ANALYSIS OF THE OECD MSLB BENCHMARK WITH THE COUPLED NEUTRONIC AND THERMAL-HYDRAULICS CODE RELAP5/PARCS

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ABSTRACT

The USNRC version of the 3D neutron kinetics code PARCS (Purdue Advanced Reactor Core Simulator) has been coupled with the USNRC thermal-hydraulics codes RELAP5. The OECD/NEA PWR MSLB benchmark problem was performed in order to provide an assessment of RELAP5/PARCS and in order to evaluate the differences in the point kinetics and spatial kinetics analysis of the MSLB transient. Results are presented using both the “best estimate” and “return to power” cross section sets provided in the benchmark problem. In both cases, an increase in the shutdown margin is provided by the spatial kinetics solution.

1. INTRODUCTION

The OECD Nuclear Science Committee has released a set of computational benchmark problems for calculation of reactivity transients in Pressurized Water Reactors (PWR). A Main Steam Line Break (MSLB) transient based on the Three Mile Island (TMI-1) PWR has been developed[1] to assess the capability of coupled neutronics and thermal-hydraulics codes to analyze complex transients having coupled core-plant interactions. The PWR MSLB accident scenario is characterized by a rupture in one of the main steam lines of the secondary system, leading to a sudden overcooling of the corresponding primary loop water. The overcooled moderator represents a positive reactivity insertion, which must be overcome by the control rods. Best-estimate modeling of this event requires three-dimensional spatial kinetics because of space-time variations of the core power distribution arising from the asymmetric cooling of the core and from the scram of the reactor with the highest worth rod stuck out of the core.

This benchmark was split into three separate exercises: a plant system model with point reactor kinetics, a spatial kinetics model of the core with the plant response modeled with time-dependent core thermal-hydraulic boundary conditions, and a plant system model with a spatial kinetics model of the core. Results for the second exercise of the problem computed with RELAP5/PARCS have been reported in an earlier paper[12]. The results presented in this paper are for the third exercise of the problem. Additional analysis was performed with the exercise 3 solution in order to evaluate the impact of spatial kinetics on the MSLB transient. A point kinetics solution was performed with RELAP5 using reactivity coefficients computed from the steady-state REALP5/PARCS 3D neutronics solution. Results are presented here for two different sets of cross section data provided in the benchmark; the Best Estimate (BE) data and the Return to Power (RP) data in which the rod scram worth in the best estimate scenario was reduced.

The work here utilized the coupled RELAP5/PARCS code that was developed by the USNRC. The RELAP5[4] and PARCS[5] codes are coupled using a General Interface (GI) which allows for the coupling of any thermal-hydraulics code to any spatial kinetics code[2]. In this design, each of the thermal-hydraulics, GI, and neutronics codes are executed as separate processes with inter-process communication made possible through the use of message-passing protocols in the Parallel Virtual Machine (PVM) package[3]. A brief overview of the coupling methods will be provided in the following section, as well as a brief review of the MSLB specifications.

2. RELAP5/PARCS COUPLING METHOD AND THE OECD MSLB SPECIFICATIONS

2.1 RELAP5/PARCS COUPLING METHOD

The spatial coupling of RELAP5 and PARCS relies on an internal integration scheme in which the solution of both the system and core thermal-hydraulics is performed by RELAP5, and PARCS performs only the spatial kinetics solution. The temporal coupling of RELAP5 and PARCS is explicit and the respective field equations of the two codes are solved with the same frequency. In this implementation, the RELAP5 solution leads the PARCS solution by a single time step and the calculation is initiated by RELAP5 first advancing the heat conduction and hydrodynamic solutions. The new solution is then passed through the GI to PARCS, which incorporates the appropriate feedback into the cross sections and calculates the spatial kinetics solution for the time step indicated by RELAP5. PARCS then transfers the neutronic solution through the GI to RELAP5, which uses these data as the heat source for the subsequent time step. This procedure is repeated until RELAP5 indicates that the calculation should be terminated based on user input or a fault signal.

2.2 MSLB BENCHMARK SPECIFICATIONS

The benchmark specifications provide the data necessary for modeling the TMI-1 reactor for this exercise. These were provided in the original problem specifications[9] and the preliminary analysis of the results from the first exercise of this benchmark[10]. However, several assumptions were necessary in order to construct models for the thermal-hydraulics and neutronics codes. A detailed description of the model and the modeling assumptions were provided in an earlier paper and will only be briefly reviewed here.

