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EFFECT OF BUNDLE SIZE ON CLADDING DEFORMATION IN LOCA SIMULATION TESTS*

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ABSTRACT

Two LOCA simulation tests were conducted to investigate the effects of temperature uniformity and radial restraint boundary conditions on Zircaloy cladding deformation. In one of the tests (B-5), boundary conditions typical of a large array were imposed on an inner 4 x 4 square array by two concentric rings of interacting guard fuel pin simulators. In the other test (B-3), the boundary conditions were imposed on a 4 x 4 square array by a non-interacting heated shroud. Test parameters conducive to large deformation were selected in order to favor rod-to-rod interactions.

The tests showed that rod-to-rod interactions play an important role in the deformation process. While burst temperatures and burst strains were not affected appreciably, the interactions in the large array significantly influenced the deformation patterns and caused greater volumetric expansion of the interior simulators. Volumetric expansion of the simulators in the small array was significantly less than that for the central array of the large test; burst strains were approximately the same. Burst temperature-pressure data for the small array and for the outer ring of simulators in the large array agreed with predictions based on single rod, heated

shroud tests. All the B-5 simulators burst at approximately the same temperature; however, the interior simulators burst generally at much lower pressures than the exterior ones and their performance did not agree as well with the prediction.

It was concluded that for conditions conducive to large deformation at least two concentric rings of deforming guard simulators are necessary to model radial temperature and mechanical boundary effects of large arrays in LOCA simulation tests and that flow area restriction may be underestimated by small unconstrained bundle tests.

Keywords: Zircaloy, nuclear fuel cladding, tubes, burst tests, loss-of-coolant-accident, deformation, boundary conditions, rod-to-rod interactions, fuel rod simulators.

1. INTRODUCTION

The acceptance criteria[1] established by the Nuclear Regulatory Commission for emergency core cooling systems (ECCS) in light water reactors requires that the calculated changes in core geometry shall be such that the core remains amenable to cooling during a loss-of-coolant accident (LOCA). Compliance with the acceptance criteria is demonstrated by detailed analyses and evaluations of various postulated design-basis accidents (DBA) using computer models. To be acceptable, the models must be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated. For this reason single rod and multirod LOCA simulation tests are conducted to provide a basis for the models, which are then assumed adequate for describing the behavior in nuclear fuel assemblies. Clearly, important considerations are the minimum array size and the boundary conditions needed for simulation tests to be representative.

These important questions are among several being addressed in the Multirod Burst Test (MRBT) Program at the Oak Ridge National Laboratory by testing single rods and 4 x 4, 6 x 6, and 8 x 8 multirod arrays. This paper presents an evaluation of the results from two tests that were conducted to determine the effects of radial temperature and restraint boundary conditions on deformation. Test parameters known to produce large deformation were selected for the tests so that conditions favorable to rod-to-rod interactions would prevail.

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

One of the two tests (identified as B-3) contained 16 and the other (identified as B-5) contained 64 electrically heated fuel rod simulators, assembled and held in square arrays by standard pressurized water reactor spacer grids. Each simulator consisted of an unirradiated cladding tube, an internal electrical heater, and temperature and pressure sensors. Since design details and characteristics of the simulators were presented in a previous paper,[2] only a summary of pertinent features will be given here.

The Zircaloy-4 cladding tubes, 10.92 mm outside diameter with a 0.635-mm wall thickness, were purchased specifically for use in this and a number of related fuel cladding research programs. Although the tubes conform to the requirements of ASTM Specifications for Wrought Zirconium and

Zirconium Alloy Seamless and Welded Tubes for Nuclear Service (B 353), additional test, inspection, and identification requirements were specified.[3] The internal heaters were developed[4] specifically for use in this research program and had a uniform axial power profile over a length of 915 mm. Prior to assembly of the heater and cladding tube, each heater was characterized under transient heating conditions, using an infrared scanning technique.[5] Each simulator was instrumented with four sheathed thermocouples, 0.71 mm in diam with type K insulated junctions, that were spotwelded to the inside surface of the Zircaloy tubes with a device developed[6] for this purpose. The thermocouple junctions were located at axial and azimuthal positions to provide overall temperature patterns in the test arrays. By their placement in four axial grooves machined (equally spaced around the periphery) in the heater surface, the sheathed thermocouples and/or tantalum wire spacers used as thermocouple extensions also centered the heater (within tolerance limitations) within the tube. A comprehensive discussion on thermometry techniques, including measurement accuracies, used in this program has been published.[7]

The instrumented fuel rod simulator arrays were tested in a vessel as shown schematically for the larger array in Fig. 1. The arrays were suspended from the vessel cover flange to allow free axial movement. A thin shroud surrounded the test arrays to provide well-defined flow boundaries.

