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Analysis of Control Rod Ejection Accident in MOX and MOX/UOX Cores with Time-Dependent Multigroup Pin-by-Pin SP_3 Methods

Chang-Ho Lee, Tomasz Kozlowski, Thomas J. Downar
School of Nuclear Engineering
Purdue University
changho@ecn.purdue.edu, tomasz@ecn.purdue.edu, downar@ecn.purdue.edu

ABSTRACT

Multigroup, pin-by-pin transport methods based on the SP_3 approximation have been implemented in the U.S. NRC neutronics code PARCS and applied to analysis of a control rod ejection transient for MOX/UOX and UOX fueled cores. The purpose of this paper is twofold. First, comparisons are made of rod ejection transient results for the MOX/UOX and UOX cores in order to assess the impact of MOX on core transient performance. Results here indicate that the MOX/UOX core shows an earlier and smaller power peak compared to the UOX core. Point kinetics parameters were generated from the spatial kinetics results in order to help explain the observed behavior. The second purpose of this paper is to assess the importance of multigroup transient transport calculations for highly heterogeneous problems. A comparison of the 8-group pin-by-pin SP_3 with the conventional two group nodal diffusion methods indicates that the difference of the predicted control rod worth is a large source of the discrepancy between the higher and lower order results.

1. INTRODUCTION

The considerable advances in computer speed and memory during the last several years has encouraged the application of integral transport methods for analyzing highly heterogeneous MOX fueled LWR cores. Advances in numerical methods such as the method of characteristics (MOC) have made it possible to analyze whole core, multigroup, pin by pin models in practical computing times. Several researchers have used integral transport methods to assess the accuracy of conventional two-group nodal diffusion methods normally used in steady-state and transient core calculations [1], [2], [3]. However, while the MOC whole-core calculation has been successful for two-dimensional steady-state cores without thermal feedback, this approach is not yet practical for core depletion or transient analyses. Therefore, a trade-off is needed in terms of complexities in the treatment of energy, angle, and space in order to achieve reasonable computational times.

During the past year, multigroup, pin-by-pin transport methods based on a SP_3 approximation have been implemented in the U.S. NRC neutronics code PARCS [4]. Innovative two-level (global/local) acceleration methods have been developed within the framework of the “one-node” solution technique to enhance the computation performance. In the work reported here, multigroup pin-by-pin SP_3 calculations are used to analyze a control rod ejection transient for MOX/UOX and UOX fueled cores. A point kinetics model with parameters based on the spatial kinetics is used to help explain observed results. Comparisons are also made between higher order multigroup, transport calculations and conventional two-group nodal diffusion calculations in order to assess the importance of transient transport calculations for highly heterogeneous problems.

2. BENCHMARK PROBLEM AND STATIC RESULTS

A MOX benchmark core was designed based upon the fuel compositions of the KAIST benchmark problem [1]. Particular attention was given to a core design that had a power distribution and reactivity characteristics similar to practical larger LWR cores fueled with MOX. For the transient calculation, 8-group partial cross sections were formulated in terms of fuel temperature, moderator temperature, and boron concentration. In order to provide a consistent comparison of the characteristics and kinetics response between MOX/UOX and UOX fueled cores, a second core was also designed with all UOX fuel. The following section will briefly review the higher order methods used to assess the accuracy of the lower order methods. The benchmark model will then be described, followed by a comparison of higher and lower order methods for the static problem. The transient results will be analyzed in Section 3.

2.1 MULTIGROUP PIN-BY-PIN SP_3 METHODS

The time-dependent SP_3 equations were implemented in PARCS using the conventional approach in which the odd-order angular moments are eliminated to yield a set of coupled diffusion-like equations as shown below in a matrix-equation form:

