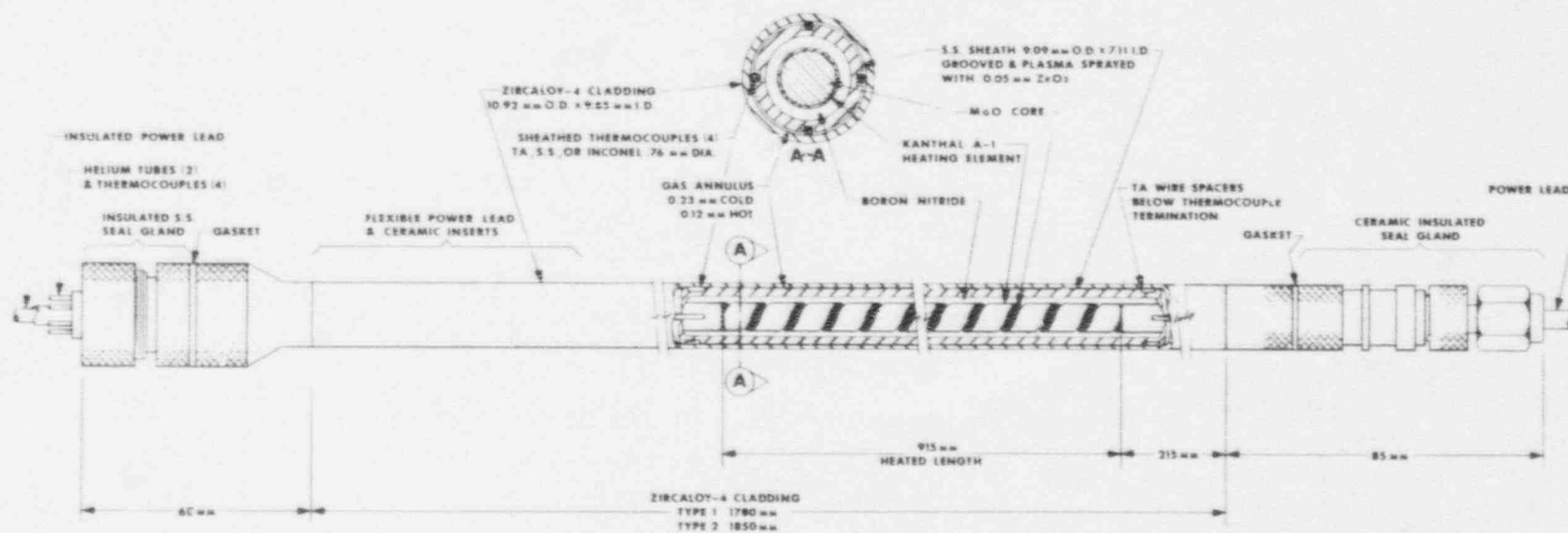


Fig. 2. Schematic of fuel pin simulator.

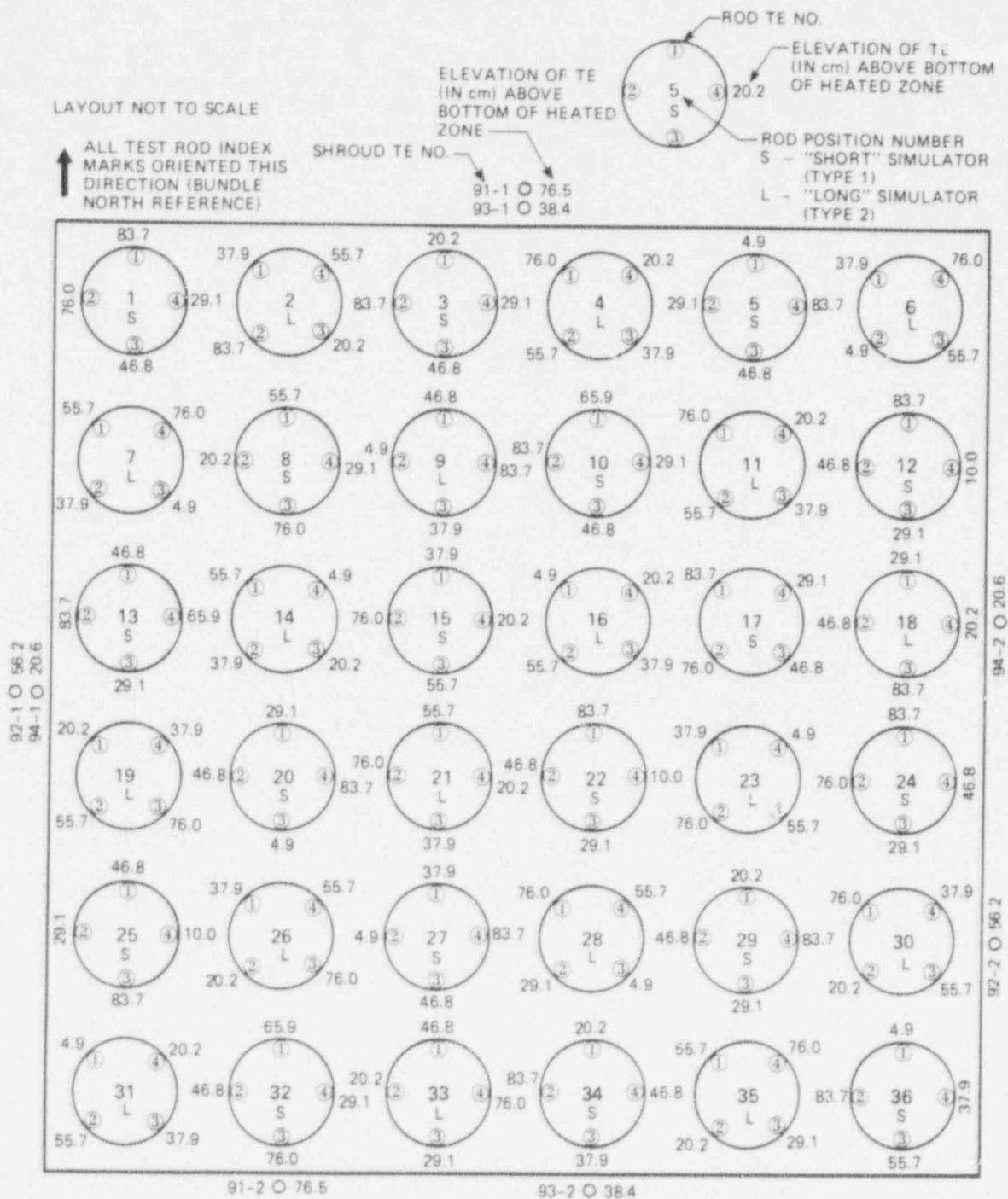


Fig. 3. Thermocouple as-built locations and identifications in B-4 simulators and shroud (plan view).

STEAM TEMPERATURE MAP

MRBT BUNDLE 4

RECORD NUMBER 289

TIME FROM START OF SCAN 28.9 SEC

AVERAGE STEAM INLET AT 187 CM ELEVATION: 326.1 DEGREES C
AVERAGE STEAM OUTLET AT 3 CM ELEVATION: 334.5 DEGREES C

1	2	3	4	5	6
			TE-320	TE-325	
			INLET * OUTLET		
			319	335	
7	8	9	10	11	12
TE-321	TE-326				
INLET * OUTLET					
331	336				
13	14	15	16	17	18
		TE-322	TE-327		
		INLET * OUTLET			
		323	336		
19	20	21	22	23	24
			TE-323	TE-328	
			INLET * OUTLET		
			336	333	
25	26	27	28	29	30
		TE-324	TE-329		
		INLET * OUTLET			
		321	333		
31	32	33	34	35	36

ALL TEMPERATURES ARE IN DEGREES C

Fig. 4. Steam thermocouple identifications and locations and temperatures measured 1 s before power-on.

TEMPERATURE MAP

MRBT BUNDLE 4

RECORD NUMBER 289

TIME FROM START OF SCAN 28.9 SEC

ELEVATION 84 CM

CROSS SECTION AVERAGE 330.5

BUNDLE AVERAGE 332.1

*					
1	2	* 3	4	5 *	6
332	329	329		333	330.8
7	8	9 *	* 10	11	12
		329	327		331
* 13	14	15	16	* 17	18
331				329	331
19	20 *	21	* 22	23	24
	332		328		332
25	26	27 *	28	29 *	30
335		329		329	331.0
31	32	33	* 34	35	* 36
			331		331
332.8	330.6	329.8	325.8	330.1	331.5

ALL TEMPERATURES ARE IN DEGREES C

Fig. 5. Temperatures measured at 84-cm elevation 1 s before power-on.

TEMPERATURE MAP					
MRBT BUNDLE 4					
RECORD NUMBER 289	TIME FROM START OF SCAN 28.9 SEC				
ELEVATION 76 CM	CROSS SECTION AVERAGE	331.3	BUNDLE AVERAGE	332.1	
* 1	2	3	* 4	5	* 6
333			331		336
7	* 8	9	10	* 11	12
335	333			338	
13	14	* 15	16	17	18
		332		338	
19	20	* 21	22	23	* 24
331		329		338	333
25	26	27	* 28	29	* 30
	316		329		332
31	32	33 *	34	35 *	36
	336	335		331	
332.9	328.1	332.1	338.2	338.4	334.8

ALL TEMPERATURES ARE IN DEGREES C

Fig. 6. Temperatures measured at 76-cm elevation 1 s before power-on.

