Introduction

The RELAP5-3D code is an outgrowth of the one-dimensional RELAP5/MOD3 code developed at the Idaho National Laboratory (INL) for the U.S. Nuclear Regulatory Commission (NRC). The U.S. Department of Energy (DOE) began sponsoring additional RELAP5 development in the early 1980s to meet its own reactor safety assessment needs. Following the accident at Chernobyl, DOE undertook a re-assessment of the safety of all of its test and production reactors throughout the United States. The RELAP5 code was chosen as the thermal-hydraulic analysis tool because of its widespread acceptance.

The application of RELAP5 to these various reactor designs created the need for new modeling capabilities. In particular, the analysis of the Savannah River reactors necessitated a three-dimensional flow model. Later, under laboratory-discretionary funding, the multi-dimensional reactor kinetics was added. Altogether, DOE sponsored improvements and enhancements have amounted to a multimillion-dollar investment in the code.

Up until the end of 1995, the INL maintained NRC and DOE versions of the code in a single source code that could be partitioned before compilation. It became clear by then, however, that the efficiencies realized by the maintenance of a single source were being overcome by the extra effort required to accommodate sometimes conflicting requirements. The code was therefore "split" into two versions, one for NRC and the other for DOE. The DOE version maintained all of the capabilities and validation history of the predecessor code, plus the added capabilities that had been sponsored by the DOE before and after the split.

The most prominent attribute that distinguishes the DOE code from the NRC code is the fully integrated, multi-dimensional thermal-hydraulic and kinetic modeling capability in the DOE code. This removes any restrictions on the applicability of the code to the full range of postulated reactor accidents. Other enhancements include a new matrix solver for 3D problems, new water properties, and improved time advancement for greater robustness. The balance of this paper focuses on the capabilities and bench marking of the three-dimensional hydrodynamic model and the multi-dimensional kinetics model.

Multi-Dimensional Hydrodynamic Model

The multi-dimensional component in RELAP5-3D was developed to allow the user to more accurately model the multi-dimensional flow behavior that can be exhibited in any component or region of a LWR system. Typically, this will be the lower plenum, core, upper plenum and downcomer regions of an LWR. However, the model is general, and is not restricted to use in the reactor vessel. The component defines a one, two, or three-dimensional array of volumes and the internal junctions connecting them. The geometry can be either Cartesian (x, y, z) or cylindrical (r, q , z). An orthogonal, three-dimensional grid is defined by mesh interval input data in each of the three coordinate directions.

The functionality of the multi-dimensional component has been under testing and refinement since it was first applied to study the K reactor at Savannah River in the early 1990s. A set of approximately twenty verification test problems was devised to demonstrate the correctness of the numerical conservation equation formulation. All of these problems have closed form solutions. Until recently, application of the model to experiments was limited to tests carried out in the L reactor at Savannah River. A program is currently underway to expand the validation base to include a wide variety of experiments that exhibit multi-dimensional flow behavior. One example is a series of experiments conducted at the Rensselaer Polytechnic Institute to examine the flow patterns in a two-dimensional test section connected to an air-water loop1 .

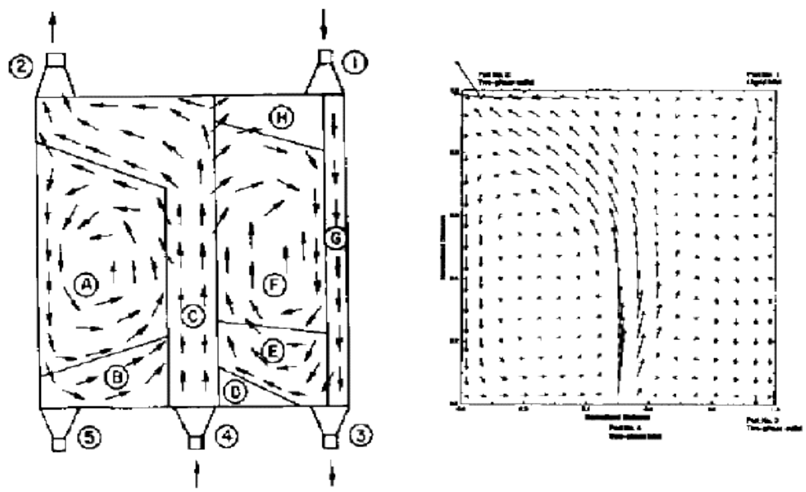

Figure 1. Observed and computed flow patterns in the RPI Two-Phase Test Section

The test section (Figure 1, left) consisted of a thin vertical channel that simulated a two-dimensional slice through the core of a pressurized water reactor. The test section was 0.91 m (3 ft) tall, 0.91 m (3 ft) wide, and 0.013 m (0.5 in.) thick. Single-phase and two-phase flows were supplied to the test section in an asymmetric manner to generate a two-dimensional flow field. An air-water mixture was injected at port 4 and liquid was injected at port 1. Ports 2 and 3 served as outlets and port 5 was closed. A traversing gamma densitometer was used to measure void fraction at many locations in the test section. High speed photographs provided information on the flow patterns and flow regimes. Figure 1, left, shows the observed flow patterns observed in the experiments, where the arrows indicate the direction of flow but not the magnitude.