The functions and, thus, design characteristics of the shroud differed importantly in the two tests. In the B-5 test, the shroud was not electrically heated and was spaced 1.8 mm from the outer surface of the simulators (i.e., one-half of a coolant-channel-thickness). It was constructed of thin (0.1 mm) stainless steel with a highly polished gold-plated surface to minimize radiative thermal losses. The thin stainless steel sheet was backed with a strong support structure that provided thermal insulation and radial restraint. In the B-3 test, the shroud was electrically heated so that its temperature was nearly the same as that of the test array during the transient and, thus, provided a good radial temperature boundary. Since electrical isolation was required between the thin (0.25-mm thick Inconel) resistance heated shroud and the test array, a larger shroud spacing of 13 mm was used. This spacing permitted considerable deformation and/or bowing of the simulators without contact and, therefore, little external radial constraint existed. Small diameter, bare-wire, type S thermocouples were spotwelded to the outside surfaces of the thin shrouds to provide temperature measurements during the tests.

Preparations for a test included equilibration at initial temperature conditions using electric heaters external to the test vessel and a small downward flow of low pressure superheated steam. Power was not applied to the simulators during equilibration. Immediately prior to the transient, the helium pressure inside the simulators was adjusted to a value that would cause failure in the high alpha temperature range, and the simulators were isolated individually from the gas supply system to assure testing under conditions of constant gas inventory. With these conditions established, direct-current voltage was applied at a constant value. Figure 2 shows typical data recorded by the computer controlled data acquisition system during the B-3 test. The data system also counted the tube bursts as they occurred and generated a signal to terminate the power input after the final tube burst.

Posttest examination included casting each array in an epoxy matrix and sectioning it at 10 to 20 mm intervals. Enlarged photographs of the sections were digitized to facilitate computer analysis of the deformation data. These data were processed to obtain strain profiles of the individual tubes, deformed tube areas and centroids, and flow area restriction as a function of bundle axial position.

RESULTS AND DISCUSSION

Results of the B-3 test have been published in a detailed data report.[8] Although a similar B-5 report has not yet been issued, the results have been published in periodic progress reports.[9-11] Table 1 summarizes conditions and results pertinent to this discussion. Variance of the experimental data is indicated by the σ-values (standard deviation of the data) noted in the table.

By virtue of the closely-fitted shroud and the two rings of deforming guard simulators, the inner 4 x 4 array of the B-5 test was subjected to radial temperature and restraint boundary conditions representative of a large array, such as a fuel bundle. On the other hand, the B-3 heated shroud imposed reasonably equivalent temperature conditions without radial restraint. As indicated in the table, the radial boundary conditions had an important effect on burst pressure and volumetric expansion.

Although all the simulators were pressurized to the same initial level, a significant variation was observed in the B-5 burst pressures for a rather narrow burst temperature range as shown in Fig. 3. As depicted in the inset, plotting the B-5 data separately for each of three radial zones, corresponding to the outer ring of simulators, the next inner ring, and the inner 4 x 4 array for comparison with the B-3 data, shows that the inner 4 x 4 array burst pressures were generally much lower than those for the outer ring of simulators and that the data for the B-3 array were in good agreement with the data for the outer ring of B-5. The curve in the figure is a prediction from a correlation[12] based on our single rod heated shroud test data. This correlation predicts higher burst temperatures than one published[13] earlier for our single rod unheated shroud tests. Although the temperatures were less than predicted, the data for the B-3 array and for the B-5 outer ring of simulators were also in reasonably good agreement with the single rod correlation. The lack of better agreement is understandable, since we use fewer thermocouples in bundle than in single rod test simulators (i.e., four versus twelve) to measure temperatures, and there is a greater statistical probability for underestimating burst temperatures in bundle tests. The B-5 interior simulators did not show the expected trend of increasing burst temperature with decreasing burst pressure for reasons that will be discussed later.

Typical sections cut from the high deformation regions of the two deformed bundles are shown at the same magnification in Fig. 4. Lines have been drawn on the photographs to show the pretest positions of the shrouds. The dashed lines enclose 16 pretest unit cells that can be considered as imaginary control volumes for comparing the effects of the boundary conditions. A number of tubes have their strains noted for comparison. The B-5 tube with zero percent strain (toward the lower right corner) was unpressurized, because of a seal leak that developed during pretest thermal equilibration. It was heated, however, to preserve the proper temperature boundary conditions during the transient.

The B-3 tubes, in general, did not interact mechanically as indicated by their more or less round shapes. Since the tubes were not constrained, they moved outward to create more space for expansion without interaction; they behaved much like single rod heated shroud tests. Note the lip of the burst tube in the lower left is clamped between the two interior neighbors, indicating these tubes were separated at the time the burst occurred.

