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WITH A ONE-DIMENSIONAL TRANSIENT ANALYSIS CODE

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SIMULATION OF THREE-DIMENSIONAL HYDRODYNAMIC COMPONENTS WITH A ONE-DIMENSIONAL TRANSIENT ANALYSIS CODE

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INTRODUCTION

The RELAP5[1] series of transient analysis codes was developed to provide the United States Nuclear Regulatory Commission with a fast-running and user convenient reactor analysis tool. Although it was developed primarily for best-estimate transient simulation of pressurized water reactors, it has been used to simulate a wide spectrum of hydraulic and thermal transients in both nuclear and non-nuclear systems involving steam-water-noncondensible fluid mixtures. In recent years it has also been applied to thermal-hydraulic analyses of various US Department of Energy production reactors.

RELAP5 is a one-dimensional code, meaning that the basic field equations are solved only in the axial direction of a component. Thus, for example, only axial flow is calculated in a reactor vessel; radial and azimuthal flows are not considered. This has been a minor limitation of the code because most hydraulic situations in reactor systems can be modeled adequately with a one-dimensional code. In those situations where three-dimensional flows were anticipated, the TRAC-PF1[2] code has generally been used. (TRAC-PF1 has the capability to model three-dimensional components; however, that option is normally only used in the reactor vessel model.)

In the past few years one of the upgrades to the RELAP5 code has been the cross-flow junction. Using a reduced form of the momentum equation, the cross-flow junction can be used to calculate flows perpendicular to the axial direction in a RELAP5 model, for example, at a tee. The development of the cross-flow model allows a multidimensional flow analysis capability in regions where multidimensional fluid momentum is not significant.

RELAP5 is currently being used in the analysis of the production reactors at the Savannah River Site (SRS). The SRS reactors are cooled and moderated with heavy water. Each reactor contains a moderator tank and six similar external loops. Each loop contains a pump, two horizontal tube-in-shell heat exchangers, and connecting piping. Each pump draws hot reactor effluent from an outlet nozzle at the bottom of the moderator tank and forces it through the heat exchangers and an inlet nozzle to a

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water plenum located at the top of the moderator tank. From the water plenum, the heavy water enters an array of approximately 500 parallel fuel assemblies. Each fuel assembly is housed separately so that the flow entering an assembly remains inside until reaching the bottom of the housing. The hot coolant exiting the assembly re-enters the moderator tank near the bottom of the tank, thus completing the flow circuit.

Significant multidimensional phenomena occur in the water plenum region of these reactors. In particular, relatively large radial pressure gradients occur within the water plenum during normal operation. Large azimuthal pressure gradients could also occur during a loss-of-coolant accident (LOCA). These multidimensional effects within the water plenum must be modeled because the pressure gradients can significantly affect flow distribution to the assemblies. Thus, a purely one-dimensional representation would not adequately represent the phenomena. Consequently, a multidimensional RELAP5 model of the water plenum and moderator tank was developed that used cross-flow junctions. The model employs hexagonal-shaped cells in the plenum and tank, with a cross-flow junction connected to each of the six faces.[3]

This paper describes the RELAP5 hexagonal model of the SRS L-Reactor as well as comparisons of benchmark calculations with SRS data. Emphasis is placed on the multidimensional phenomena.

MODEL DESCRIPTION

The RELAP5 input model used in the subject calculations was developed at the Idaho National Engineering Laboratory (INEL) to represent the SRS L-Reactor. The model includes the moderator tank and water plenum, the fuel assemblies, all six loops, and many of the peripheral systems. Discussions about the ex-vessel model can be found in Ref. 3.

A three-dimensional noding scheme using the cross-flow model was employed in the water plenum and moderator tank models and is shown schematically in Fig. 1. The hexagonal shape of the cells was chosen because it is a natural consequence of the triangular pitch of the assemblies. Each interior hexagon is an integral multiple of the basic triangular pattern of the assemblies. Imposing the hexagonal pattern on the water plenum resulted in a total of 49 hydrodynamic volumes, of which 37 were connected to assemblies containing active fuel.

Each of the hexagonal cells was modeled with the RELAP5 BRANCH component and was oriented vertically. A cross-flow junction was connected at each lateral face of each hexagon. Note that because the plenum was modeled as a single hydrodynamic level in the vertical direction, and that cross-flow junctions connect only at volume centers, all of the plenum junctions necessarily connect at the vertical midpoint of the plenum.