TEMPERATURE MAP					
MRBT BUNDLE 4					
RECORD NUMBER 289	TIME FROM START OF SCAN 28.9 SEC				
ELEVATION 66 CM	CROSS SECTION AVERAGE	332.8	BUNDLE AVERAGE	332.1	
1	2	3	4	5	6
7	8	9	* 10	11	12
			338		338.5
13 *	14	15	16	17	18
332					332.3
19	20	21	22	23	24
25	26	27	28	29	30
31	* 32	33	34	35	36
	336				335.5
332.3	335.5		338.5		

ALL TEMPERATURES ARE IN DEGREES C
TEMPERATURES IN THIS CROSS SECTION NOT INCLUDED IN BUNDLE AVERAGE TEMPERATURE

Fig. 7. Temperatures measured at 66-cm (upper grid) elevation 1 s before power-on.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 289		TIME FROM START OF SCAN 28.9 SEC				
ELEVATION 56 CM		CROSS SECTION AVERAGE 333.1		BUNDLE AVERAGE 332.1		
1	2 *	3	4	5	6	334.5
	336		332		336 *	
7	8 *	9	10	11	12	334.2
336	335			332		
13	14 *	15	16	17	18	333.2
	332	335	(331)			
19	20	21 *	22	23	24	332.1
332		332		332 *		
25	26 *	27	28 *	29	30	332.2
	333		331		332	
31	32	33	34	35	36	332.6
333				332	333	
333.5	333.8	333.2	331.8	332.8	333.7	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 8. Temperatures measured at 56-cm elevation 1 s before power-on.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 289		TIME FROM START OF SCAN 28.9 SEC				
ELEVATION 47 CM		CROSS SECTION AVERAGE 332.4		BUNDLE AVERAGE 332.1		
1	2	3	4	5	6	332.3
*		*		*		
331		331		334		
7	8	9	10	11	* 12	332.5
			*			
		335	331		331	
*						
13	14	15	16	17	* 18	331.9
				*		
331				332	332	
19	* 20	21	* 22	23	24 *	332.9
	335		332		332	
*						
25	26	27	28	* 29	30	332.1
		*				
335		329		332		
31	* 32	33	34 *	35	36	332.5
	334	333	331			
332.5	334.1	332.8	331.6	332.8	331.9	

ALL TEMPERATURES ARE IN DEGREES C

Fig. 9. Temperatures measured at 47-cm elevation 1 s before power-on.

TEMPERATURE MAP

MRBT BUNDLE 4

RECORD NUMBER 289

TIME FROM START OF SCAN 28.9 SEC

ELEVATION 38 CM

CROSS SECTION AVERAGE 331.7

BUNDLE AVERAGE 332.1

1	2	3	4	5	6	331.5
	330		330		334	
7	8	9	10	11	12	332.8
334		334		331		
13	14	15	16	17	18	333.0
	331	335	(331)			
19	20	21	22	23	24	331.7
331		332		332		
25	26	27	28	29	30	331.7
	332	332			331	
31	32	33	34	35	36	329.8
329			331		329	
331.2	331.2	333.1	330.7	331.4	331.5	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 10. Temperatures measured at 38-cm elevation 1 s before power-on.

TEMPERATURE MAP

MRBT BUNDLE 4

RECORD NUMBER 289

TIME FROM START OF SCAN 28.9 SEC

ELEVATION 29 CM

CROSS SECTION AVERAGE 332.2

BUNDLE AVERAGE 332.1

1	2	3	4	5	6	331.5
330		331		334		
7	8	9	10	11	12	332.2
	334		331		331	
13	14	15	16	17	18	331.4
331				332	331	
19	20	21	22	23	24	333.1
	336		332		332	
25	26	27	28	29	30	332.3
335			330	331		
31	32	33	34	35	36	332.6
	333	334		331		
332.6	334.1	332.3	331.2	332.2	331.2	

ALL TEMPERATURES ARE IN DEGREES C

Fig. 11. Temperatures measured at 29-cm elevation 1 s before power-on.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 289		TIME FROM START OF SCAN 28.9 SEC				
ELEVATION 20 CM		CROSS SECTION AVERAGE 332.0		BUNDLE AVERAGE 332.1		
* 1	* 2	* 3	* 4	* 5	* 6	330.6
	331	330	331			
* 7	* 8	* 9	* 10	* 11	* 12	332.8
	334			331		
* 13	* 14	* 15	* 16	* 17	* 18	331.5
	331	332	(331)		331	
* 19	* 20	* 21	* 22	* 23	* 24	332.5
333		332				
* 25	* 26	* 27	* 28	* 29	* 30	332.2
	333			332	331	
* 31	* 32	* 33	* 34	* 35	* 36	332.0
331		335	333	332		
332.1	332.3	332.2	332.1	331.8	331.4	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 12. Temperatures measured at 20-cm elevation 1 s before power-on.

T E M P E R A T U R E M A P						
MRBT BUNDLE 4						
RECORD NUMBER 289			TIME FROM START OF SCAN 28.9 SEC			
ELEVATION 10 CM		CROSS SECTION AVERAGE 333.9		BUNDLE AVERAGE 332.1		
1	2	3	4	5	6	
7	8	9	10	11	12 *	332.3
					332	
13	14	15	16	17	18	
19	20	21	22 *	23	24	332.3
			332			
25 *	26	27	28	29	30	336.9
337						
31	32	33	34	35	36	
336.9		332.3		332.3		

ALL TEMPERATURES ARE IN DEGREES C
TEMPERATURES IN THIS CROSS SECTION NOT INCLUDED IN BUNDLE AVERAGE TEMPERATURE

Fig. 13. Temperatures measured at 10-cm (lower grid) elevation 1 s before power-on.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 289		TIME FROM START OF SCAN 28.3 SEC				
ELEVATION 5 CM		CROSS SECTION AVERAGE 334.3		BUNDLE AVERAGE 332.		
1	2	3	4	5	6	335.5
				335	336	
7	8	9	10	11	12	335.5
336		335				
13	14	15	16	17	18	331.9
	332		(332)			
19	20	21	22	23	24	334.1
	336			333		
25	26	27	28	29	30	332.3
		332	333			
31	32	33	34	35	36	335.3
334					337	
334.9	333.7	333.4	332.7	333.9	336.5	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 14. Temperatures measured at 5-cm elevation 1 s before power-on.

ROD AVERAGE TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 289	TIME FROM START OF SCAN 28.9 SEC					
	BUNDLE AVERAGE 332.1 DEGREES C					
1	2	3	4	5	6	332.3
332	332	330	331	334	335	
7	8	9	10	11	12	332.6
335	334	333	330	331	331	
13	14	15	16	17	18	331.7
331	332	333	(332)	331	331	
19	20	21	22	23	24	332.1
332	334	331	331	332	332	
25	26	27	28	29	30	331.2
335	328	331	331	331	332	
31	32	33	34	35	36	332.5
332	334	334	332	332	333	
332.7	332.3	332.1	331.8	331.7	332.6	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING ROW & COLUMN AVERAGES

Fig. 15. Average simulator temperatures measured 1 s before power-on.

P R E S S U R E M A P									
H8BT BUNDLE 4									
RECORD NUMBER 289		TIME FROM START OF SCAN 28.9 SEC							
		AVERAGE PRESSURE		9091 KPA (DIFFERENTIAL)		STEAM PRESSURE		206 KPA (GAGE)	
1	9101	2	3	4	5	6	7	8	9090
7		9	10	11	12	13	14	15	9081
13		16	17	18	19	20	21	22	9083
19		23	24	25	26	27	28	29	9093
25		30	31	32	33	34	35	36	9100
31		37	38	39	40	41	42	43	9101
37		44	45	46	47	48	49	50	9093
43		51	52	53	54	55	56	57	9086
49		58	59	60	61	62	63	64	9063
55		65	66	67	68	69	70	71	9067
61		72	73	74	75	76	77	78	9081
67		79	80	81	82	83	84	85	9083
73		86	87	88	89	90	91	92	9083
79		93	94	95	96	97	98	99	9083
85		100	101	102	103	104	105	106	9083
91		107	108	109	110	111	112	113	9083
97		114	115	116	117	118	119	120	9083
103		121	122	123	124	125	126	127	9083
109		128	129	130	131	132	133	134	9083
115		135	136	137	138	139	140	141	9083
121		142	143	144	145	146	147	148	9083
127		149	150	151	152	153	154	155	9083
133		156	157	158	159	160	161	162	9083
139		163	164	165	166	167	168	169	9083
145		170	171	172	173	174	175	176	9083
151		177	178	179	180	181	182	183	9083
157		184	185	186	187	188	189	190	9083
163		191	192	193	194	195	196	197	9083
169		198	199	200	201	202	203	204	9083
175		205	206	207	208	209	210	211	9083
181		212	213	214	215	216	217	218	9083
187		219	220	221	222	223	224	225	9083
193		226	227	228	229	230	231	232	9083
199		233	234	235	236	237	238	239	9083
205		240	241	242	243	244	245	246	9083
211		247	248	249	250	251	252	253	9083
217		254	255	256	257	258	259	260	9083
223		261	262	263	264	265	266	267	9083
229		268	269	270	271	272	273	274	9083
235		275	276	277	278	279	280	281	9083
241		282	283	284	285	286	287	288	9083
247		289	290	291	292	293	294	295	9083
253		296	297	298	299	300	301	302	9083
259		303	304	305	306	307	308	309	9083
265		310	311	312	313	314	315	316	9083
271		317	318	319	320	321	322	323	9083
277		324	325	326	327	328	329	330	9083
283		331	332	333	334	335	336	337	9083
289		338	339	340	341	342	343	344	9083
295		345	346	347	348	349	350	351	9083
301		352	353	354	355	356	357	358	9083
307		359	360	361	362	363	364	365	9083
313		366	367	368	369	370	371	372	9083
319		373	374	375	376	377	378	379	9083
325		380	381	382	383	384	385	386	9083
331		387	388	389	390	391	392	393	9083
337		394	395	396	397	398	399	400	9083
343		401	402	403	404	405	406	407	9083
349		408	409	410	411	412	413	414	9083
355		415	416	417	418	419	420	421	9083
361		422	423	424	425	426	427	428	9083
367		429	430	431	432	433	434	435	9083
373		436	437	438	439	440	441	442	9083
379		443	444	445	446	447	448	449	9083
385		450	451	452	453	454	455	456	9083
391		457	458	459	460	461	462	463	9083
397		464	465	466	467	468	469	470	9083
403		471	472	473	474	475	476	477	9083
409		478	479	480	481	482	483	484	9083
415		485	486	487	488	489	490	491	9083
421		492	493	494	495	496	497	498	9083
427		499	500	501	502	503	504	505	9083
433		506	507	508	509	510	511	512	9083
439		513	514	515	516	517	518	519	9083
445		520	521	522	523	524	525	526	9083
451		527	528	529	530	531	532	533	9083
457		534	535	536	537	538	539	540	9083
463		541	542	543	544	545	546	547	9083
469		548	549	550	551	552	553	554	9083
475		555	556	557	558	559	560	561	9083
481		562	563	564	565	566	567	568	9083
487		569	570	571	572	573	574	575	9083
493		576	577	578	579	580	581	582	9083
499		583	584	585	586	587	588	589	9083
505		590	591	592	593	594	595	596	9083
511		597	598	599	600	601	602	603	9083
517		604	605	606	607	608	609	610	9083
523		611	612	613	614	615	616	617	9083
529		618	619	620	621	622	623	624	9083
535		625	626	627	628	629	630	631	9083
541		632	633	634	635	636	637	638	9083
547		639	640	641	642	643	644	645	9083
553		646	647	648	649	650	651	652	9083
559		653	654	655	656	657	658	659	9083
565		660	661	662	663	664	665	666	9083
571		667	668	669	670	671	672	673	9083
577		674	675	676	677	678	679	680	9083
583		681	682	683	684	685	686	687	9083
589		688	689	690	691	692	693	694	9083
595		695	696	697	698	699	700	701	9083
601		702	703	704	705	706	707	708	9083
607		709	710	711	712	713	714	715	9083
613		716	717	718	719	720	721	722	9083
619		723	724	725	726	727	728	729	9083
625		730	731	732	733	734	735	736	9083
631		737	738	739	740	741	742	743	9083
637		744	745	746	747	748	749	750	9083
643		751	752	753	754	755	756	757	9083
649		758	759	760	761	762	763	764	9083
655		765	766	767	768	769	770	771	9083
661		772	773	774	775	776	777	778	9083
667		779	780	781	782	783	784	785	9083
673		786	787	788	789	790	791	792	9083
679		793	794	795	796	797	798	799	9083
685		800	801	802	803	804	805	806	9083
691		807	808	809	810	811	812	813	9083
697		814	815	816	817	818	819	820	9083
703		821	822	823	824	825	826	827	9083
709		828	829	830	831	832	833	834	9083
715		835	836	837	838	839	840	841	9083
721		842	843	844	845	846	847	848	9083
727		849	850	851	852	853	854	855	9083
733		856	857	858	859	860	861	862	9083
739		863	864	865	866	867	868	869	9083
745		870	871	872	873	874	875	876	9083
751		877	878	879	880	881	882	883	9083
757		884	885	886	887	888	889	890	9083
763		891	892	893	894	895	896	897	9083
769		898	899	900	901	902	903	904	9083
775		905	906	907	908	909	910	911	9083
781		912	913	914	915	916	917	918	9083
787		919	920	921	922	923	924	925	9083
793		926	927	928	929	930	931	932	9083
799		933	934	935	936	937	938	939	9083
805		940	941	942	943	944	945	946	9083
811		947	948	949	950	951	952	953	9083
817		954	955	956	957	958	959	960	9083
823		961	962	963	964	965	966	967	9083
829		968	969	970	971	972	973	974	9083
835		975	976	977	978	979	980	981	9083
841		982	983	984	985	986	987	988	9083
847		989	990	991	992	993	994	995	9083
853		996	997	998	999	1000	1001	1002	9083