During the B-5 test, tube expansion throughout the array caused the tubes to touch and generate contact forces. Since the simulators were constrained, these forces could not be relieved by tube bowing and, thus, formation of additional void space. With further expansion the tubes tended toward square cross sections to fill the available space. The external contact forces caused redistribution of the straining pattern in both the azimuthal and longitudinal directions. As a result, the rate of expansion decreased at those axial locations in contact and continued unimpeded at other ballooning locations. Analysis of the simulator pressure histories indicated redistribution and growth of the ballooned regions occurred with great rapidity. These dynamic processes, enhanced by the very uniform temperature distribution in the interior of the array, continued until local conditions at some point in each tube satisfied the burst criteria. The sequences of bursting (all the interior tubes burst in a 3.20-s interval) also influenced the interactions, since a burst tube offered less resistance to encroachment of neighboring tubes still undergoing deformation. As a result of these rapid and complex interactions, the interior simulators deformed more (in terms of volumetric expansion) and burst at lower pressures than the exterior ones.

Figure 5 depicts deformation profiles for typical interior simulators from the two tests. Since, for the simulator pitch-to-diameter ratio used in the tests, rod-to-rod contact occurs for coincident strains of 32 percent, the figure indicates that contact occurred over greater lengths of the B-5 simulators than for the B-3 simulators. The deformation profiles were integrated to obtain the volumetric expansion data plotted in Fig. 6. Other than grouping the B-5 data into three radial zones, the scale used for displaying the data within each group is completely arbitrary. The figure shows clearly that volumetric expansion of the B-5 simulators was a strong function of simulator radial position within the array and that it was also greater in the B-5 inner 4 x 4 array than in the B-3 array. The variation in total deformation from the center to the outer regions of the B-5 array confirms the burst pressure variation shown in Fig. 3. Evidently, the larger volumetric expansion in the center region was caused by more intense rod-to-rod interactions and smaller azimuthal temperature gradients than in the outer simulators. Since the B-3 array and B-5 interior array were subjected to approximately the same temperature conditions, the greater total deformation in the latter is attributed primarily to mechanical interaction effects.

Comparison of the burst strain data, depicted in a similar format in Fig. 7, did not show a strong effect of simulator position in B-5. The closely-fitted unheated shroud around the B-5 array induced azimuthal temperature gradients sufficient, as will be discussed below, to influence burst directions and, in a number of cases, the burst strain of the exterior simulators. However, other mechanisms apparently mitigated the temperature gradient effect sufficiently to permit surprisingly large deformation before failure of a number of the simulators. There was little

Orientation of the bursts in B-5, a few of which are shown in Fig. 4, exhibited a strong preference for the open coolant channel areas as indicated in Fig. 8; very few bursts were directed toward adjacent tubes. This preference appears to be the result of redistribution of the straining patterns after rod-to-rod contact. In addition, azimuthal temperature gradients strongly influenced the direction of the bursts in the outer ring of simulators and to a lesser extent in the next inner ring. This effect appeared negligible in the inner 4 x 4 array. The more random distribution of the B-3 burst directions indicated negligible effects of rod-to-rod interactions and temperature gradients. Apparently the B-3 heated shroud was effective in producing radial temperature boundary conditions reasonably equivalent to those produced by the outer two rings of simulators in the large test.

The individual strain profiles were also used to calculate the coolant channel flow area restriction in the B-5 inner 4 x 4 array for comparison to B-3. The restriction, or loss of flow area, was determined at each axial node by dividing the area increase of the 16 tubes by the original flow area within the dashed-line boundaries shown in Fig. 4. This parameter is related to the average deformation at any axial position and is shown for the two arrays in Fig. 9. The figure shows that flow area restriction in B-5 was greater over virtually the entire heated length and, as expected, that deformation was limited in the immediate vicinity of the grids.

CONCLUSIONS

The test results show that, for conditions conducive to large deformation, the exterior simulators restrain and confine the interior simulators in a large array and that confinement causes rod-to-rod mechanical interactions during the deformation process. Although they have no significant effect on burst temperature and burst strain, the interactions have a significant influence on deformation patterns and cause greater volumetric expansion of the interior simulators. Interpretation of the test results indicates that, during the final stages of deformation, the interactions retard the rate of expansion at axial locations in contact, while expansion continues unimpeded at other ballooning locations. These rapid and complex interactive mechanisms continue, causing greater axial extension (and total volumetric expansion) of the ballooned region, until local conditions at some point satisfy the failure criteria.

The test results and observations permit the following conclusions:

1. Temperature uniformity and rod-to-rod mechanical interactions are important parameters in modeling cladding deformation in large bundles.

2. The equivalent of at least two concentric rings of interacting guard simulators are required to duplicate the effects of these parameters in large bundles.

3. These parameters modify burst temperature-burst pressure correlations derived from non-interactive single rod heated shroud tests.