Note also that, in a LOCA initiated by a plenum inlet break for example, the hexagonal pattern permits fluid flow directly across the center of the water plenum toward the broken loop. In the past, RELAP5 and TRAC models of the water plenum have utilized an r-theta nodalization pattern.[4,5] The r-theta models have a point, rather than a cell, at the center of the water plenum. That means that, in the event of a LOCA, all coolant flow from the plenum to the break must traverse azimuthally around the plenum instead of directly toward the break. The hexagonal model is thus considered to be capable of a more realistic representation of such a break.

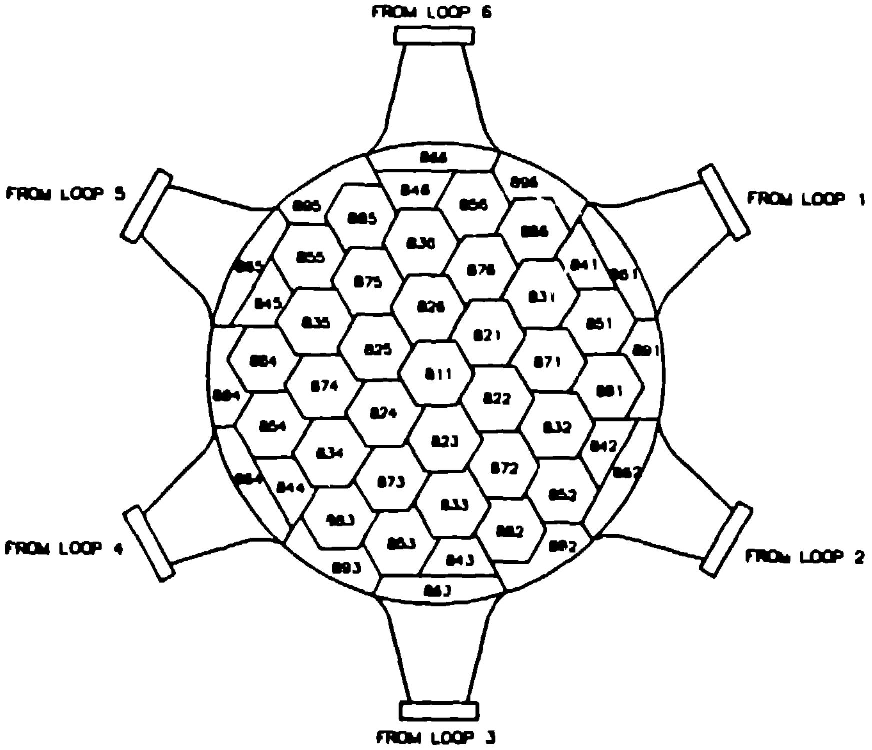

Figure 1. Nodalization of the Water Plenum.

The form loss coefficients in the water plenum and moderator tank were originally calculated from Idel'chik[6] based on flow across a tube bundle. The loss coefficients in the moderator tank were not adjusted; however, the loss coefficients in the plenum were adjusted to match data from SRS tests to be described later. Those adjustments were done with the assumption that the form loss factors for all of the internal junctions had to be identical, and, thus could only be adjusted by a uniform factor. The interior and radially-directed junctions to the outer ring were adjusted until reasonable agreement with symmetric flow test data was achieved. The azimuthal form losses between cells in the relatively open outer ring were tuned uniformly with asymmetric test data. The magnitudes of the adjustments were normally less than a factor of two.

A total of 38 fuel assemblies (37 lumped and 1 hot channel) were used to represent the 510 fuel assemblies in L-Reactor. Each is a parallel flow path connected to the plenum and the bottom of the moderator tank. A lumped, average fuel assembly model was attached to each cell in the plenum that had active fuel assemblies present; only plenum cells 861-866 and 891-896 have no lumped assemblies connected to them. The fuel assemblies were modeled as one-dimensional components, each with 7 volumes. The top volume of each assembly is connected with a cross-flow junction at the midplane of the water plenum volumes. Normal junctions were used at the assembly exit into the moderator tank.

The basic hexagonal nodalization pattern was also used in the moderator tank. The principal difference is that three axial levels were used in the moderator tank model.

BENCHMARK RESULTS

The RELAP5 six-loop, hexagonal model described above was benchmarked using four separate sets of SRS data; however, for brevity only the comparisons to two of the 1985 AC Process Flow Tests data are included in this paper. (Ref. 3 has complete results of the benchmarking.)

1985 AC Process Flow Test I

Test I was performed under full flow, isothermal conditions with all six pumps operating. That configuration most closely reflected typical operating conditions in that a nearly symmetric flow pattern results in the plenum.