The hydrodynamics model is based on 18 flow channels in the active core which was modeled using 18 separate pipe components in RELAP5 as depicted in Figure 1. An additional channel was defined for the radial reflector region, and thus the RELAP5 hydrodynamic model consisted of 19 parallel pipe components. It should be noted that cross flow between channels was not provided in this model. The nodalization used for the heat structures in this model follows closely that used for the neutronics model and the core is represented by 193 heat structure components using the RELAP5 pin geometry model. Each heat structure was divided into 14 axial nodes using the same criteria established for the thermal-hydraulic volumes. The radial nodalization within each heat structure consists of a total of 10 mesh: 7 in the fuel region, 1 in the gap, and 2 in the cladding. The correlations for thermal conductivity and heat capacity are provided in the benchmark problem.

The neutronics core model used in this exercise is based on an end-of-cycle (EOC) state of the TMI-1 nuclear power plant. The core consists of 177 fuel assemblies (FA), and has a rated core power of 2772 MWth. The PARCS model represents separately each of the 177 fuel assemblies with a single neutronic node. The mapping of the neutronic to hydrodynamic mesh is depicted in Figure 2. The benchmark specifications provide for 29 types of fuel assemblies, with each assembly consisting of 15 compositions. The group constants for each composition consist of two sets of macroscopic cross section data: one for rodded and one for unrodded fuel assemblies. The group constant data were provided as three data files. The first file is for unrodded compositions, while the second and third files are for rodded compositions. The second cross section set ensures the preservation of the rod worth from the point kinetics solution, ie. Best Estimate (BE) solution, and the third set provides a rod worth which results in a return to power, ie. Return to Power (RP) solution. Results will be shown here using both sets of data.

3. RESULTS FOR MSLB PROBLEM

RELAP5/PARCS results were first computed for exercise 3 of the benchmark problem. Reactivity coefficients were then computed using PARCS at the steady-state, hot full power conditions. The calculated Doppler and MTC were –2.70 pcm/ K and –65.67 pcm / K, respectively, which are about 5% larger than the values specified for exercise 1 of the benchmark problem. Also, the magnitude of the scram worth computed with PARCS was about 0.5% smaller than that specified for exercise 1. The point kinetics solution was then computed with the RELAP5 code using these reactivity coefficients and the results were compared to the spatial kinetics solution. Results will be presented first for the Best Estimate cross section set and then for the Return to Power data.

3.1 BEST ESTIMATE SOLUTION

The reactivity and core power for the Best Estimate solution of the spatial kinetics and point kinetics solutions are shown in Figures 3 and 4. Each component of the reactivity is shown separately in order to identify the important differences in the solutions. As shown in Figure 3, the total reactivity of the spatial kinetics solution is substantially less than the point kinetics solution. This is primarily because the positive moderator density feedback determined in the spatial kinetics solution is significantly less than that predicted by point kinetics. Some of the important core performance parameters are summarized in Table 1. A primary concern of this accident is a return to criticality from the large positive moderator reactivity feedback. The point kinetics solution returns to critical at about 60 seconds, whereas the spatial kinetics solution does not return to critical and has a minimum shutdown margin of about 2.6$.

3.2 RETURN TO POWER SOLUTION

The reactivity and core power for the Return to Power solution of the spatial kinetics and point kinetics solutions are shown in Figures 5 and 6. A comparison of Figures 3 and 5 indicates that the scram worth in the Return to Power (RP) case is reduced by about 3 dollars, therefore the overall system reactivity in the RP solution is higher after the reactor is scrammed. As in the Best Estimate solution, the reactivity of the spatial kinetics solution is less than the point kinetics solution. A comparison of some of the important core performance parameters is shown in Table 1. As in the Best Estimate case, the point kinetics solution returns to critical and the spatial kinetics solution does not. However, the shutdown margin in the RP spatial kinetics solution is reduced to about 0.25$ at 61.28 seconds.