4. Flow area restriction in large arrays may be underestimated by small unconstrained bundle tests.

ACKNOWLEDGMENT

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Table 1. Test conditions and results

	B-3 (4 x 4)	B-5 (8 x 8)
Bundle heating rate (°C/s)	9.5	9.8
Inlet steam flow $[g(s \cdot m^2)^{-1}]$	288	288
Inlet steam temperature (°C)	320	355
Inlet steam pressure (kPa absolute)	300	300
Inlet steam Reynolds Number	260	140
Bundle inlet temperature (°C)	329 (σ = 2)	335 (σ = 4)
Shroud initial temperature (°C)	334 (σ = 3)	339 (σ = 4)
Initial pressure (MPa)	11.61 (σ = 0.04)	11.62 (σ = 0.03)
Maximum pressure (MPa)	12.11 (σ = 0.05)	12.15 (σ = 0.04)
Burst pressure (MPa)	9.42 (σ = 0.37)	8.81 (σ = 0.52)
Burst temperature (°C)	764 (σ = 9)	768 (σ = 7)
Burst time (s)	46.06 (σ = 0.77)	46.29 (σ = 1.05)
Burst strain (%)	58 (σ = 10)	60 (σ = 15)
Tube volume increase (%)	43 (σ = 7)	50 (σ = 10)
$T_{bundle} - T_{shroud}$ at burst time (°C)	80[a]	240[b]

[a] Electrically heated shroud

[b] Reflective shroud

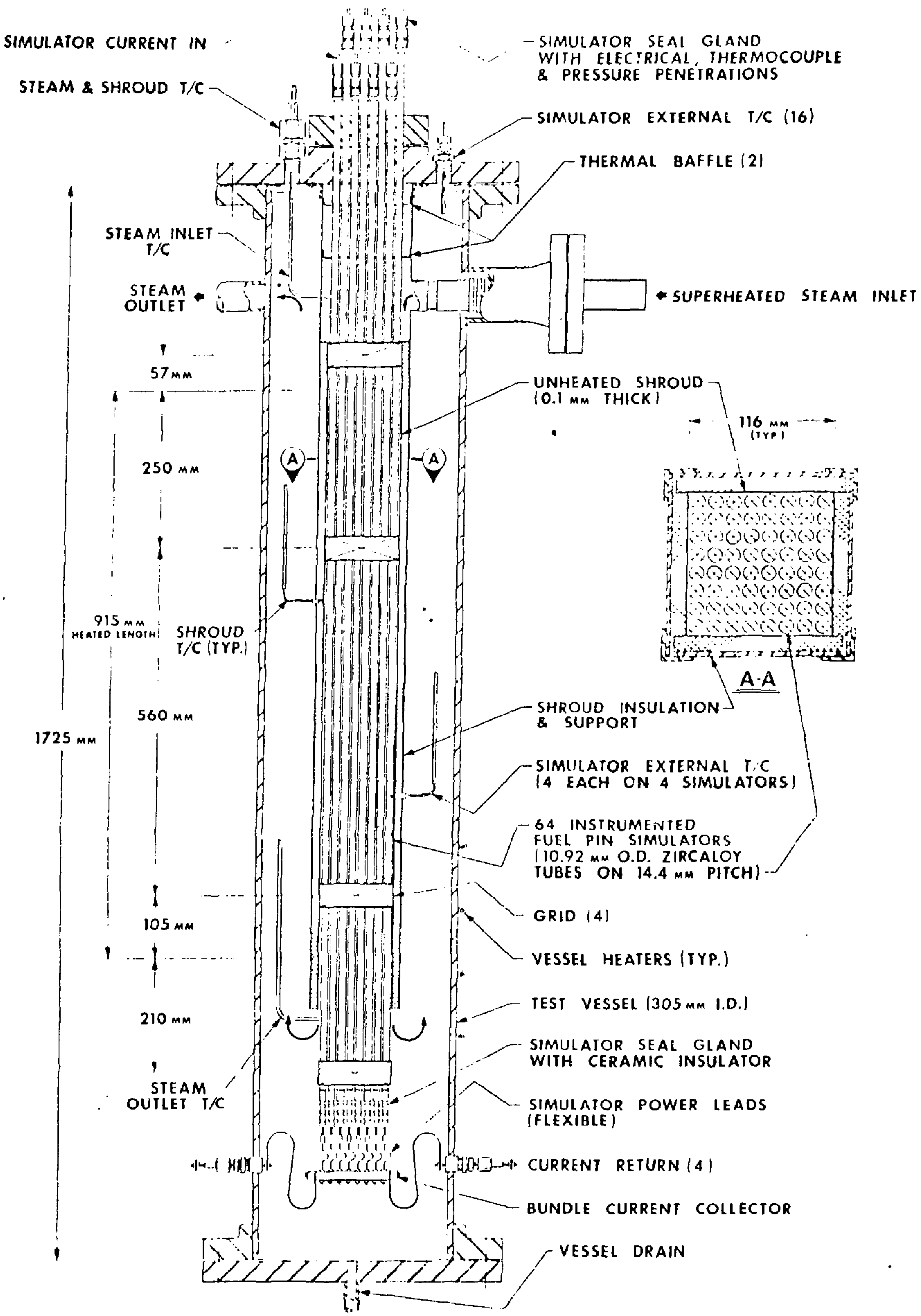

Fig. 1. Schematic of B-5 (8 x 8) test assembly.