Comparisons of the calculated and measured water plenum pressure results for Test I are shown in Fig. 2, in which plenum pressures are presented as a function of radial distance from the plenum center. In general, RELAP5 and the hexagonal model of L-Reactor provided a good representation of Test I water plenum conditions. The strong radial pressure gradient near the periphery of the plenum was well simulated. In the center region of the plenum, the calculated pressures were typically within 2 psi; and in the outer region, the calculated pressures lie near the center of the data scatter.

The model did not exhibit the range of azimuthal scatter seen in the data because that scatter results from swirl patterns in the plenum. Those swirl patterns are caused by separation of the boundary layer from the surface of the inlet nozzles, resulting in nozzle stall. These boundary layer effects are beyond the predictive capabilities of current thermal-hydraulic systems analysis codes.

Reference 3 includes comparisons of the plenum pressures as functions of azimuthal angle, as well as comparisons of loop results.

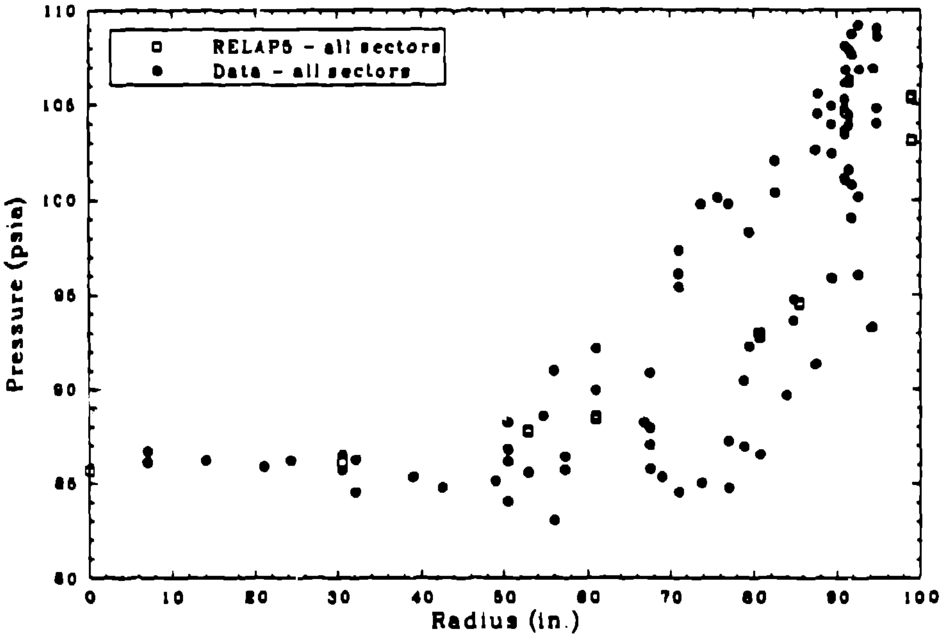

Figure 2. Radial Plenum Pressure Comparison for Test I.

1985 AC Process Flow Test D

Test D was chosen for comparison because it represents hydraulic conditions similar to those that would occur in the event of a LOCA. Test D was performed with five of the primary coolant pumps operating normally and one pump off (the one in loop six). This pumping configuration resulted in an asymmetric flow pattern in the water plenum and positive flow in five loops and reverse flow in the other loop.

Comparisons of calculated and measured results for Test D are presented in Figs. 3 through 6. In Fig. 3, the pressures are again presented as functions of radial distance from the plenum centerline. In Test D, as compared to Test I, the data scatter azimuthally is not only due to nozzle stall; it is in part due to the low pressure region that results from loop six pump not operating. Without the pressure head provided by normal operation of that pump, loop six experienced reverse flow. That, in turn, resulted in a low pressure region in sector six of the water plenum. The resulting asymmetric flow patterns in the plenum are a good example of highly multidimensional hydraulic conditions that a safety analysis code must be capable of predicting if the SRS reactors are to be well simulated. And, as shown in Fig. 3, RELAP5 and the hexagonal model results are in excellent agreement with the data.