ALL SIMULATOR PRESSURES ARE DIFFERENTIAL AND ARE IN KPA

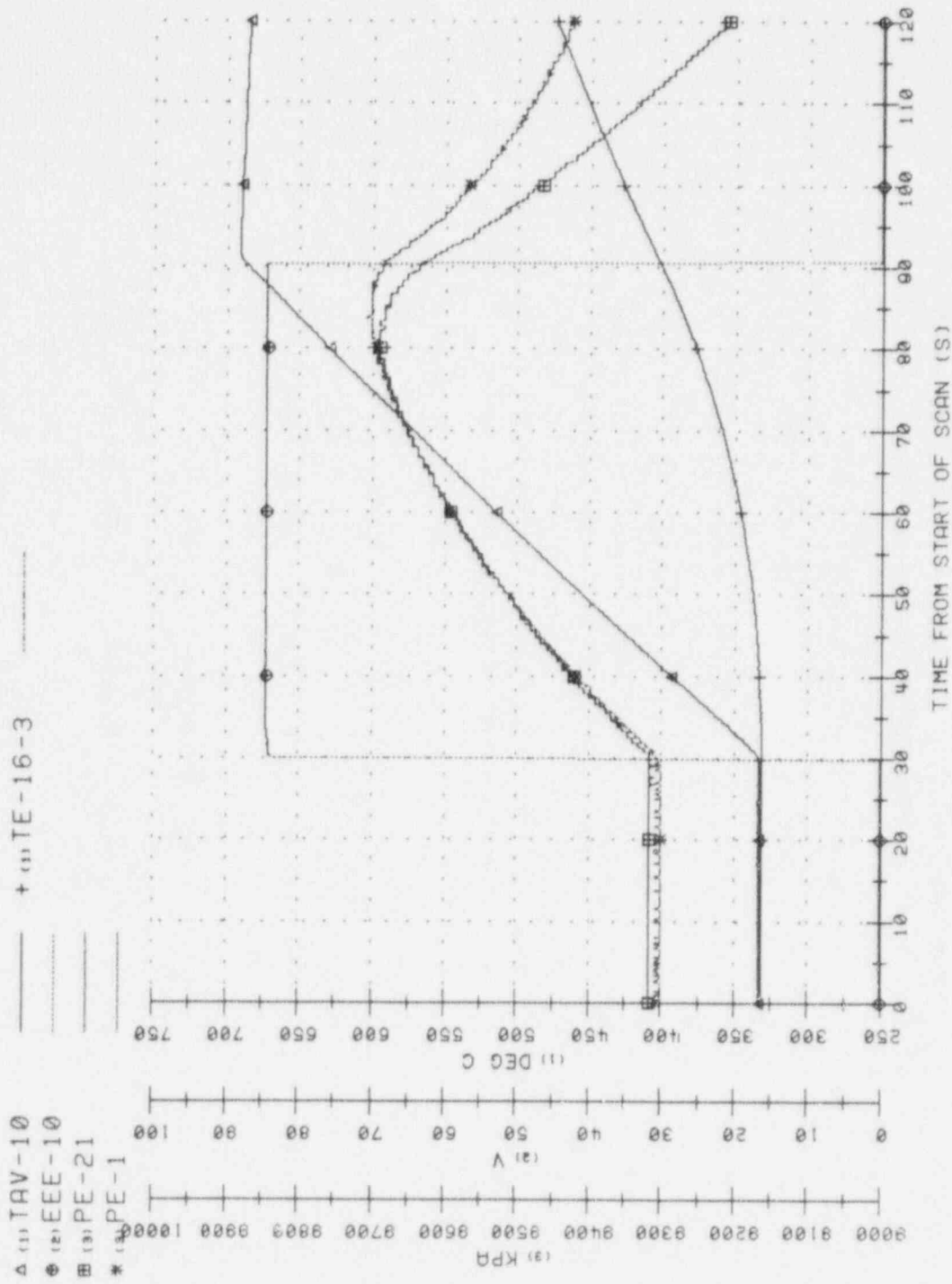


Fig. 17. Characteristic temperatures and pressures during powered portion of transient.

PRESSURE MAP

HRBT BUNDLE 4

RECORD NUMBER 983

TIME FROM START OF SCAN 98.3 SEC

AVERAGE PRESSURE 9437 KPA (DIFFERENTIAL)
STEAM PRESSURE 287 KPA (GAGE)

1	2	3	4	5	6	
9472	9446	9452	9483	9436	9428	9453
7	8	9	10	11	12	
9424	9448	9398	9432	9421	9427	9424
13	14	15	16	17	18	
9433	9453	9438	()	9434	9419	9434
19	20	21	22	23	24	
9447	9467	9423	9433	9402	9417	9432
25	26	27	28	29	30	
9446	9456	9432	9478	9437	9486	9441
31	32	33	34	35	36	
9444	9431	9443	9448	9443	9435	9448
9445	9458	9428	9452	9429	9422	

ALL SIMULATOR PRESSURES ARE DIFFERENTIAL AND ARE IN KPA
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES

Fig. 18. Simulator pressures measured
0.2 s before power-off.

TEMPERATURE MAP

HRBT BUNDLE 4

RECORD NUMBER 983

TIME FROM START OF SCAN 98.3 SEC

ELEVATION 84 CM

CROSS SECTION AVERAGE 666.9

BUNDLE AVERAGE 678.7

1	2	3	4	5	6	
669	671	668		678		669.5
7	8	9	10	11	12	
		671	666		664	667.1
13	14	15	16	17	18	
664				659	664	662.3
19	20	21	22	23	24	
	688		665		664	669.7
25	26	27	28	29	30	
669		678		672		678.2
31	32	33	34	35	36	
			662		657	659.2
667.2	675.5	669.7	664.2	666.8	662.3	

ALL TEMPERATURES ARE IN DEGREES C

Fig. 19. Temperatures measured at 84-cm
elevation 0.2 s before power-off.

TEMPERATURE MAP						
HRT BUNDLE 4						
RECORD NUMBER 903			TIME FROM START OF SCAN 90.3 SEC			
ELEVATION 76 CM		CROSS SECTION AVERAGE 670.4		BUNDLE AVERAGE 670.7		
* 1	2	3	* 4	5	6 *	669.4
669			663		677	
7 *	8	9	10	* 11	12	681.8
683	684			679		
13	14	* 15	16	17	18	669.6
		677		* 662		
19	20	* 21	22	23	* 24	675.8
668 *		679		* 679	674	
25	26	27	* 28	29	* 30	666.3
	647 *		673		679	
31	32	33 *	34	35 *	36	650.4
	646	663		666		
673.8	659.9	672.9	660.2	671.8	676.3	

ALL TEMPERATURES ARE IN DEGREES C

Fig. 20. Temperatures measured at 76-cm elevation 0.2 s before power-off.