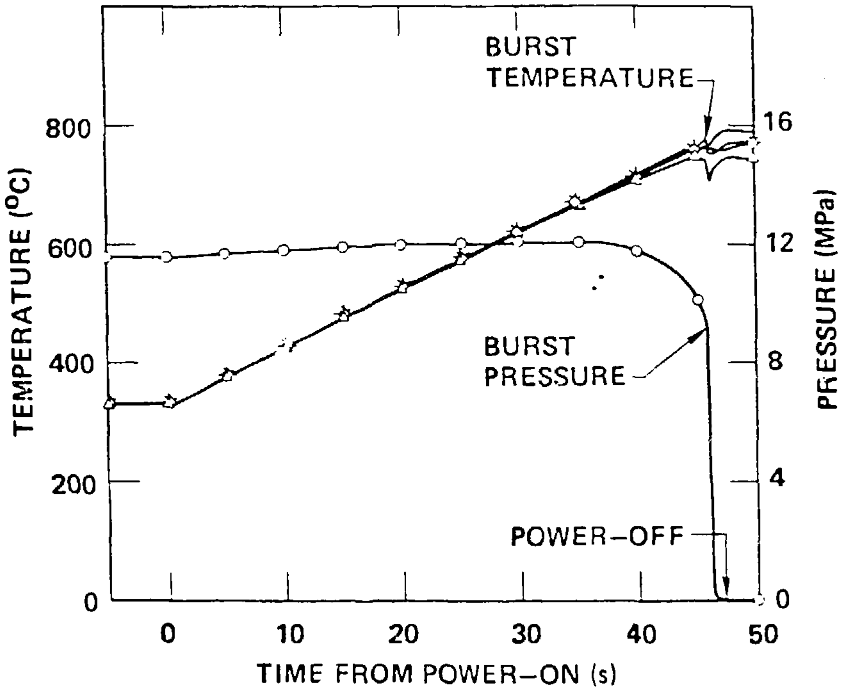

Fig. 2. Typical simulator response in B-3 test.