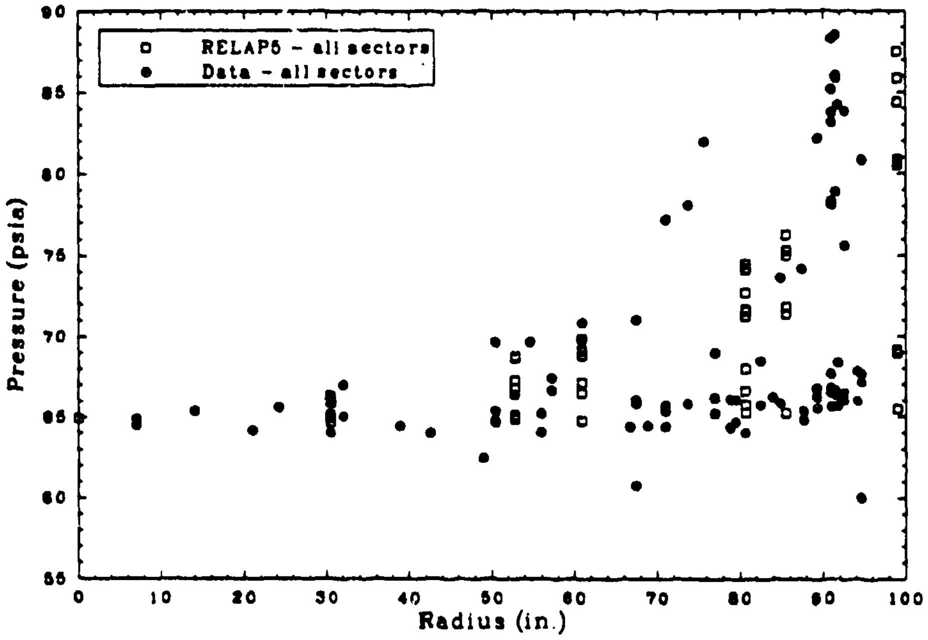

Figure 3. Radial Pressure Comparison for Test D.

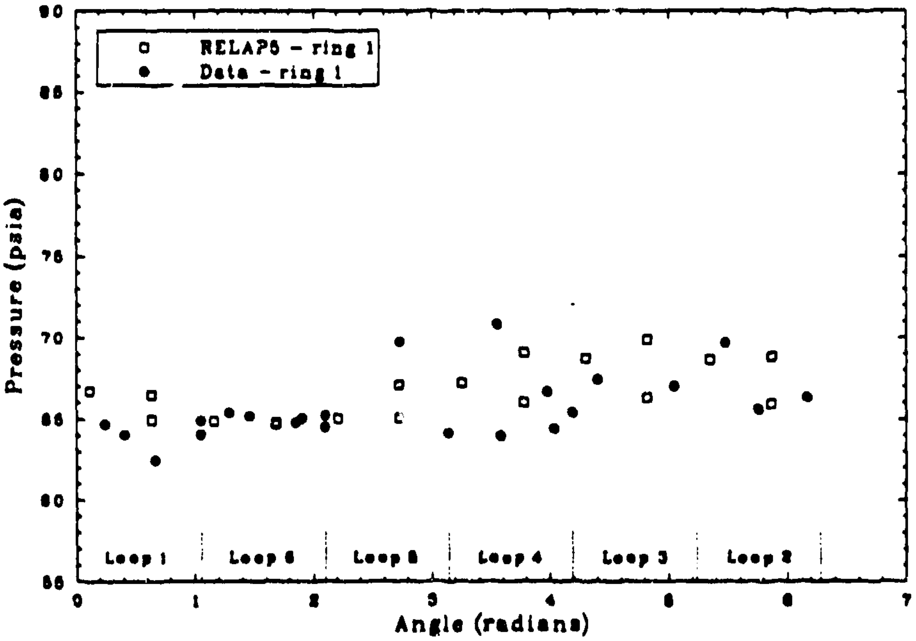

Figure 4. Plenum Pressure Comparison for Inner Cells During Test D.

