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BOUNDARY EFFECTS ON ZIRCALOY-4 CLADDING DEFORMATION IN LOCA SIMULATION TESTS*

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Deformation behavior of Zircaloy-4 cladding under simulated loss-of-coolant accident (LOCA) conditions is being investigated in the Multirod Burst Test (MRBT) program in single rod and multirod tests. In these tests, internally-pressurized unirradiated Zircaloy-4 tubes containing internal electrical heaters are heated to failure in a low-pressure, superheated-steam environment (200 < Re < 800). The results provide a data base for evaluating deformation and blockage models employed with design-basis accident sequences to assess LWR core coolability for licensing purposes. Results of a recent 8 X 8 test indicate that models derived from smaller test arrays may not be representative of the behavior in large arrays, particularly for those temperature ranges in which large deformation can be expected.

Two MRBT LOCA simulation tests conducted under the same nominal conditions (∿10 K/s heating rate from ∿340°C to failure at ∿770°C) were examined to determine the effects of array size and boundary conditions on deformation.[1] One test (B-3) was a 4 X 4 array with an electrically-heated oversized shroud that provided a reasonable thermal boundary but no radial restraint of the fuel pin simulators. The second test (B-5) was an 8 X 8 array with a highly reflective shroud that was not electrically heated but provided radial restraint of the simulators during deformation. The thermal and geometrical boundary conditions for the inner 4 X 4 array of the 8 X 8 bundle closely approximated those that would be present in the interior of a fuel bundle.

Results of the two tests show that the unconstrained B-3 array did not experience the boundary effects existing in the central region of the larger array. Deformation patterns were different. Also, the rupture temperature-pressure data for the interior simulators of the B-5 array deviated from the predictions of a correlation[2] derived from freely deforming tubes. Significant differences in the average deformation in each of three radial zones in B-5, Fig. 1, apparently reflect the quality of the thermal and geometrical boundary conditions experienced by the fuel pin simulators in each zone; the B-3 (4 X 4) average deformation data are shown for comparison with the inner 4 X 4 array of B-5. The figure shows that greater deformation occurred in the interior simulators than in the exterior simulators of the 8 X 8 array and that the inner 4 X 4 of the 8 X 8 array deformed more than the corresponding B-3 array.

Differences in the deformation patterns in the two tests are also revealed in the cross sections taken through a high deformation region of each bundle (Fig. 2). Note that the expansion of the outer ring of B-5 tubes to slightly beyond the pretest shroud location indicates some yielding of the shroud and its supporting insulation. This appears to be a logical result of radial tube expansion throughout the array (and greater in the center) accompanied by tube bowing in the outer regions caused by radial forces generated by tube-to-tube contact. In this process, the inner 4 X 4 was constrained sufficiently to cause formation of the irregular-shaped tube cross sections. The associated rod-to-rod interactions may have caused rapid axial propagation of the deformation late in the test, contributing to the larger average deformation and correspondingly lower burst pressures than were observed in the B-3 test. As evident in Fig. 2, the unconstrained B-3 tubes were free to move outward and thus retained their roundness to a large degree.

In summary, the results indicate that temperature uniformity and rod-to-rod interactions play important roles in the deformation process and enhance total deformation under worst-case conditions where larger than tube contact deformation can be expected. The equivalent of two rows of deforming simulators appears necessary to simulate the thermal and geometrical boundary conditions of large arrays.

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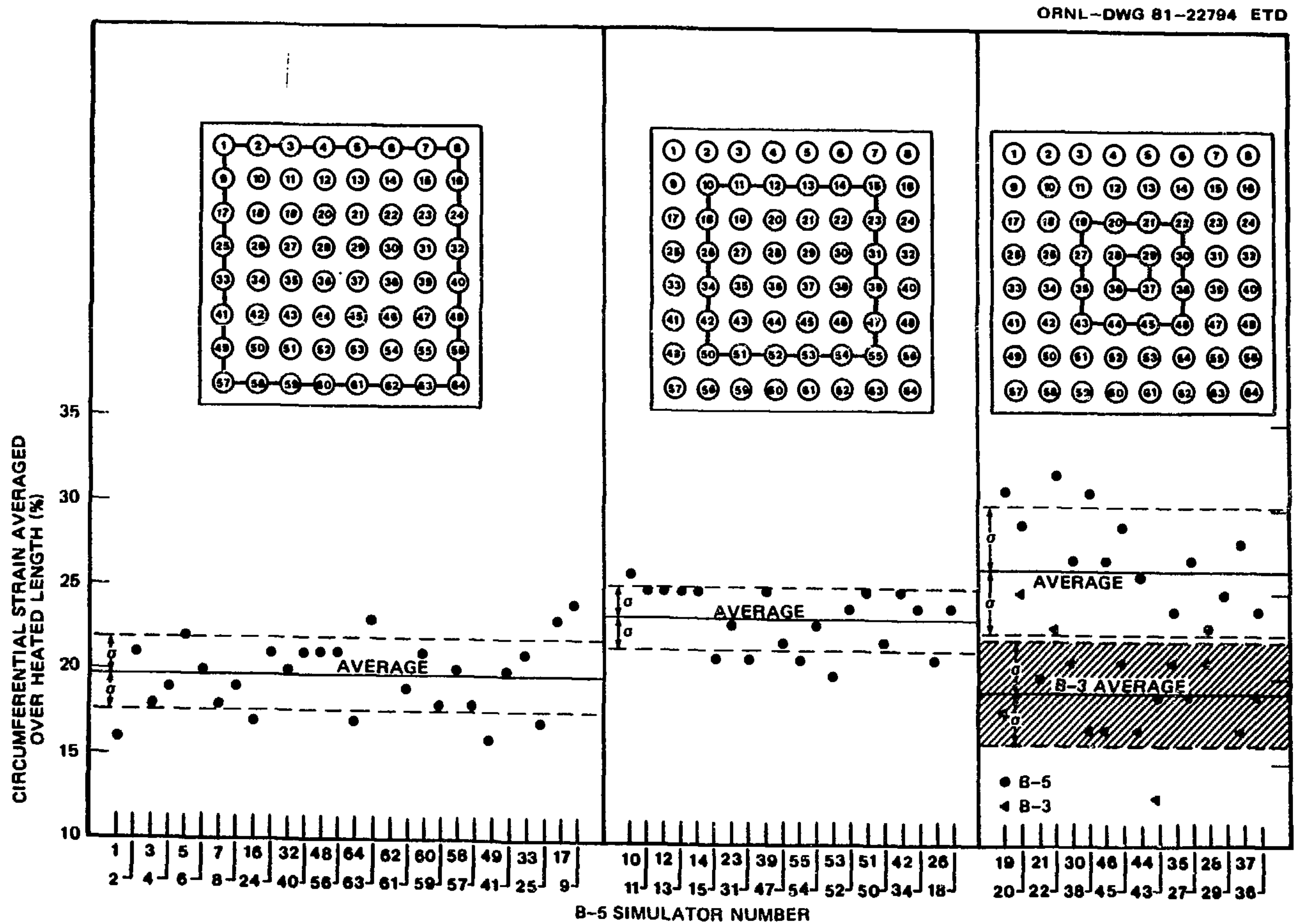