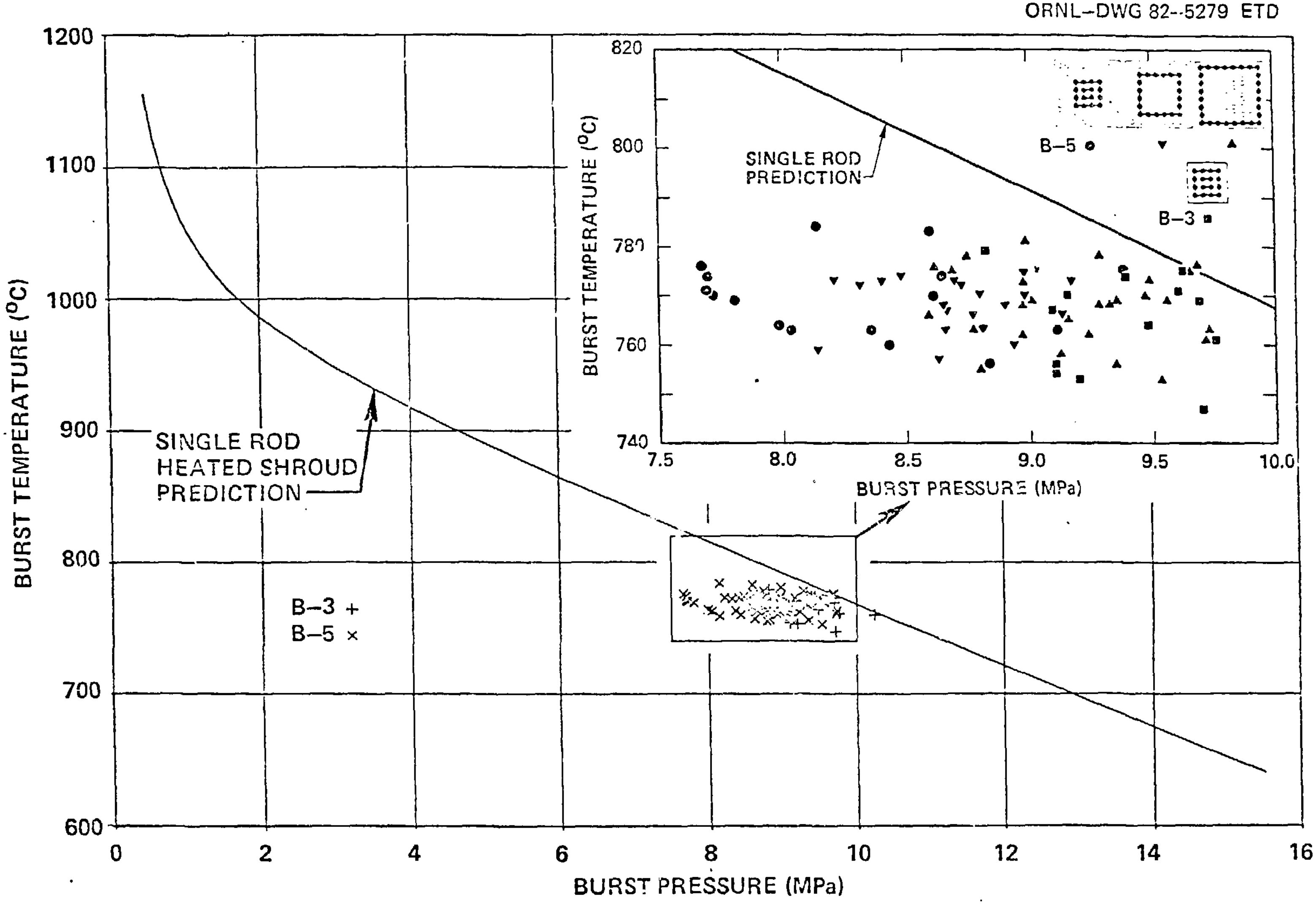

Fig. 3. Comparison of bundle burst data with prediction from single rod heated shroud tests.

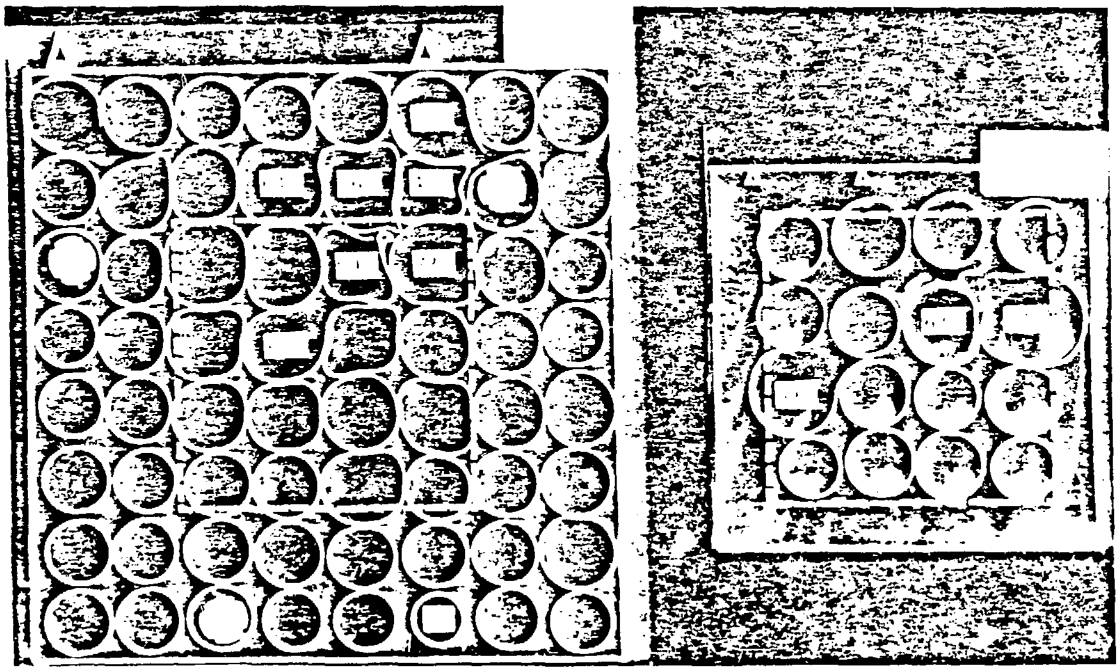

Fig. 4. Sections from highly deformed regions of B-5 and B-3 bundles showing effects of confinement. Some strains are noted for comparison.