The RPI test section was modeled2 using the multi-dimensional component in RELAP5-3D . Cartesian geometry was selected and the test section was represented with 1 interval in the x-direction, 17 intervals in the y-direction, and 16 intervals in the z-direction. The z-coordinate was selected to be in the vertical direction. Figure 1, right, shows the steady-state flow pattern predicted by RELAP5-3D for Test 2AN4. The direction and length of each vector was computed based on resolving the liquid and air flow velocities in the y and z directions as follows:

$$\vec{v}_y = \alpha v_{gy} + (1-\alpha) v_{fy}$$
$$\vec{v}_z = \alpha v_{gz} + (1-\alpha) v_{fz}$$

$$\vec{v} = \vec{v}_y + \vec{v}_z$$

where a is the void fraction, vgyand vgz are the gas velocities in the y and z directions respectively, and vfy and vfz are the liquid velocities in the y and z directions, respectively.

The predicted flow pattern is seen to closely match that observed in the experiment, exhibiting a general upward flow in the center towards the port 2 outlet, and recirculation regions on either side.

Multi-Dimensional Neutron Kinetics

The multi-dimensional neutron kinetics model in RELAP5-3D is based on the NESTLE code3developed by Paul Turinsky and co-workers at North Carolina State University under an INL initiative. The NESTLE code solves the two or four group neutron diffusion equations in either Cartesian or hexagonal geometry using the Nodal Expansion Method (NEM) and the non-linear iteration technique. Three, two, or one-dimensional models may be used. Several different core symmetry options are available including quarter, half, and full core options for Cartesian geometry and 1/6, 1/3, and full core options for hexagonal geometry. Zero flux, non-reentrant current, reflective, and cyclic boundary conditions are available. The steady-state eigenvalue and time dependent neutron flux problems can be solved by the NESTLE code as implemented in RELAP5-3D .

The implementation of the NESTLE neutron kinetics has been verified by the simulation of the NEACRP4 three dimensional benchmark problems5. Four of the PWR rod ejection scenarios, ejection of a control rod and a peripheral rod from Hot Zero Power (HZP) and Hot Full Power (HFP) conditions were simulated by RELAP5-3D . Quarter core symmetry was used for the simulation. The RELAP5-3D core model for the benchmark problem consisted of a sequence of 47 parallel pipes, each consisting of a series of heat structures and control volumes to model the fuel and coolant from a single assembly. The results of the two HFP rod ejection cases are compared with the reference results in Figure 2. As shown, excellent agreement was obtained.

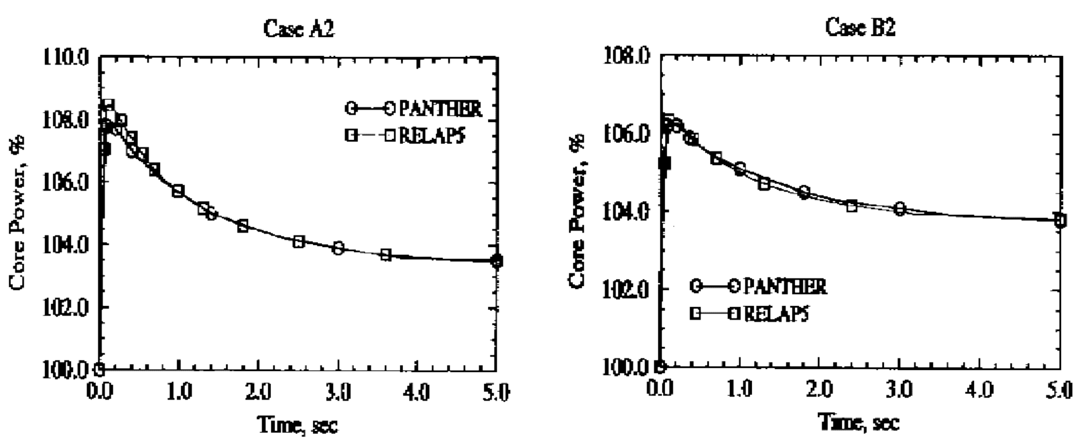

Figure 2. Comparisons of RELAP5-3D and PANTHER Predictions of Power Excursions Following Rod Ejection from Hot Full Power

BPLU Matrix Solver

The Border Profiled Lower Upper (BPLU) matrix solver 6 is used to efficiently solve sparse linear systems of the form AX = B. BPLU is designed to take advantage of pipelines, vector hardware, and shared-memory parallel architecture to run fast. BPLU is most efficient for solving systems that correspond to networks, such as pipes, but is efficient for any system that it can permute into border-banded form.

Speed-ups are achieved for RELAP5-3D; running with BPLU over the default solver. For almost all one-dimensional problems, there is no speed-up; however, for problems with wider bandwidths, especially those with three-dimensional regions, significant speed-ups can be achieved. One of the standard installation problems, "3dflown.i" illustrates the reduction in run time that can be achieved. The problem is a simple cube subdivided into a 3x3 region in each of the Cartesian coordinate directions. There are nine cases examined with this model, comprised of flow in each coordinate direction (x,y,z) of vapor only, liquid only, and a two-phase mixture. Table 1 compares the run times for the default and BPLU solvers.

Table 1. CPU Times for 3dflown.i Problem Using Default and BPLU Solvers

Case	Default Solver (CPU sec.)	BPLU Solver (CPU sec.)	Ratio
1	7.180	2.437	2.946
2	7.142	2.110	3.385
3	6.903	2.718	2.540
4	6.142	2.422	2.536
5	5.513	2.117	2.604
6	5.818	2.698	2.156
7	6.167	2.432	2.535
8	7.404	2.116	3.499
9	6.396	2.697	2.372
Note: All times on a DEC Alpha 4100 Workstation			

The results show speed-ups ranging from 2.1 to 3.5 for this simple three-dimensional problem.

References

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