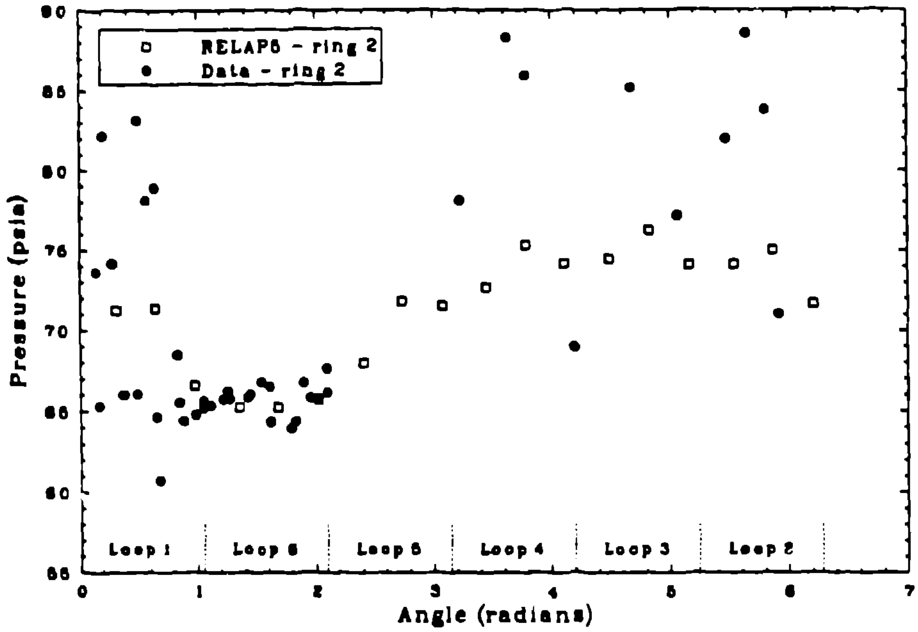

Figure 5. Plenum Pressure Comparison for Middle Radial Region During Test D.

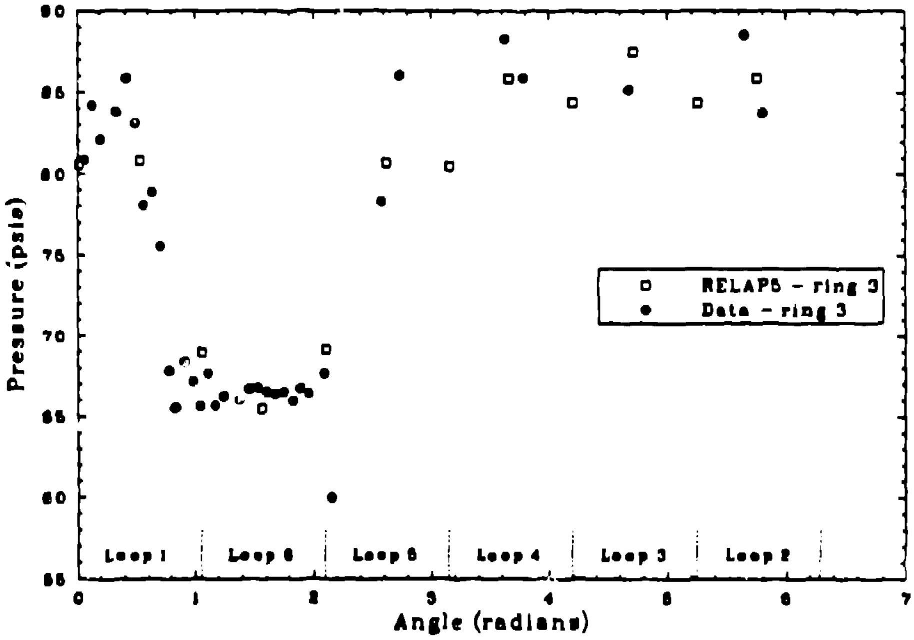

Figure 6. Plenum Pressure Comparison for Outer Radial Region During Test D.

It is especially important that a code and model be capable of simulating the pressure in the central regions of the SRS water plenum during conditions such as those in Test D. In the event of a LOCA occurring in a loop, the assemblies connected to the relatively low pressure center of the water plenum could be starved for coolant thus increasing the potential for melting of the fuel. Figure 3 shows that RELAP5 and the subject model simulated the conditions in not only the center, but also the periphery, of the water plenum very well.

Figures 4 through 6 present the plenum pressures as a function of azimuthal angle for three different radial regions of the plenum. This presentation illustrates the low pressure region that occurs in the sector associated with the backflow loop. In the center region of the plenum (Fig. 4), little evidence of backflow-induced low pressure is seen. In the middle radial region, however, the depression in pressure near loop six is clearly visible (Fig. 5). And, finally, in the outermost area of the plenum shown in Fig. 6, the pressure depression is fully developed. Note that except for the scatter discussed earlier, RELAP5 and the hexagonal model produced results that are in excellent agreement with the Test D data.

CONCLUSIONS

The geometry of the water plenum, as well as the hydraulic conditions that can occur in the SRS reactors, clearly present multidimensional problems for safety analysis. The ability of the codes and models to accurately simulate those conditions is of extreme importance. The results presented in this paper indicate, however, that a one-dimensional code such RELAP5, in conjuction with a carefully designed input model, can accurately predict those hydraulic conditions, even when large multidimensional effects are present.

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