While the core remained subcritical throughout the transient in the RP spatial kinetics calculations, RELAP5/PARCS predicted a nontrivial increase in the core power which reaches it maximum at about 63 seconds into the transient. The subcritical return to power has been explained[11] as the multiplication of the initial delayed neutron source which is largest in the vicinity of the stuck rod. The maximum relative assembly power during the transient is shown in Figure 7, and the assembly axially integrated average radial power distribution at the time of the maximum core power is shown in Figure 8. It is interesting that although the core does not return to critical, the maximum assembly power during the transient is greater than the nominal core average assembly power when the core is critical.

CONCLUSIONS

The USNRC version of the 3D neutron kinetics code PARCS (Purdue Advanced Reactor Core Simulator) has been coupled with the USNRC thermal-hydraulics codes RELAP5. The OECD/NEA PWR MSLB benchmark problem was performed in order to provide an assessment of RELAP5/PARCS and in order to evaluate the differences in the point kinetics and spatial kinetics analysis of the MSLB transient. Results were presented using both the Best Estimate and the Return to Power cross section sets provided in the benchmark problem. In both cases, an increase in the shutdown margin is provided by the spatial kinetics solution.

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Table 1 Comparison of Transient Results for Point and Spatial Kinetics Solutions

	Best Estimate		Return to Power	
	3D Kinetics sec (value)	Point Kinetics sec (value)	3D Kinetics sec (value)	Point Kinetics sec (value)
Break Opens	0.00	0.00	0.00	0.00
Reactor Trip	5.37	4.83	5.37	4.83
Turbine Valve Close	5.87	5.33	5.87	5.33
High Pressure Injection Starts	35.51	34.65	35.70	35.02
Maximum Core Reactivity	100.0 (-2.59$)	65.20 (0.17$)	61.28 (-0.25$)	60.20 (0.10$)
Maximum Return to Power	N/A	69.80 (30.2%)	63.46 (30.4%)	62.70 (57.4%)
Transient Ends	100.0	100.0	100.0	100.0