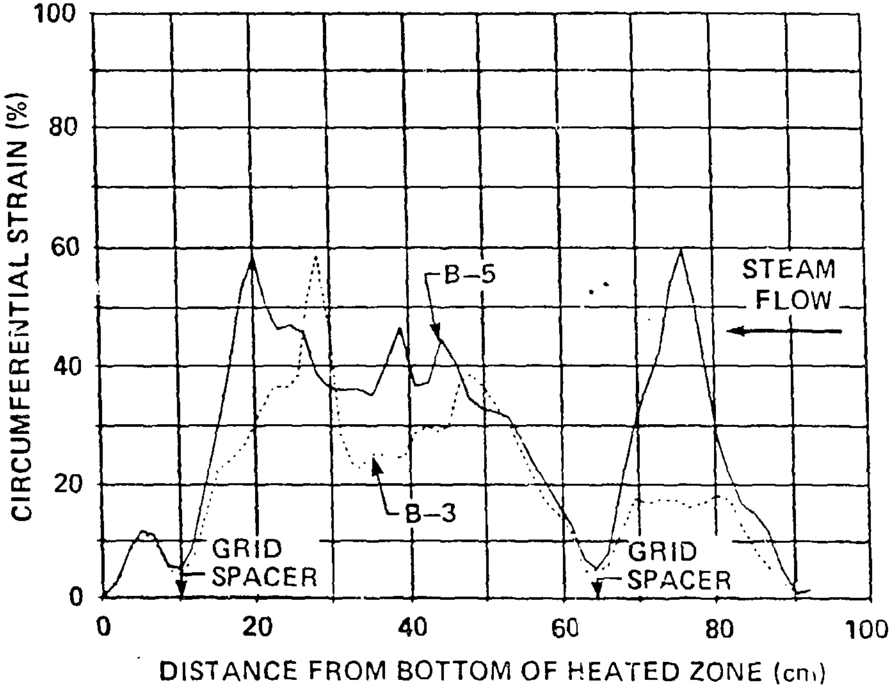

Fig. 5. Comparison of deformation profiles of typical interior tubes in B-5 and B-3.

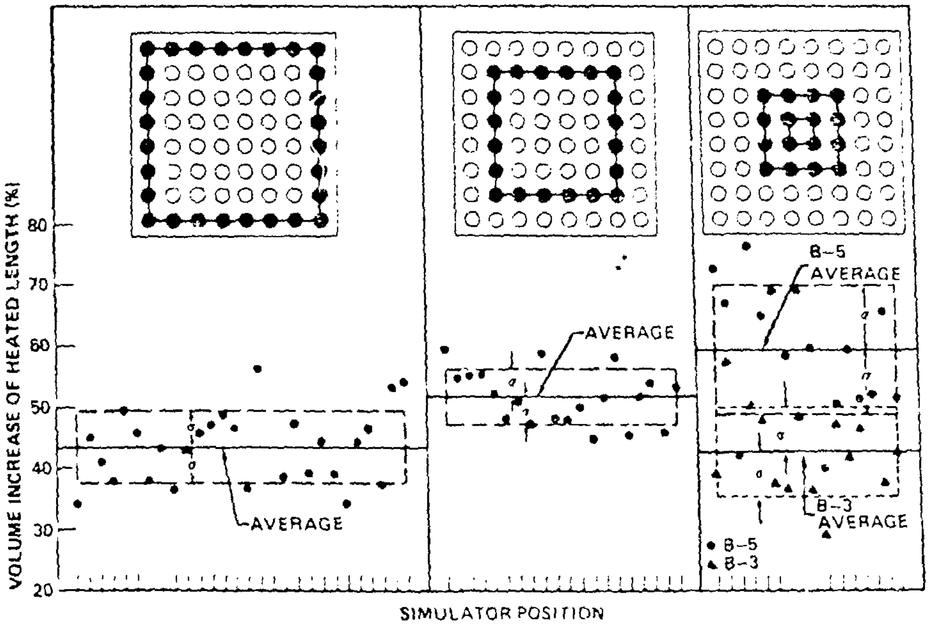

Fig. 6. Volumetric expansion of B-5 tubes. B-3 (4 x 4) data are shown for comparison with inner 4 x 4 array of B-5.