Fig. 1. Average cladding circumferential strains by zones in bundle B-5. Average strains for bundle B-3 (4 X 4) are shown for comparison.

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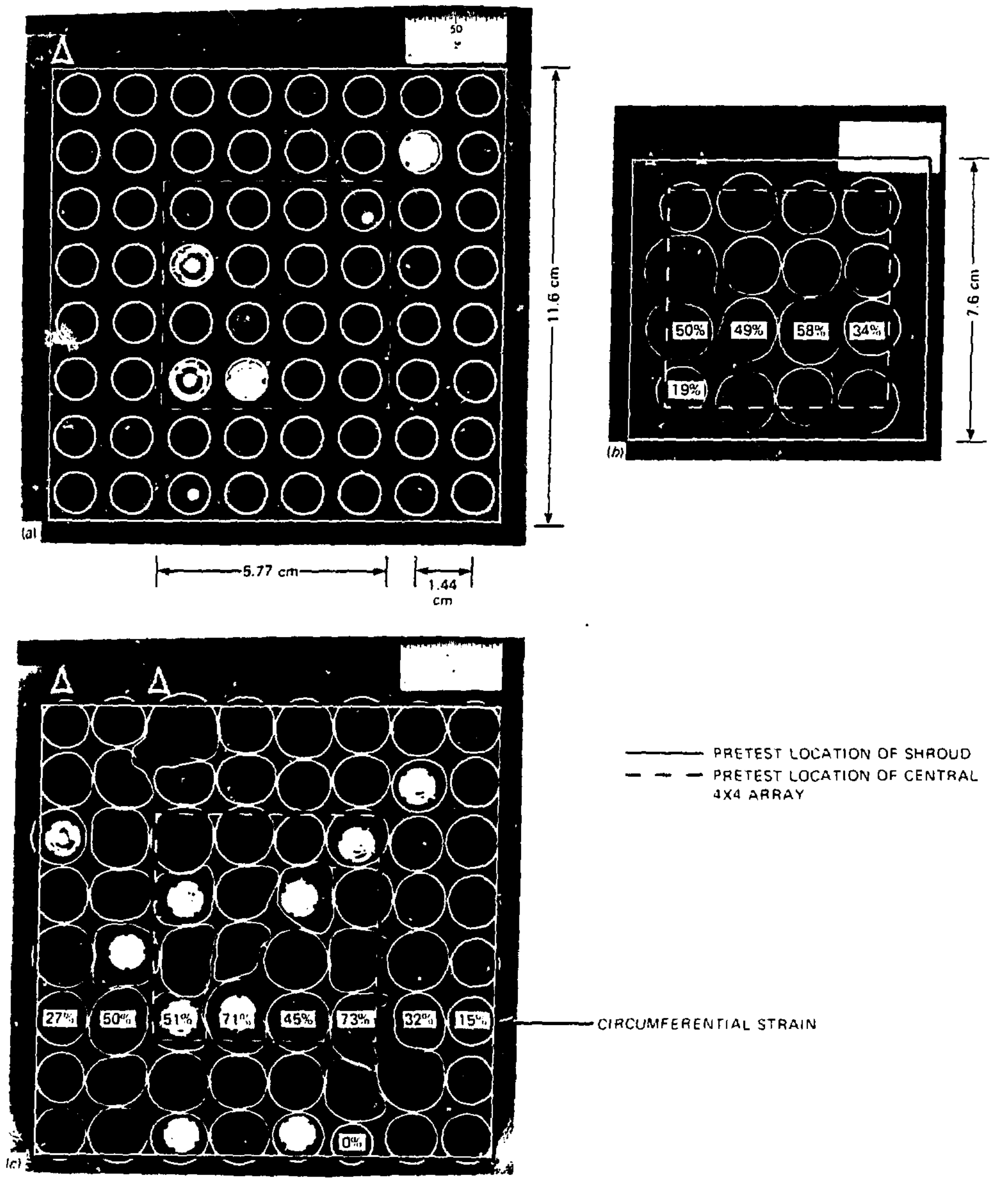

Fig. 2. Comparison of deformation patterns in bundle B-5 (with radial restraint) with bundle B-3 (without radial restraint): (a) undeformed section of B-5; (b) deformed section of B-3; and (c) deformed section of B-5.