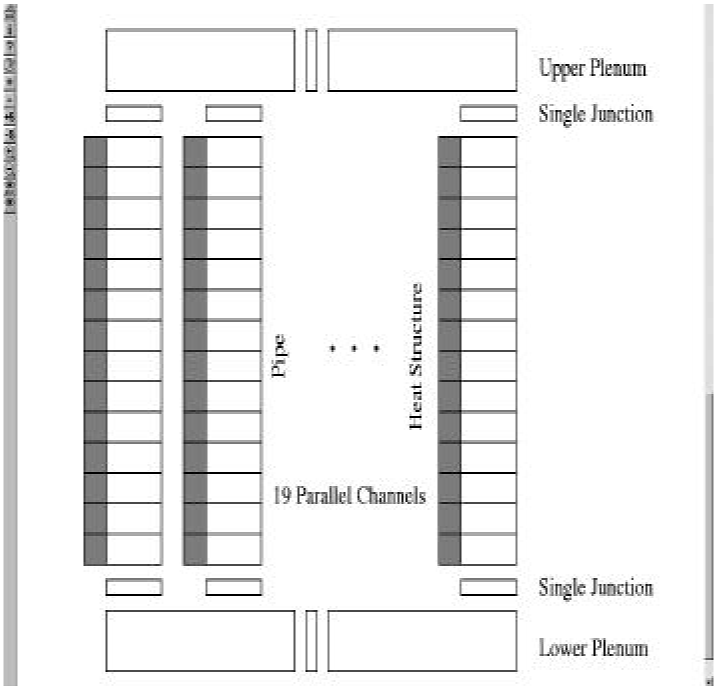

Figure 1 RELAP5 Core Nodalization

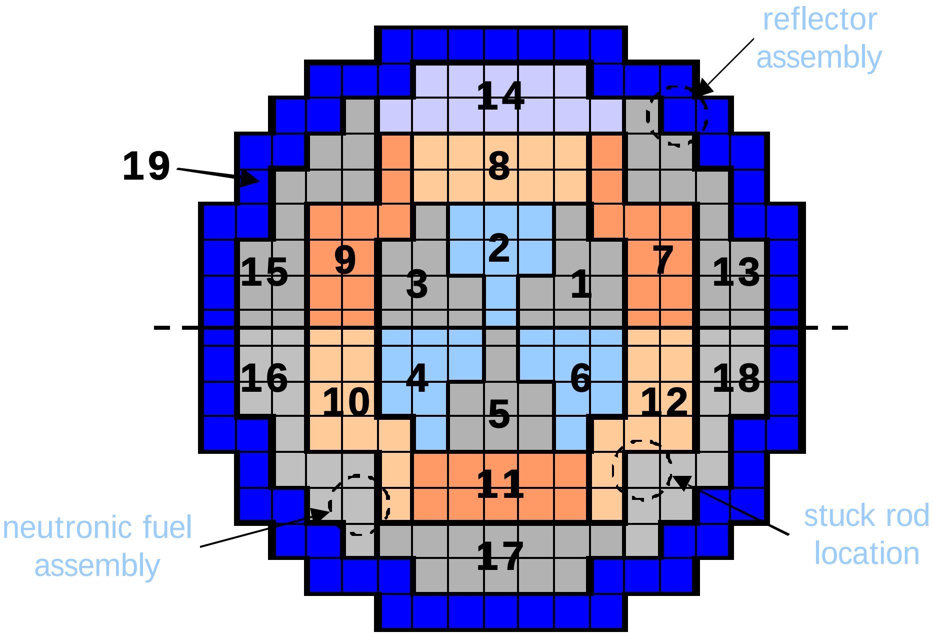

Figure 2 PARCS Core Nodalization and RELAP5 Thermal Hydraulic Channel Mapping

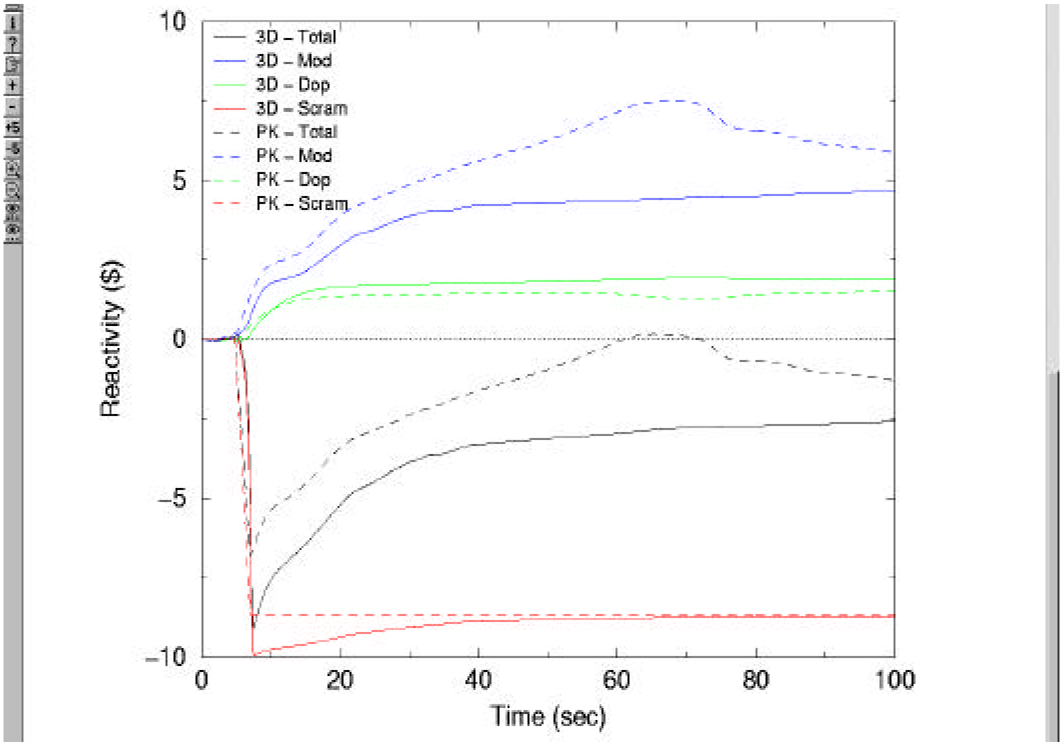