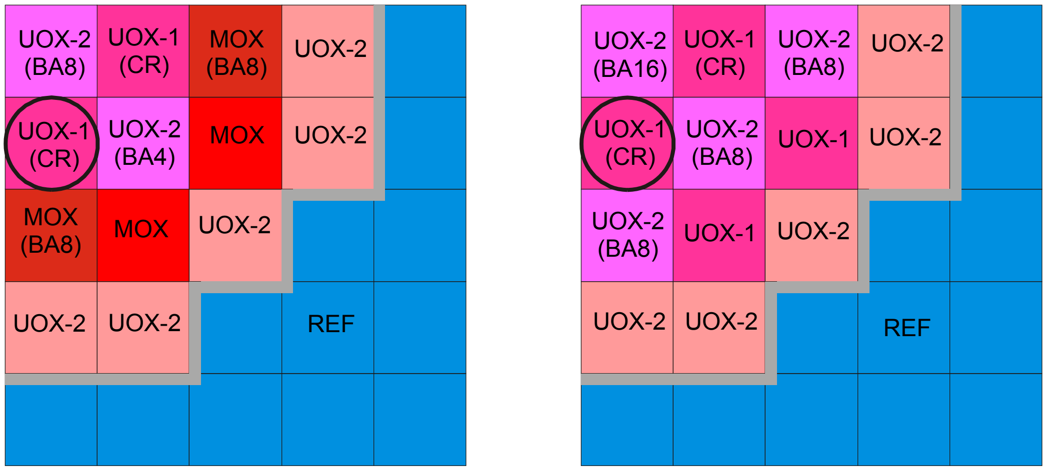
$$\begin{bmatrix} -D_1^*\nabla^2+\Sigma_r^* & -2D_1^*\nabla^2 \\ -\frac{2}{5}D_1^*\nabla^2 & -\left(\frac{3}{5}D_3^*+\frac{4}{5}D_1^*\right)\nabla^2+\Sigma_t^* \end{bmatrix}\begin{bmatrix}\phi_0^{n+1}\\ \phi_2^{n+1}\end{bmatrix}=\begin{bmatrix} q_0^n-3D_1^*\nabla\cdot q_1^n+S_{0t}^{n+1} \\ q_2^n-\frac{6}{5}D_1^*\nabla\cdot q_1^n-\frac{7}{5}D_3^*\nabla\cdot q_3^n \end{bmatrix}, \quad (1)$$

where $D_1^*\equiv\frac{1}{3\Sigma_{tr}^*}$, $D_3^*\equiv\frac{3}{7\Sigma_t^*}$, $\Sigma_\alpha^*=\Sigma_\alpha+\frac{1}{\upsilon\Delta t}$, $q_i^n=\frac{1}{\upsilon}\frac{\phi_i^n}{\Delta t}$, n = time index.

As discussed in previous papers [4], a two-level acceleration method was implemented in order to accelerate solution of the multigroup, pin by pin SP_3 method. The implementation of these methods was assessed using various benchmarks such as the VENUS-2 MOX critical experiment which is reported at this meeting [5].

2.2 CORE MODELS

The MOX/UOX and UOX cores used in the analysis here are shown in Fig. 1. The reactor grade MOX assemblies were replaced with UOX assemblies of an equivalent enrichment in the UOX-only core to insure that the two cores have similar eigenvalues. Two-group cross sections were also generated based upon the conventional homogenization and collapse procedures which use single fuel assembly calculations with reflective boundary conditions. These cross sections were used for the conventional two-group nodal diffusion calculation, and the results were compared with those of the multigroup pin-by-pin SP_3 method.



(a) (b)

(UOX-1: 2.0 w/o, UOX-2: 3.3 w/o, MOX: 4.3 w/o, 7.0 w/o, 8.7 w/o)

(◯ : position from which a rod is ejected)

Figure 1. Core Loading Patterns ((a) MOX/UOX Core, (b) UOX Core)

A comparison of the critical boron concentrations at hot, zero power (HZP) all rods in (ARI) and hot, full power (HFP) all rods out conditions is shown in Table I for the higher (8 energy group, 4 mesh per pin, SP_3) and lower order (2 energy group, nodal diffusion) methods. As indicated in the Table I, the most noticeable difference in results is for the HFP, ARO case in the MOX/UOX core in which there is a 33 ppm difference between the higher and lower order calculation, whereas the critical boron is essentially identical for the UOX core.

Table I. Comparison of Critical Boron Concentration at HZP, ARI and HFP, ARO Conditions between MOX/UOX and UOX Cores

(unit: ppm)

Condition	Solution Kernel	MOX/UOX Core	UOX Core
HZP, ARI	8-G pin-by-pin SP_3	2017	1241
	2-G Nodal Diffusion	2025	1227
HFP, ARO	8-G pin-by-pin SP_3	1951	1305
	2-G Nodal Diffusion	1984	1306

A comparison of the core power distributions for the MOX/UOX and UOX cores is shown in Figs. 2 and 3. As indicated in the Figures, the power distribution error is larger in the MOX/UOX core than in the UOX core. In particular, the RMS pin error in the MOX/UOX cores is higher than 5% in several of the assemblies.