T E M P E R A T U R E M A P						
HRT BUNDLE 4						
RECORD NUMBER 903			TIME FROM START OF SCAN 90.3 SEC			
ELEVATION 66 CM		CROSS SECTION AVERAGE 649.8		BUNDLE AVERAGE 670.7		
1	2	3	4	5	6	
7	8	9	* 10	11	12	648.2
			648			
13 *	14	15	16	17	18	649.2
649						
19	20	21	22	23	24	
25	26	27	28	29	30	
31	* 32	33	34	35	36	652.1
	652					
649.2	652.1		648.2			

ALL TEMPERATURES ARE IN DEGREES C
TEMPERATURES IN THIS CROSS SECTION NOT INCLUDED IN BUNDLE AVERAGE TEMPERATURE

Fig. 21. Temperatures measured at 66-cm (upper grid) elevation 0.2 s before power-off.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 983		TIME FROM START OF SCAN 98.3 SEC				
ELEVATION 56 CM		CROSS SECTION AVERAGE 673.5		BUNDLE AVERAGE 678.7		
* 1	* 2	* 3	* 4	* 5	* 6	671.5
	678		665		671	
* 7	* 8	* 9	* 10	* 11	* 12	679.5
679	686			674		
* 13	* 14	* 15	* 16	* 17	* 18	679.1
	683	675	(489)			
* 19	* 20	* 21	* 22	* 23	* 24	675.4
672		679		675		
* 25	* 26	* 27	* 28	* 29	* 30	674.6
	684		677		663	
* 31	* 32	* 33	* 34	* 35	* 36	662.7
661				664	663	
678.6	683.8	677.1	671.8	678.9	665.6	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 22. Temperatures measured at 56-cm elevation 0.2 s before power-off.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 983	TIME FROM START OF SCAN 98.3 SEC					
ELEVATION 47 CM	CROSS SECTION AVERAGE 673.1		BUNDLE AVERAGE 678.7			
* 1 *	* 2 *	* 3 *	* 4 *	* 5 *	* 6 *	668.2
662		668		675		
* 7 *	* 8 *	* 9 *	* 10 *	* 11 *	* 12 *	677.6
		682	678		681	
* 13 *	* 14 *	* 15 *	* 16 *	* 17 *	* 18 *	668.5
669				667	669	
* 19 *	* 20 *	* 21 *	* 22 *	* 23 *	* 24 *	675.7
	682		674		672	
* 25 *	* 26 *	* 27 *	* 28 *	* 29 *	* 30 *	675.3
672		675		679		
* 31 *	* 32 *	* 33 *	* 34 *	* 35 *	* 36 *	673.5
	677	678	674			
667.9	679.2	673.6	672.6	673.6	673.7	

ALL TEMPERATURES ARE IN DEGREES C

Fig. 23. Temperatures measured at 47-cm elevation 0.2 s before power-off.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 983			TIME FROM START OF SCAN 90.3 SEC			
ELEVATION 38 CM		CROSS SECTION AVERAGE 671.5		BUNDLE AVERAGE 670.7		
* 1	2	3	4	5	* 6	662.1
	664		668		662	
7	8	9	10	11	12	675.3
* 677		677		672		
13	14	* 15	16	17	18	680.7
	* 685	676	(481)			
19	* 20	21	22	* 23	24	676.5
671		686		672		
25	* 26	* 27	28	29	* 30	676.3
	683	678			667	
31	32	33	34	35	36	661.1
663			670		658	
670.4	677.6	679.4	664.9	672.4	659.8	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 24. Temperatures measured at 38-cm elevation 0.2 s before power-off.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 983		TIME FROM START OF SCAN 90.3 SEC				
ELEVATION 29 CM		CROSS SECTION AVERAGE 672.4		BUNDLE AVERAGE 670.7		
1 *	2	3 *	4	* 5	6	668.7
663		669		674		
7	8 *	9	10 *	11	12	675.0
	683		669		* 673	
13	14	15	16	* 17	* 18	668.3
* 668				672	665	
19	* 20	21	22	23	24	676.7
	684		* 677		* 669	
* 25	26	27	28	29	30	674.6
669			* 690	* 675		
31	32 *	33	34	35	36	671.4
	680	* 671		* 663		
666.6	682.2	670.2	675.3	670.9	669.2	

ALL TEMPERATURES ARE IN DEGREES C

Fig. 25. Temperatures measured at 29-cm elevation 0.2 s before power-off.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 983		TIME FROM START OF SCAN 98.3 SEC				
ELEVATION 20 CM		CROSS SECTION AVERAGE 678.4		BUNDLE AVERAGE 678.7		
* 1	* 2	* 3	* 4	* 5	* 6	666.7
	673	661	666			
* 7	* 8	* 9	* 10	* 11	* 12	678.9
	682			676		
* 13	* 14	* 15	* 16	* 17	* 18	669.5
	679	666	(4853)		664	
* 19	* 20	* 21	* 22	* 23	* 24	669.8
663		675				
* 25	* 26	* 27	* 28	* 29	* 30	674.8
	688			679	663	
* 31	* 32	* 33	* 34	* 35	* 36	667.7
668		672	673	658		
665.2	678.4	668.5	669.5	671.2	663.3	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 26. Temperatures measured at 20-cm elevation 0.2 s before power-off.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 983		TIME FROM START OF SCAN 98.3 SEC				
ELEVATION 10 CM		CROSS SECTION AVERAGE 647.7		BUNDLE AVERAGE 678.7		
1	2	3	4	5	6	
7	8	9	10	11	12 *	641.8
					642	
13	14	15	16	17	18	
19	20	21	22 *	23	24	653.3
			653			
25 *	26	27	28	29	30	648.8
648						
31	32	33	34	35	36	
648.8			653.3		641.8	

ALL TEMPERATURES ARE IN DEGREES C
TEMPERATURES IN THIS CROSS SECTION NOT INCLUDED IN BUNDLE AVERAGE TEMPERATURE

Fig. 27. Temperatures measured at 10-cm (lower grid) elevation 0.2 s before power-off.

TEMPERATURE MAP

MRBT BUNDLE 4

RECORD NUMBER 903

TIME FROM START OF SCAN 90.3 SEC

ELEVATION 5 CM

CROSS SECTION AVERAGE 665.4

BUNDLE AVERAGE 670.7

1	2	3	4	5	6	665.3
				663	667	
7	8	9	10	11	12	674.1
674		674				
13	14	15	16	17	18	669.5
	669		(398)			
19	20	21	22	23	24	659.8
	675			663		
25	26	27	28	29	30	664.4
		666	663			
31	32	33	34	35	36	652.3
652					653	
662.9	672.4	670.2	662.8	663.8	668.8	

ALL TEMPERATURES ARE IN DEGREES C

VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 28. Temperatures measured at 5-cm elevation 0.2 s before power-off.

ROD AVERAGE TEMPERATURE MAP

MRBT BUNDLE 4

RECORD NUMBER 903

TIME FROM START OF SCAN 90.3 SEC

BUNDLE AVERAGE 670.7 DEGREES C

1	2	3	4	5	6	667.9
666	672	667	663	670	669	
7	8	9	10	11	12	676.1
678	683	676	668	675	673	
13	14	15	16	17	18	678.2
667	679	673	(403)	665	665	
19	20	21	22	23	24	673.8
668	680	680	672	672	678	
25	26	27	28	29	30	672.3
678	674	672	673	676	668	
31	32	33	34	35	36	664.1
661	669	669	670	663	656	
668.3	676.3	672.9	669.2	670.4	666.5	

ALL TEMPERATURES ARE IN DEGREES C

VALUES IN PARENTHESES ARE NOT USED IN DETERMINING ROW & COLUMN AVERAGES

Fig. 29. Average simulator temperatures measured 0.2 s before power-off.

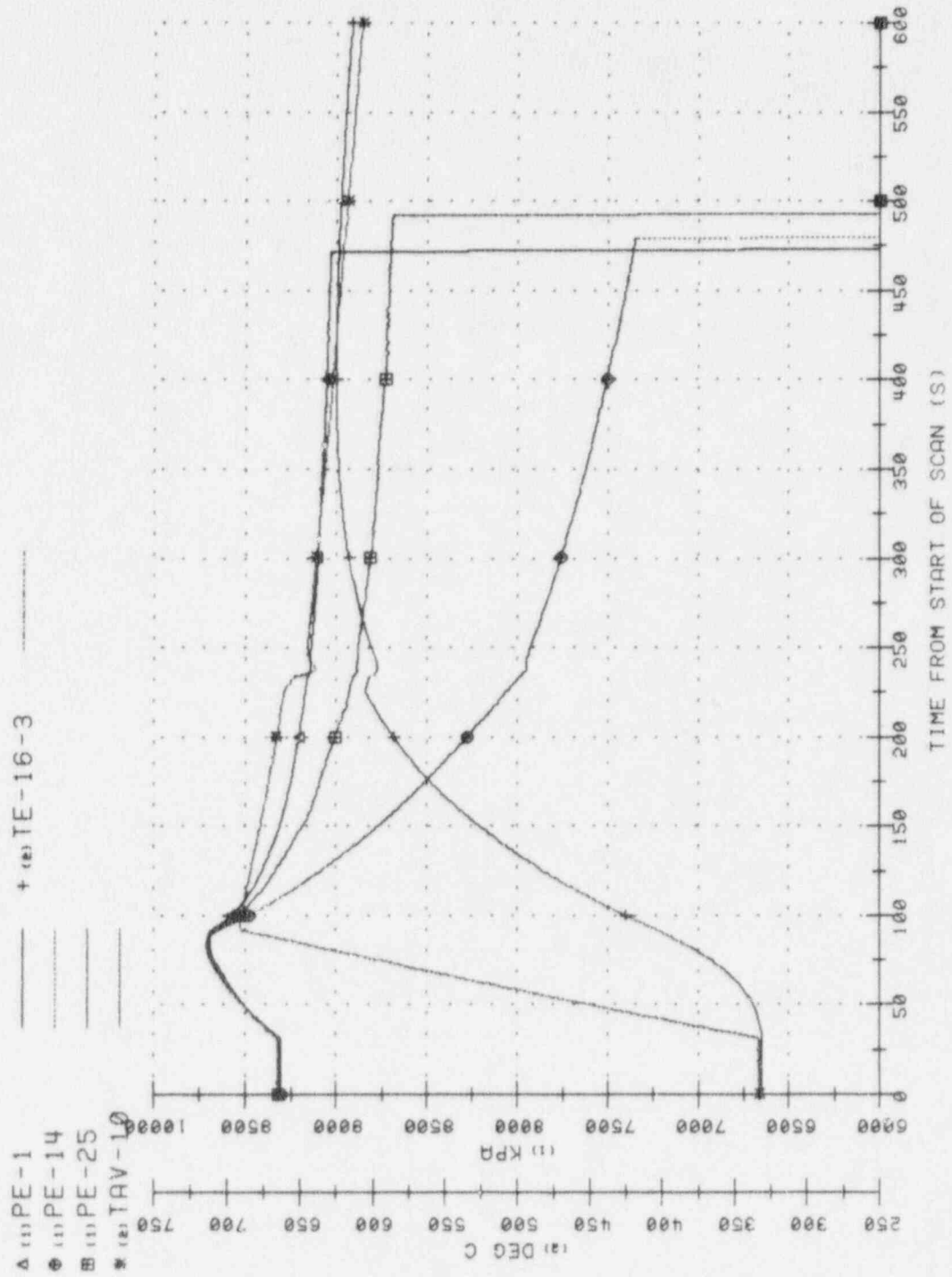


Fig. 30. Characteristic temperatures and pressures during transient.