Figure 3 Comparison of Best Estimate Reactivity for Point and Spatial Kinetics

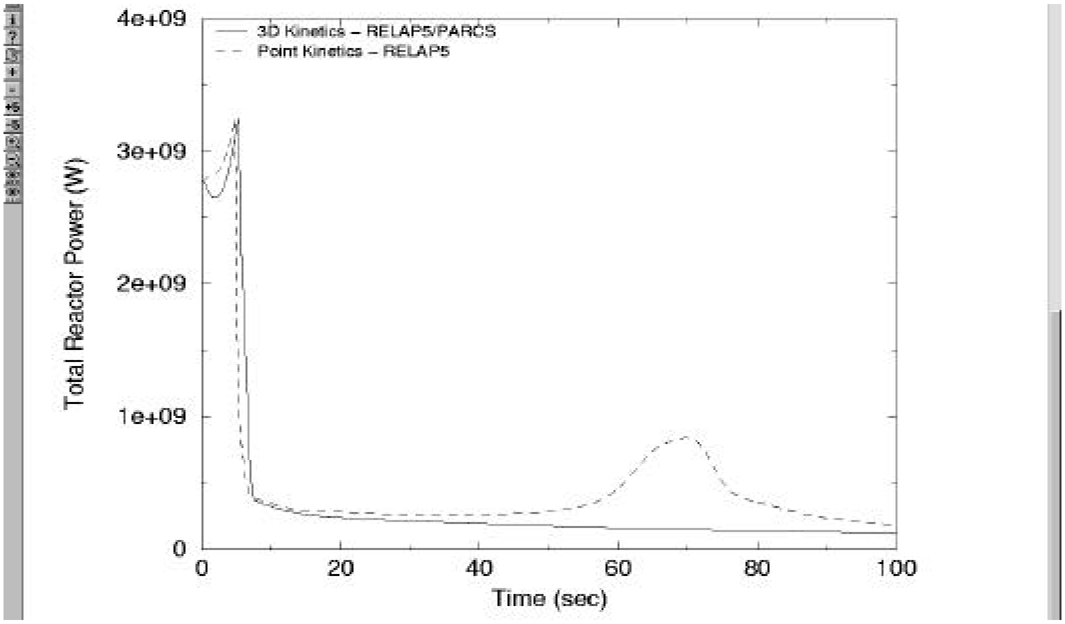

Figure 4 Comparison of Best Estimate Reactor Power for Point and Spatial Kinetics