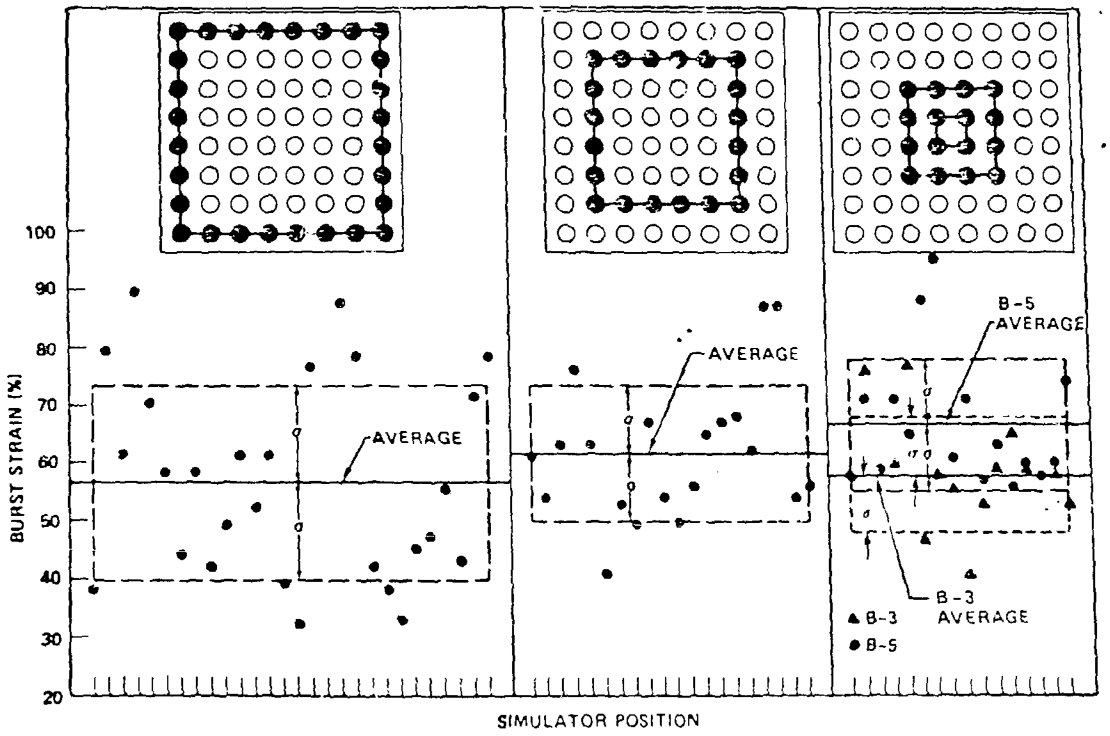

Fig. 7. Burst strain of B-5 tubes. B-3 (4 x 4) data are shown for comparison with inner 4 x 4 array of B-5.

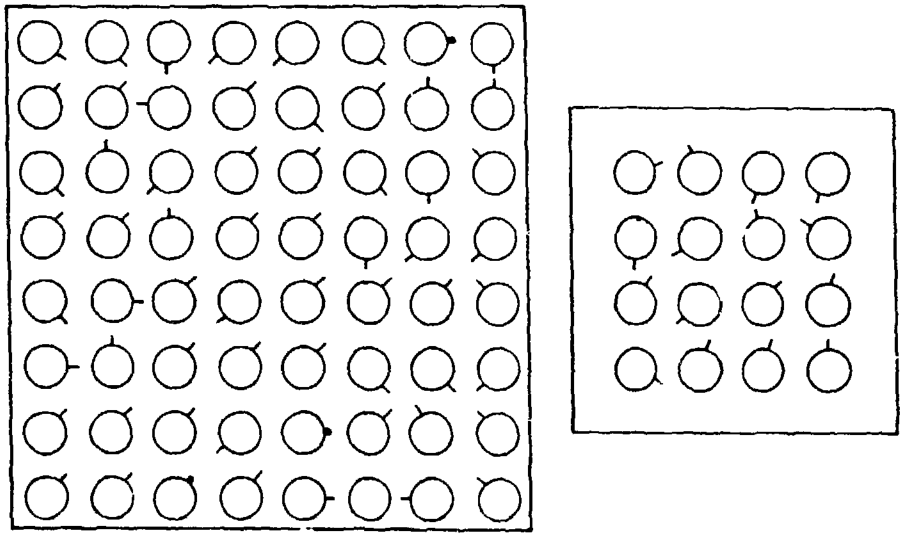

Fig. 8. Burst directions in B-5 showing effects of azimuthal temperature gradients in exterior simulators and tube confinement. Absence of confinement and reduced gradients caused more random distribution in B-3.

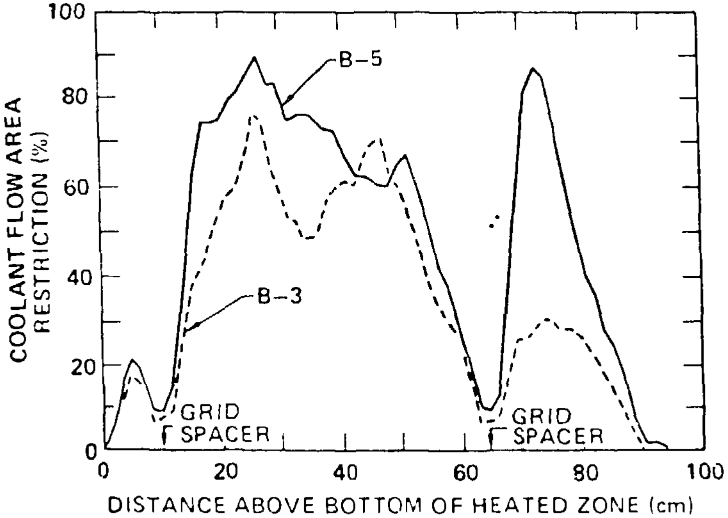

Fig. 9. Comparison of B-5 inner 4 x 4 flow area restriction with B-3 array.