P R E S S U R E M A P

NRBT BUNDLE 4

RECORD NUMBER 4710

TIME FROM START OF SCAN 471.0 SEC

AVERAGE PRESSURE 8266 KPA (DIFFERENTIAL)
STEAM PRESSURE 281 KPA (GAGE)

1	2	3	4	5	6	8642
8825	8515	8528	8581	8611	8799	
7	8	9	10	11	12	8149
8311	7769	7823	8283	8197	8513	
13	14	15	16	17	18	8884
8325	7164	8814	(488)	8482	8515	
19	20	21	22	23	24	8816
8383	7743	7457	7976	8887	8531	
25	26	27	28	29	30	8859
8583	7738	7646	7982	7963	8622	
31	32	33	34	35	36	8645
8821	8536	8484	8478	8634	8927	
8528	7911	7991	8239	8382	8651	

ALL SIMULATOR PRESSURES ARE DIFFERENTIAL AND ARE IN KPA
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES

Fig. 31. Simulator pressures measured
0.7 s before depressurization.

T E M P E R A T U R E M A P

NRBT BUNDLE 4

RECORD NUMBER 4710

TIME FROM START OF SCAN 471.0 SEC

ELEVATION 84 CM

CROSS SECTION AVERAGE 515.5

BUNDLE AVERAGE 503.5

1	2	3	4	5	6	511.4
588	514	514		589		
7	8	9	10	11	12	513.3
		528	513		587	
13	14	15	16	17	18	516.1
524				512	512	
19	20	21	22	23	24	521.1
	527		521		515	
25	26	27	28	29	30	528.9
528		526		517		
31	32	33	34	35	36	509.4
			517		582	
517.4	528.7	528.8	516.9	512.8	509.8	

ALL TEMPERATURES ARE IN DEGREES C

Fig. 32. Temperatures measured at 84-cm
elevation 0.7 s before depressurization.

TEMPERATURE MAP					
MRBT BUNDLE 4					
RECORD NUMBER 4718		TIME FROM START OF SCAN 471.8 SEC			
ELEVATION 76 CM	CROSS SECTION AVERAGE	565.9	BUNDLE AVERAGE	583.5	
* 1 .	. 2 .	. 3 .	* 4 .	. 5 .	. 6 *
549			561		542
. 7 .	. 8 .	. 9 .	. 10 .	* 11 .	. 12 .
568	581			567	
. 13 .	. 14 .	* 15 .	. 16 .	. 17 .	. 18 .
		587		* 578	
. 19 .	. 20 .	* 21 .	. 22 .	. 23 .	* 24 .
569		583		576	564
. 25 .	. 26 .	. 27 .	* 28 .	. 29 .	* 30 .
	551		578		558
. 31 .	. 32 .	. 33 *	. 34 .	. 35 *	. 36 .
	558	569		556	
561.9	563.1	579.4	569.8	567.2	554.5

ALL TEMPERATURES ARE IN DEGREES C

Fig. 33. Temperatures measured at 76-cm elevation 0.7 s before depressurization.

TEMPERATURE MAP					
MRBT BUNDLE 4					
RECORD NUMBER 4718		TIME FROM START OF SCAN 471.8 SEC			
ELEVATION 66 CM	CROSS SECTION AVERAGE	584.3	BUNDLE AVERAGE	583.5	
. 1 .	. 2 .	. 3 .	. 4 .	. 5 .	. 6 .
. 7 .	. 8 .	. 9 .	* 10 .	. 11 .	. 12 .
			593		
. 13 *	. 14 .	. 15 .	. 16 .	. 17 .	. 18 .
583					
. 19 .	. 20 .	. 21 .	. 22 .	. 23 .	. 24 .
. 25 .	. 26 .	. 27 .	. 28 .	. 29 .	. 30 .
. 31 .	* 32 .	. 33 .	. 34 .	. 35 .	. 36 .
	578				
582.5	577.7		592.6		

ALL TEMPERATURES ARE IN DEGREES C
TEMPERATURES IN THIS CROSS SECTION NOT INCLUDED IN BUNDLE AVERAGE TEMPERATURE

Fig. 34. Temperatures measured at 66-cm (upper grid) elevation 0.7 s before depressurization.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718		TIME FROM START OF SCAN 471.8 SEC				
ELEVATION 56 CM	CROSS SECTION AVERAGE 608.8		BUNDLE AVERAGE 583.5			
1	2	3	4	5	6	589.7
	588		592		(578)	
7	8	9	10	11	12	598.6
588	608			599		
13	14	15	16	17	18	615.2
	611	619	(611)			
19	20	21	22	23	24	607.3
596		619		607		
25	26	27	28	29	30	599.7
	608		611		588	
31	32	33	34	35	36	585.8
(566)				585	(559)	
591.7	603.8	619.4	601.2	597.2	588.3	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 35. Temperatures measured at 56-cm elevation 0.7 s before depressurization.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718		TIME FROM START OF SCAN 471.8 SEC				
ELEVATION 47 CM	CROSS SECTION AVERAGE 604.9		BUNDLE AVERAGE 583.5			
1	2	3	4	5	6	595.8
(578)		608		592		
7	8	9	10	11	12	607.2
		619	614		588	
13	14	15	16	17	18	604.3
604				611	598	
19	20	21	22	23	24	613.5
	622		626		593	
25	26	27	28	29	30	609.3
599		620		609		
31	32	33	34	35	36	596.3
	589	602	598			
601.2	605.2	618.4	612.5	604.1	593.1	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 36. Temperatures measured at 47-cm elevation 0.7 s before depressurization.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718		TIME FROM START OF SCAN 471.8 SEC				
ELEVATION 38 CM	CROSS SECTION AVERAGE 611.5		BUNDLE AVERAGE 583.5			
1	2	3	4	5	6	593.6
	591		597		(577)	
7	8	9	10	11	12	609.3
598		623		606		
13	14	15	16	17	18	629.0
	626	632	(627)			
19	20	21	22	23	24	619.1
606		633		619		
25	26	27	28	29	30	608.8
	611	626			589	
31	32	33	34	35	36	603.6
(572)			604		(561)	
602.0	609.2	628.4	608.2	612.7	589.4	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 37. Temperatures measured at 38-cm elevation 0.7 s before depressurization.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718		TIME FROM START OF SCAN 471.8 SEC				
ELEVATION 29 CM	CROSS SECTION AVERAGE 608.2		BUNDLE AVERAGE 583.5			
1	2	3	4	5	6	596.9
(573)		600		594		
7	8	9	10	11	12	610.6
	620		618		593	
13	14	15	16	17	18	607.1
607				616	598	
19	20	21	22	23	24	620.1
	630		630		599	
25	26	27	28	29	30	610.7
596			624	612		
31	32	33	34	35	36	608.3
	600	608		593		
601.7	616.8	604.3	624.4	603.4	597.0	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 38. Temperatures measured at 29-cm elevation 0.7 s before depressurization.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718			TIME FROM START OF SCAN 471.8 SEC			
ELEVATION 20 CM	CROSS SECTION AVERAGE 683.9		BUNDLE AVERAGE 583.5			
1	2	* 3	* 4	5	6	596.3
	595	596	598			
7	* 8	9	10	* 11	12	614.1
	619			610		
13	14	15 *	* 16	17	* 18	610.4
	627	(631)	(625)		594	
* 19	20	21 *	22	23	24	602.0
602		(633)				
25	26	27	28	* 29	30	604.6
	* 611			614	* 598	
* 31	32	* 33	* 34	35	36	600.5
(577)		606	605	* 591		
602.0	612.9	600.6	601.0	604.0	591.1	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION ± 25 C)

Fig. 39. Temperatures measured at 20-cm elevation 0.7 s before depressurization.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718			TIME FROM START OF SCAN 471.8 SEC			
ELEVATION 10 CM	CROSS SECTION AVERAGE 594.1		BUNDLE AVERAGE 583.5			
1	2	3	4	5	6	
7	8	9	10	11	12 *	577.5
					578	
13	14	15	16	17	18	
19	20	21	22 *	23	24	614.2
			614			
25 *	26	27	28	29	30	590.5
591						
31	32	33	34	35	36	
590.5			614.2		577.5	

ALL TEMPERATURES ARE IN DEGREES C
TEMPERATURES IN THIS CROSS SECTION NOT INCLUDED IN BUNDLE AVERAGE TEMPERATURE

Fig. 40. Temperatures measured at 10-cm (lower grid) elevation 0.7 s before depressurization.

TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718			TIME FROM START OF SCAN 471.8 SEC			
ELEVATION 5 CM	CROSS SECTION AVERAGE		565.5	BUNDLE AVERAGE 583.5		
1 2 3 4 5 6						546.6
				548	545	
7 8 9 10 11 12						568.6
551		586				
13 14 15 16 17 18						578.6
	571		(575)			
19 20 21 22 23 24						573.4
	577			578		
25 26 27 28 29 30						578.8
		571	578			
* 31 32 33 34 35 36						
(535)					(528)	
551.2	573.7	578.6	578.4	558.9	545.2	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING AVERAGES (VARIATION +/-25 C)

Fig. 41. Temperatures measured at 5-cm elevation 0.7 s before depressurization.

ROD AVERAGE TEMPERATURE MAP						
MRBT BUNDLE 4						
RECORD NUMBER 4718			TIME FROM START OF SCAN 471.8 SEC			
BUNDLE AVERAGE 583.5 DEGREES C						
* 1 * 2 3 4 5 6						567.6
558	572	577	587	561	558	
* 7 * 8 9 10 11 12						586.3
576	607	587	582	596	563	
* 13 * 14 15 16 17 18						592.1
578	609	617	(609)	577	576	
* 19 * 20 21 22 23 24						592.1
593	589	617	592	593	568	
* 25 * 26 27 28 29 30						586.6
571	595	586	596	588	579	
* 31 * 32 33 34 35 36						572.9
562	582	596	591	581	537	
571.7	592.8	596.8	587.7	582.6	563.6	

ALL TEMPERATURES ARE IN DEGREES C
VALUES IN PARENTHESES ARE NOT USED IN DETERMINING ROW & COLUMN AVERAGES

Fig. 42. Average simulator temperatures measured 0.7 s before depressurization.