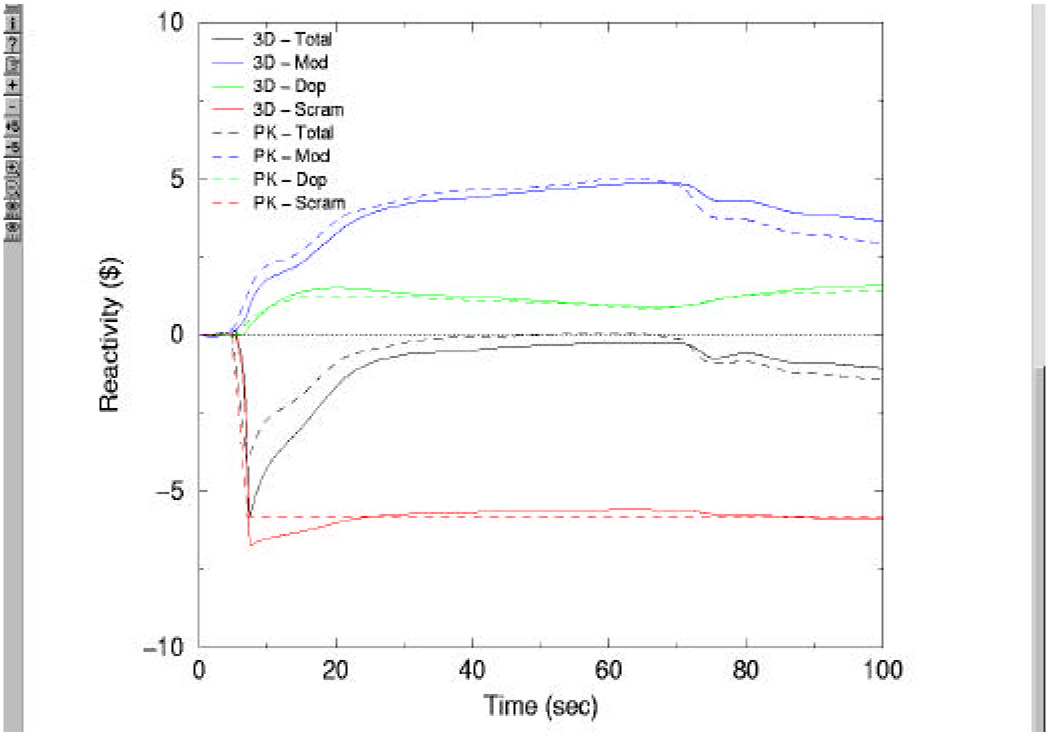

Figure 5 Comparison of Return to Power Reactivity for Point and Spatial Kinetics

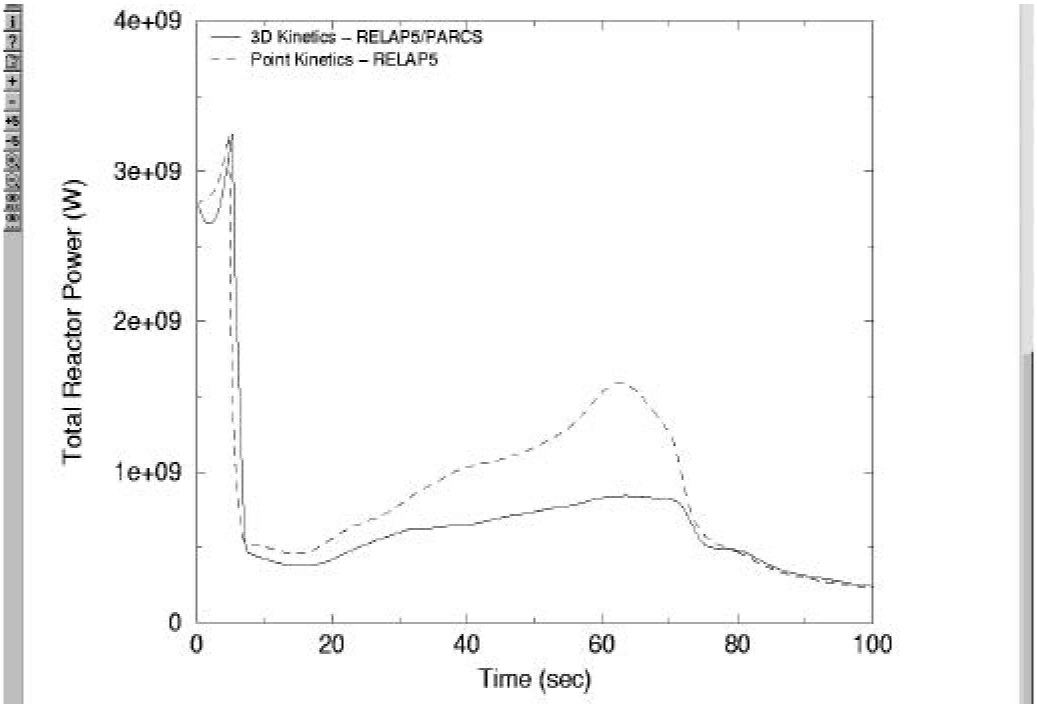

Figure 6 Comparison of Return to Power Reactor Power for Point and Spatial Kinetics