1.13 -3.11 3.20 4.89 -3.87		FMFD FA Power FA % diff Pin % RMS Pin max % diff Peak pin % diff
0.98 -1.66 2.04 3.82 -0.49	1.26 0.82 1.70 6.36 1.62	
1.30 1.04 1.26 3.37 0.63	1.27 2.06 2.16 4.86 2.39	0.71 -0.17 5.67 15.42 3.73
0.80 -0.33 4.53 12.40 2.30	0.60 -1.29 6.10 16.38 2.62	

Figure 2. Comparison of Power Distributions between 8-G pin-by-pin SP_3 and 2-G Nodal Diffusion Calculations for MOX/UOX core

-1.94 1.99 3.11 -2.08		FA % diff Pin % RMS Pin max % diff Peak pin % diff
-0.36 0.57 1.39 -0.01	-0.23 0.56 2.17 -0.67	
0.88 1.05 1.93 0.12	-0.18 0.97 4.41 0.37	-0.86 4.19 10.92 -0.59
1.31 3.10 6.97 3.51	-0.39 4.11 11.00 0.95	

Figure 3. Comparison of Power Distributions between 8-G pin-by-pin SP_3 and 2-G Nodal Diffusion Calculations for UOX core

3. CONTROL ROD EJECTION RESULTS AND ANALYSIS

The control rod ejection transient was then analyzed for the two cores. First, the cores were analyzed using just the multigroup, SP_3 pin by pin method in PARCS to assess differences in the MOX/UOX and UOX core response. The cores were then analyzed using both higher and lower order methods to assess the importance of higher order transient analysis for heterogeneous cores.

3.1 COMPARISON OF MOX/UOX AND UOX CORE RESPONSE

Using the multigroup, SP_3 transport method with 4 mesh per pin, the absorption cross sections in the MOX/UOX and UOX core were adjusted until the rod worth in both cores was identical ($1.085). The rod was then ejected in 0.1 sec resulting in the familiar bell-shape power transient for a super-prompt critical transient as shown in Figure 4. A comparison of the energy deposition in the peak pins for the MOX/UOX and UOX cores is shown in Figure 5.