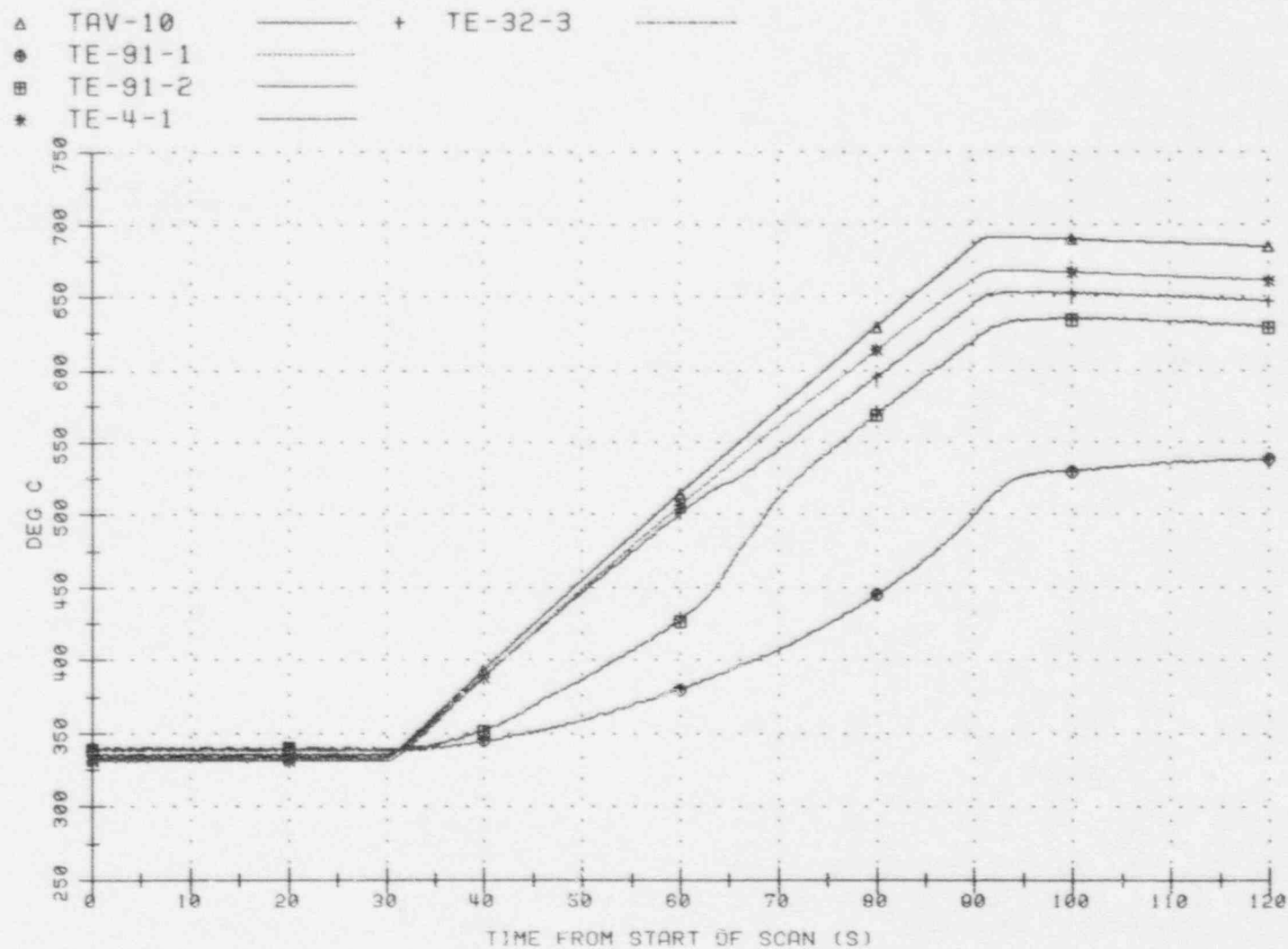


Fig. 43. Shroud and simulator temperatures measured at 76-cm elevation during powered portion of transient.

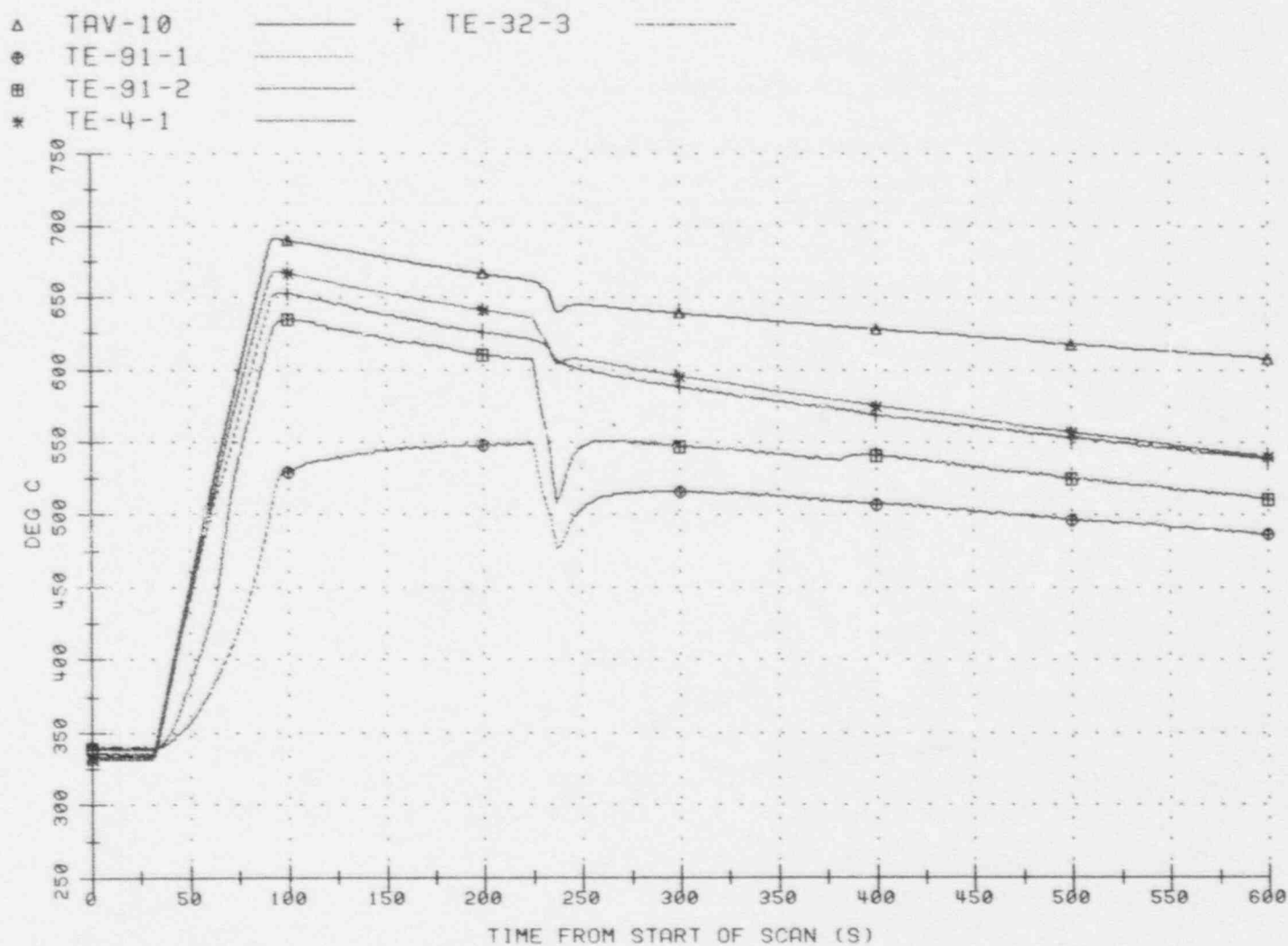


Fig. 44. Shroud and simulator temperatures measured at 76-cm elevation during transient.