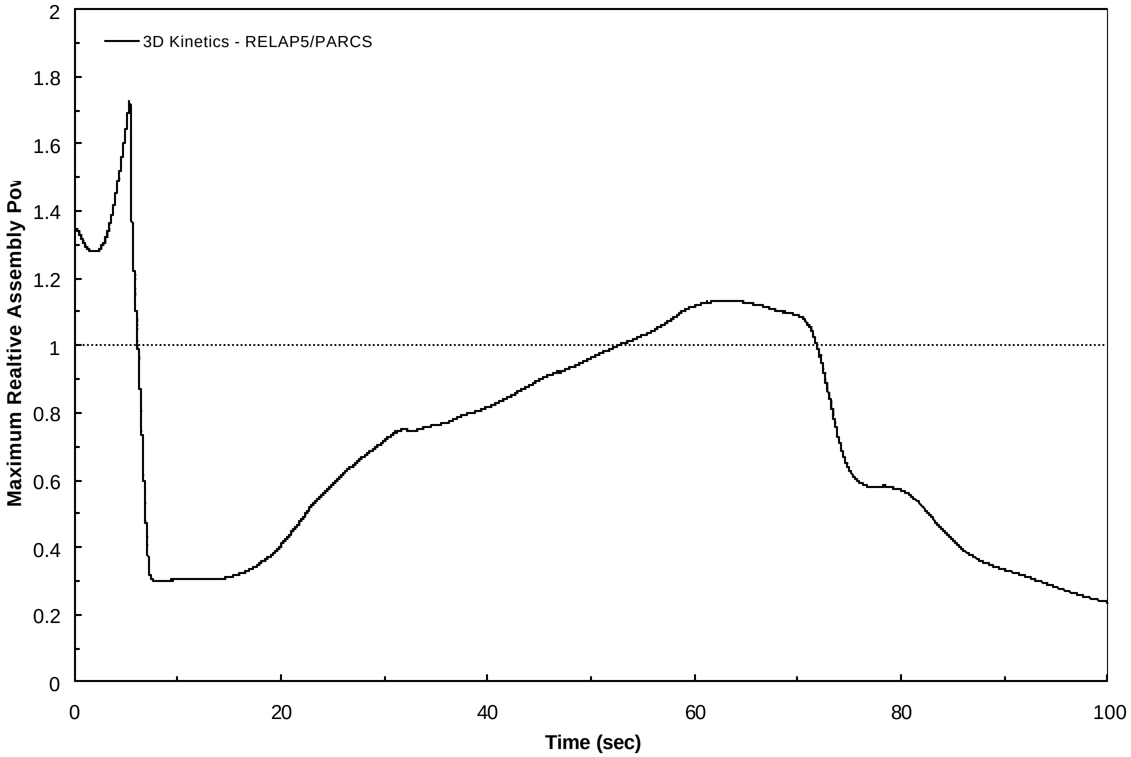

Figure 7 Maximum Relative Assembly Power During the Transient (RP Solution)

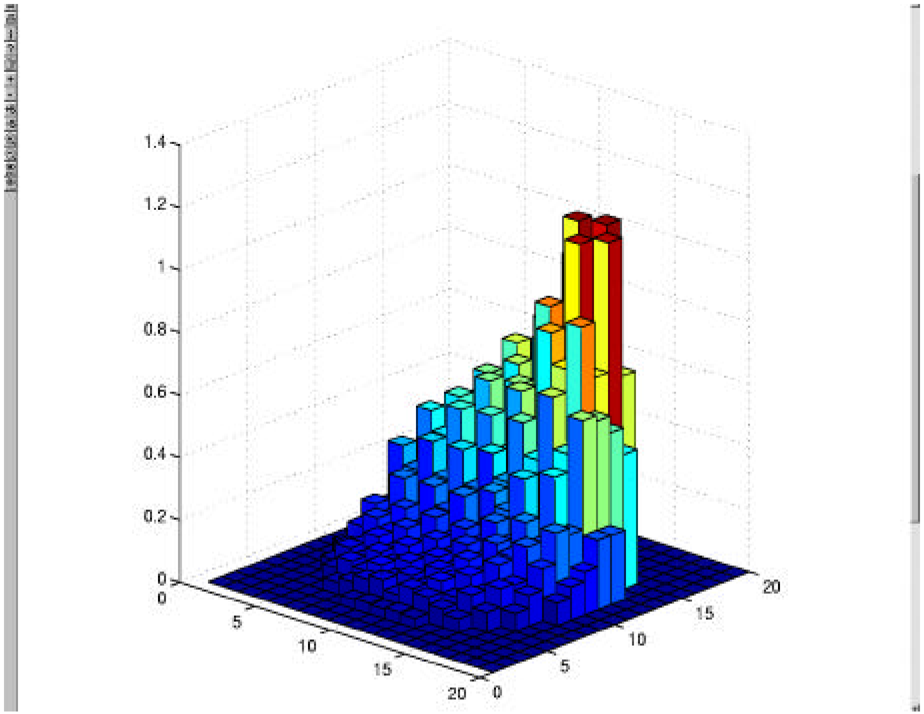

Figure 8 Radial Power Distribution at the Time (63.46 secs) of the Maximum Relative Assembly Power