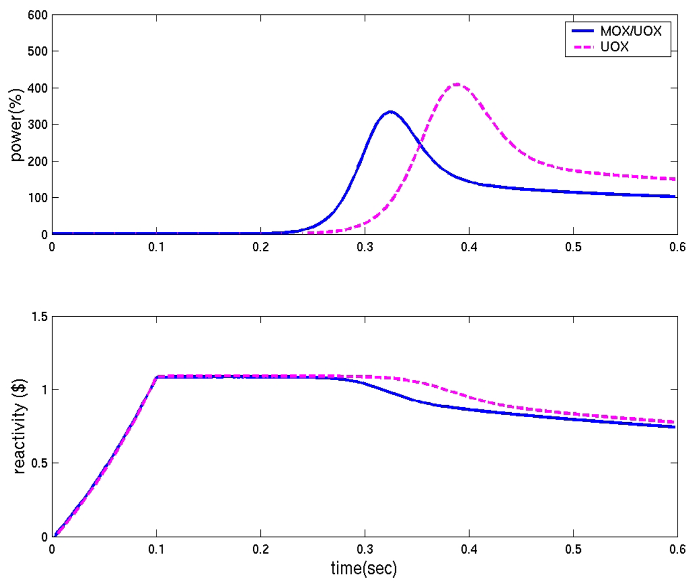


Figure 4. Comparison of Power and Reactivity for MOX/UOX and UOX Cores

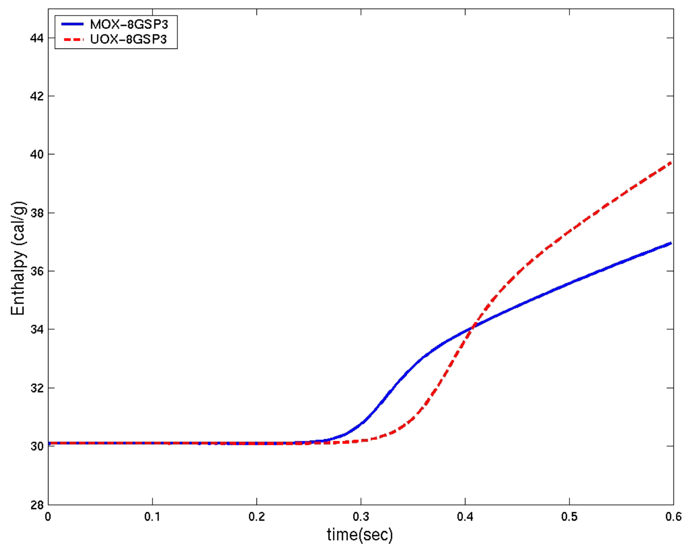


Figure 5. Comparison of Energy Deposition in the Peak Pins for the MOX/UOX and UOX Cores

For purposes of interpreting spatial kinetics results and for providing a consistent comparison of the MOX/UOX and UOX cores, exact point kinetics equation was used in which the kinetics parameters were calculated using the exact time-dependent flux. The point kinetics parameters for the MOX/UOX and UOX core are shown in Table II.

Table II. Point Kinetics Parameters of MOX/UOX and UOX Cores

Core	β	Λ	ρ	γ^*	Λ / β	γ^* / β
MOX/UOX	0.0057	1.28E-05	1.085	-3.12	0.0022	-547
UOX	0.0077	2.15E-05	1.085	-2.99	0.0028	-388

* Note that γ^* is a Doppler coefficient which is different from γ in Eq. (2)

As expected, both the delayed neutron fraction, β, and the neutron generation time, Λ, are smaller in the MOX/UOX core because of the high Plutonium inventory. The feedback coefficient, γ^*, is the Doppler coefficient which is slightly larger in the MOX/UOX core because of the increased resonance absorption in Plutonium. The control rod absorption cross section was adjusted in the MOX/UOX core in order to provide the same rod worth of 1.085 dollars.

These coefficients were used in the "prompt kinetics" approximation of the point kinetics equations, which is applicable for the super-prompt critical transients transient [6]:

$$p(t) = \exp\left(\frac{\rho_1 - \beta}{\Lambda} t\right) p_0 , \quad p_{\max} = -\frac{\rho_b^2}{2\Lambda\gamma} , \quad p_{\max} \overline{\Delta t} \cong -\frac{2(\rho_1 - \beta)}{\gamma} , \tag{2}$$

where $\rho_b^2 = (\rho_1 - \beta)^2 - \frac{2\Lambda\gamma\rho_1}{\rho_1 - \beta} p_0 \approx (\rho_1 - \beta)^2 , \quad \rho_1 = \rho(t) + \gamma \int_0^t \left(p(t') - p_0\right) \, dt' ,$

$\gamma < 0$ (thermal feedback coefficient).

It should be noted that γ in these equations is the total thermal feedback coefficient, whereas the γ^* shown in Table II is only the Doppler coefficient. Nonetheless, these equations still can provide insight regarding the relative response of the MOX/UOX and UOX cores to a control rod ejection. Specifically, it is evident that when the same amount of reactivity is inserted, the maximum power is determined by Λ / β and γ / β . Using the data in Table II, Equation 2 predicts the maximum power in the UOX core to be about 13% higher than the maximum power in the MOX/UOX core. This is reasonably close to the 16% difference shown in Figure 4. The product of the maximum power and the pulse half-height is proportional to the energy deposition and, as indicated in Equation 2, it is inversely proportional to the ratio γ / β . As shown in Table II, this ratio is about 41% higher in the MOX/UOX and therefore the energy deposition in the UOX core should be about that much higher than in the MOX/UOX core. This is reasonably similar to the spatial kinetics result shown in Figure 4 in which the integration of the pulses shows an energy deposition in the UOX core about 50% greater than in the MOX/UOX core. It should be noted that these results are core averaged and that the pin energy depositions, as shown in Figure 5, are only about 10% higher in the UOX core. This can be partly attributed to the more severe local power peaking in the MOX/UOX core.