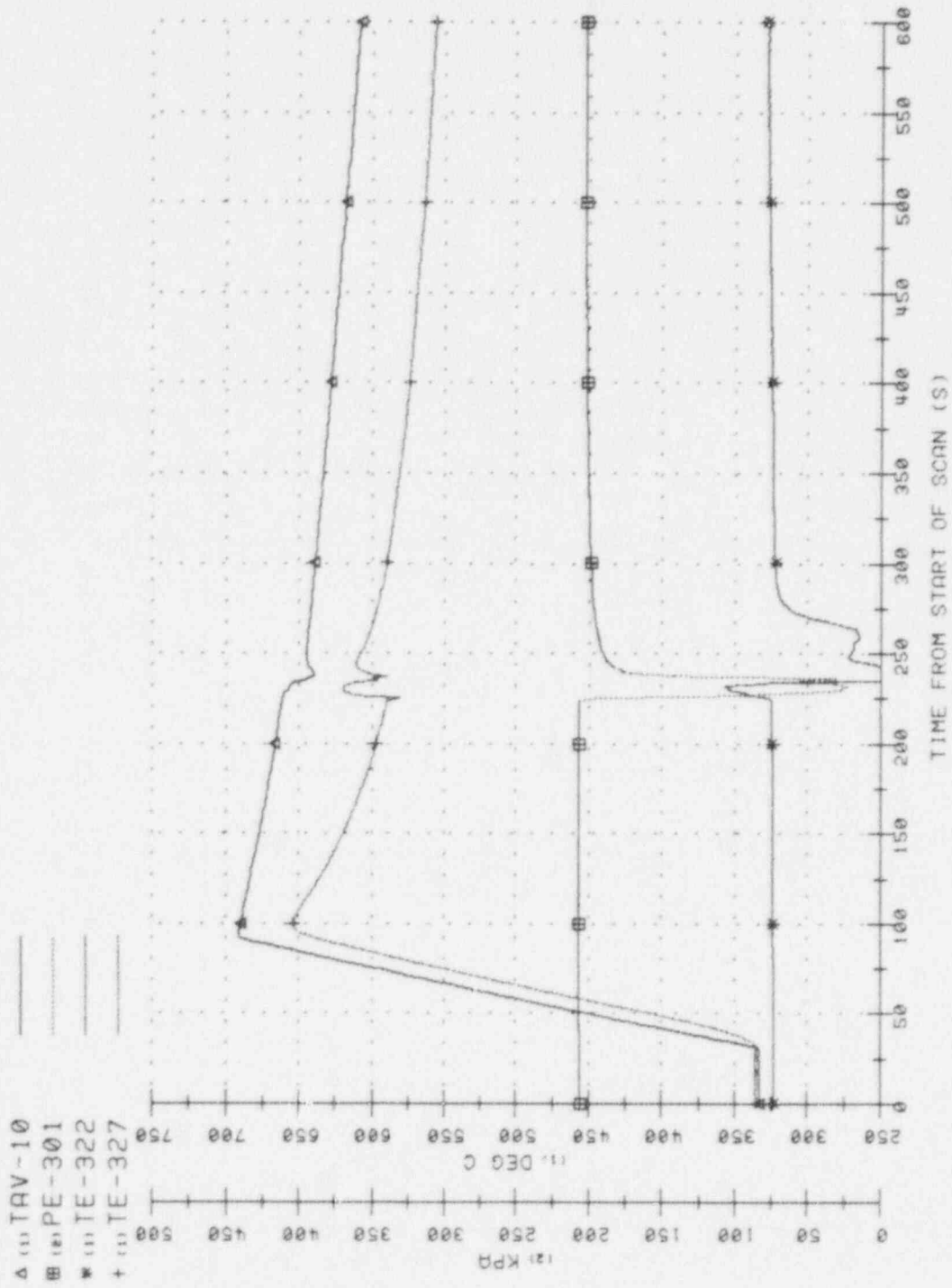
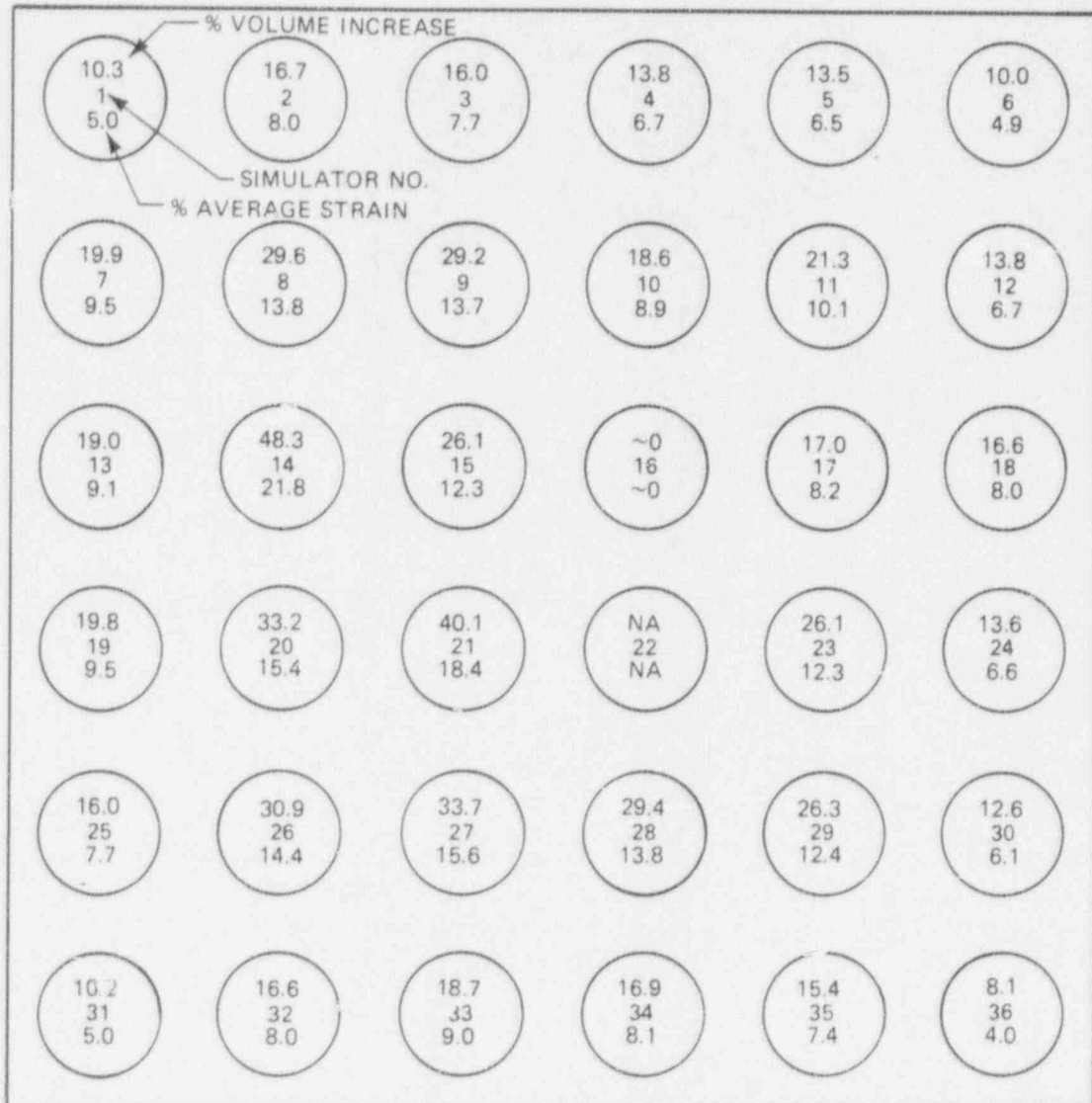


Fig. 45. Steam pressure and characteristic temperatures measured during transient.



NA - NOT MEASURED DUE TO LEAK

Fig. 46. Heated length volume increase and equivalent average strain.

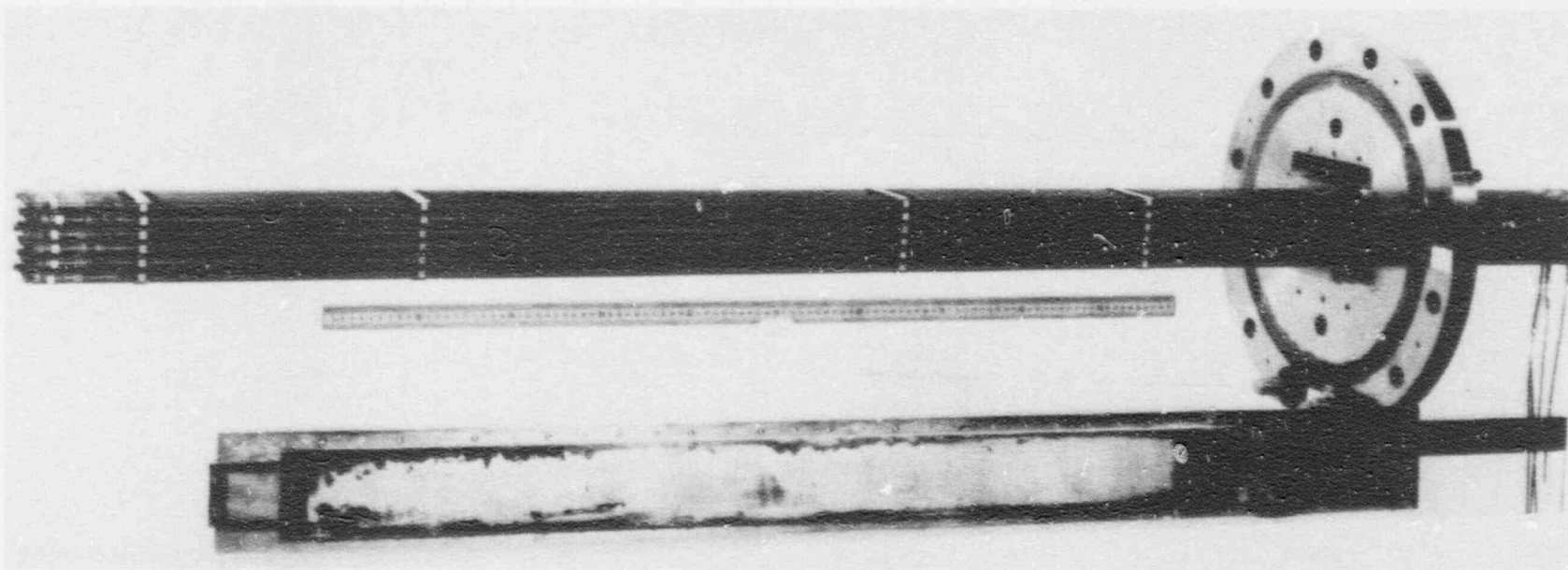


Fig. 47. Posttest view of west face of bundle and shroud.

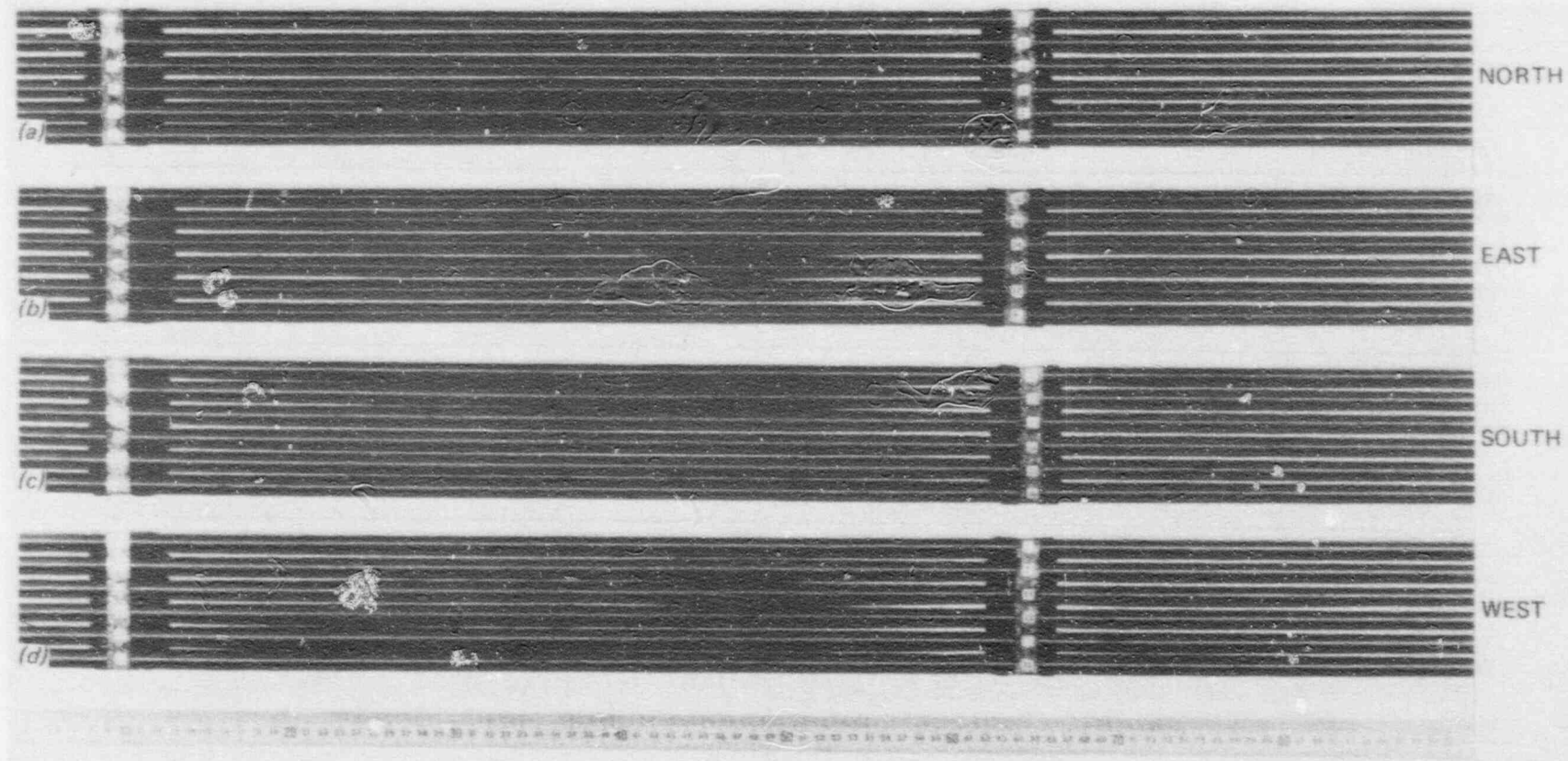


Fig. 48. Posttest views of (a) north, (b) east, (c) south, and (d) west faces of bundle.

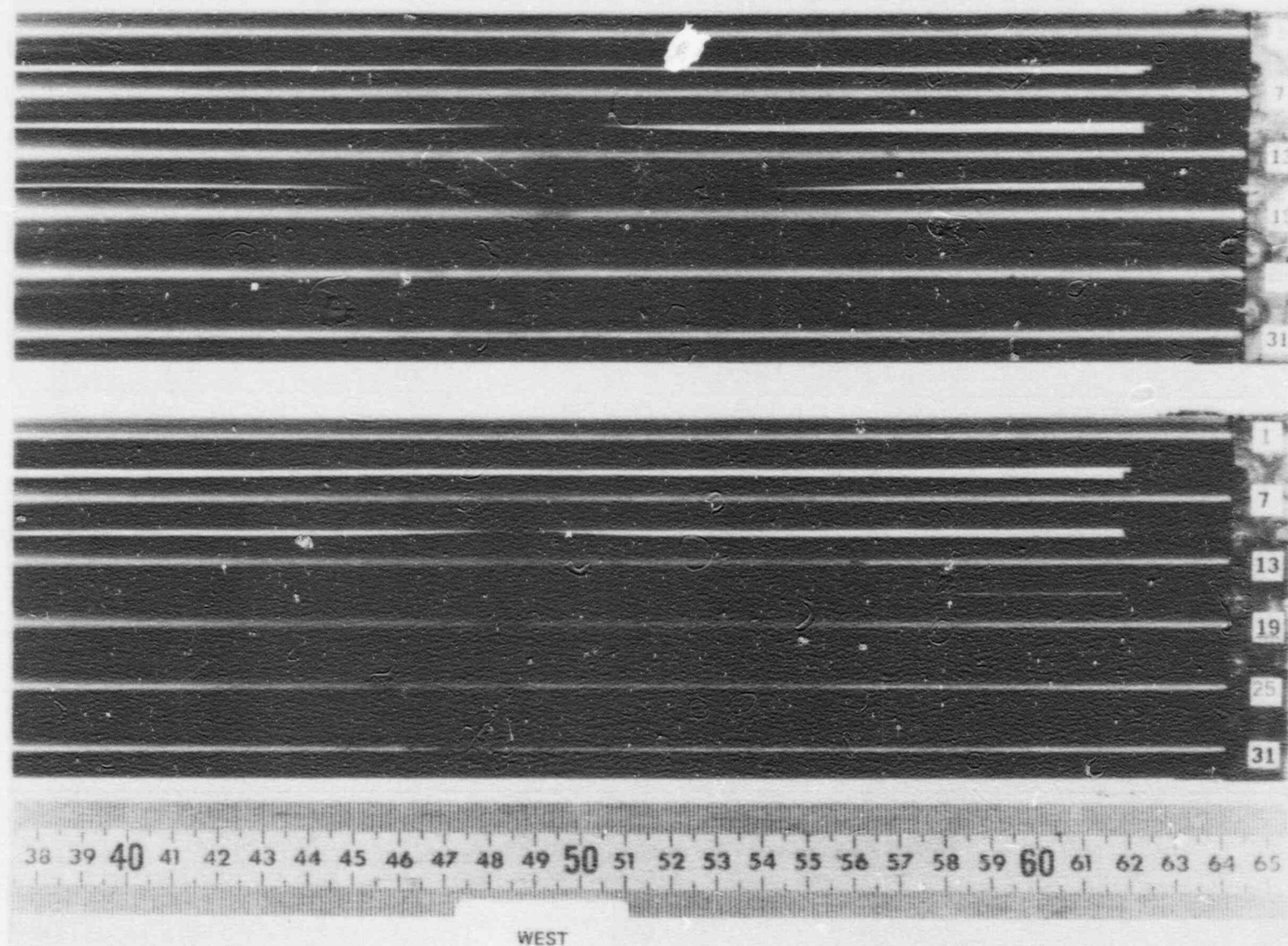


Fig. 49. Closeup views of west face of bundle showing ballooned zone of No. 14 simulator.

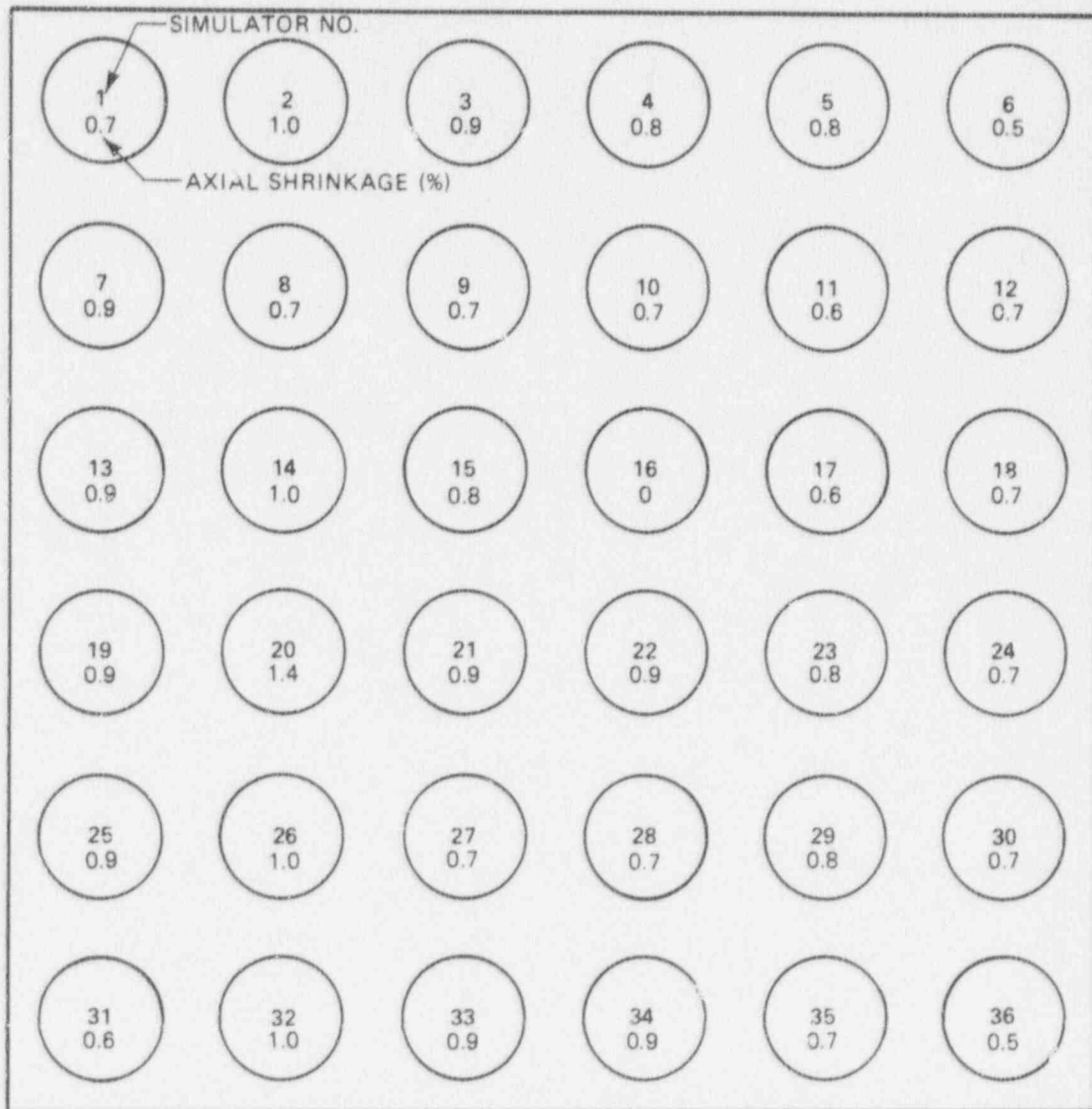


Fig. 50. Simulator axial shrinkage.

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