3.2 ASSESSMENT OF TRANSIENT TWO-GROUP NODAL DIFFUSION RESULTS

The 8-group pin-by-pin SP_3 and 2-group nodal diffusion transient results were then compared in order to assess the error in lower order calculations for highly heterogeneous cores. The difference in the transient results can be caused by several reasons such as control rod worth, delayed neutron fraction, etc. In order to isolate the reasons for the differences, the control rod worth was adjusted in the 2-group calculation such that the reactivity is the same as the 8-group, higher order method. The results shown in Figs. 6 and 7 for the MOX/UOX and UOX cores, respectively, suggest that the difference in the control rod worths is a large source of the discrepancy between the higher and lower order results. However, a large error is still observed in the higher and lower order calculations when the rod worth is the same.

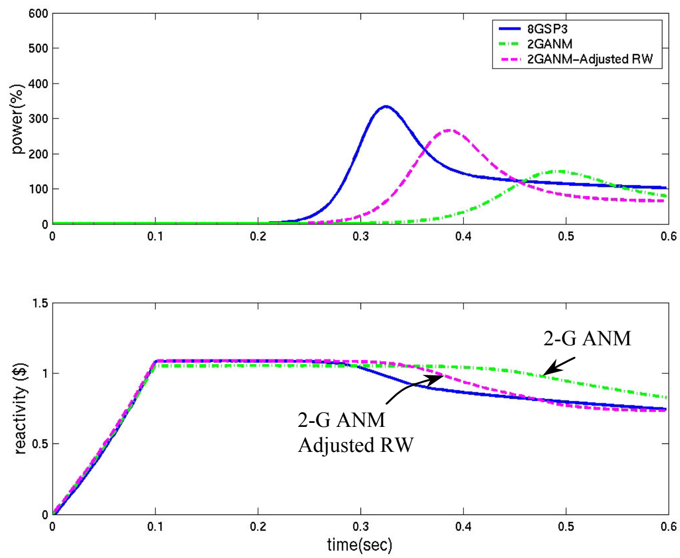


Figure 6 Comparison of Power and Reactivity for High and Low Order for MOX/UOX Core

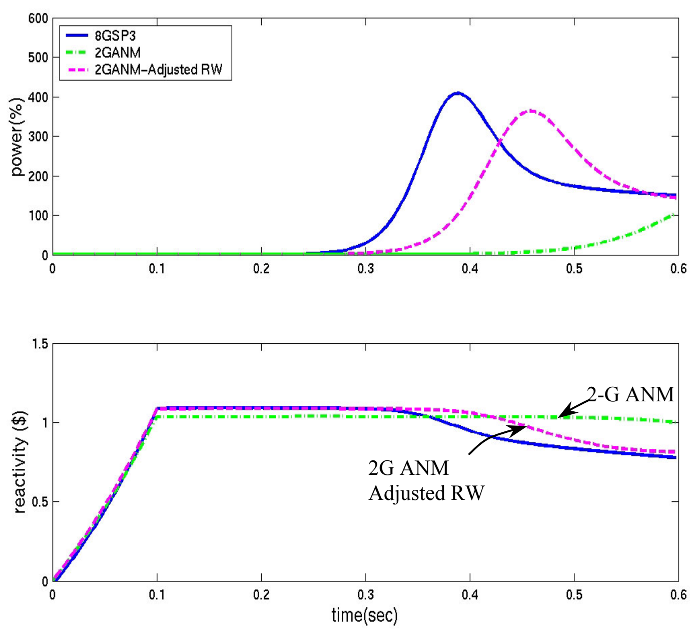


Figure 7 Comparison of Power and Reactivity for High and Low Order for UOX Core

SUMMARY AND CONCLUSIONS

Multigroup, pin-by-pin transport methods based on a SP_3 approximation have been implemented in the U.S. NRC neutronics code PARCS and in the work here were applied to the analysis of a control rod ejection transient for MOX/UOX and UOX fueled cores. The purpose of this work was first to assess the impact of MOX on core transient performance. Results here indicate that the MOX/UOX core shows an earlier and smaller power peak compared to the UOX core. Point kinetics parameters were generated from the spatial kinetics results in order to help explain the observed behavior. The second purpose of this paper was to assess the importance of multigroup transient transport calculations for highly heterogeneous problems. A comparison of the 8-group pin-by-pin SP_3 with the conventional two group nodal diffusion methods indicates that the difference of the predicted control rod worth is a large source of the discrepancy between the higher and lower order results. Work is continuing on the implementation of superhomogenization (SPH) factors for the transient calculation and on further acceleration of the transient solution using adaptive methods.

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