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Two-Dimensional Benchmark Calculations for PNL-30 through PNL-35

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Interest in critical experiments with lattices of mixed-oxide (MOX) fuel pins has been revived by the possibility that light water reactors will be used for disposition of weapons-grade plutonium. A series of six experiments[1,2] with MOX lattices, designated PNL-30 through PNL-35, was performed at Pacific Northwest Laboratories in 1975 and 1976, and a set of benchmark specifications[3] for these experiments subsequently was adopted by the Cross Section Evaluation Working Group (CSEWG). Although there appear to be some problems with these experiments, they remain the only CSEWG benchmarks for MOX lattices.

The number of fuel pins in these experiments is relatively low, corresponding to fewer than 4 typical pressurized-water-reactor fuel assemblies. Accordingly, they are more appropriate as benchmarks for lattice-physics codes than for reactor-core simulator codes. Unfortunately, the CSEWG specifications retain the full three-dimensional (3D) detail of the experiments, while lattice-physics codes almost universally are limited to two dimensions (2D). This paper proposes an extension of the benchmark specifications to include a 2D model, and it justifies that extension by comparing results from the MCNP Monte Carlo code[4] for the 2D and 3D specifications.

The 3D specifications describe lattices of MOX pins in borated or (essentially) unborated water, with egg-crate grids near the top and bottom, a support plate at the bottom, and a lead shield at the top. The 2D specifications are identical to the 3D specifications except that they ignore the grids, support plate, shield, and top and bottom reflectors, producing an axially uniform model. Instead, the reactivity effects of the axial nonuniformities, including finite height, are treated in terms of the measured axial buckling.[5]

Table I presents results from MCNP for both the 2D and 3D specifications. All the calculations were performed with 300 generations of 4,000 neutrons each, and the first 50 generations were excluded from the statistics. Consequently, all of the results are based on 1 million active histories. The calculations were performed with MCNP's continuous-energy ENDF/B-V and ENDF/B-VI cross-section libraries. The ENDF/B-VI results were obtained with libraries based on Release 2 (ENDF/B-VI.2), but additional calculations have shown that the changes to the ^{235}U cross sections introduced in ENDF/B-VI.3 would not produce statistically significant differences. The 3D results are taken from a previous benchmark study.[6]

As has been noted before,[6] the CSEWG specifications produce trends with both the pin-cell pitch and the presence of soluble boron. In particular, k_{eff} always is higher for the borated case than for the unborated case with the same pitch. In addition, k_{eff} increases with increasing pin-cell pitch for both borated and unborated cases. These trends are observable for both the 2D and 3D specifications and for both the ENDF/B-V and ENDF/B-VI libraries. Furthermore, the same trends are observed when specifications from a recent reevaluation[7] of these experiments are used.

The 2D specifications produce a bias of approximately 0.002 Δk relative to the 3D specifications. However, that bias is consistent from case to case, for both ENDF/B-V and ENDF/B-VI libraries. Consequently, it appears that the 2D specifications, possibly with a bias included, can be used as benchmarks with the same degree of confidence as the 3D specifications.

Although the current CSEWG specifications do not include them, pin power distributions were measured near the axial center of the active core.[1] It is suggested that the CSEWG benchmarks be extended to include these power distributions. The 2D specifications produce good agreement with those measurements for all six experiments. A summary of those results is presented in Table II. Standard deviations between measured and calculated pin powers range from approximately 0.05 for the central pin to nearly 0.01 for pins in octant-symmetric locations.

In conclusion, it has been shown that the proposed 2D benchmark specifications for PNL-30 through PNL-35 are consistent with the existing 3D specifications. Furthermore, the 2D specifications produce good agreement with measured pin power distributions.

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Table I

Reactivity Results for 2D and 3D PNL MOX Lattices

Case	Fuel Pins	Pitch (in.)	Soluble Boron (PPM)	Axial Buckling (m^{-2})	Benchmark k_{eff}	Library	k_{eff}, 2D	k_{eff}, 3D	Δk
PNL-30	469	0.700	2	9.091	1.0002	ENDF/B-V	1.0013 ± 0.0007	0.9979 ± 0.0008	0.0034 ± 0.0011
						ENDF/B-VI	0.9948 ± 0.0008	0.9917 ± 0.0007	0.0031 ± 0.0011
PNL-31	761	0.700	681	9.381	1.0001	ENDF/B-V	1.0051 ± 0.0008	1.0023 ± 0.0007	0.0028 ± 0.0011
						ENDF/B-VI	0.9990 ± 0.0007	0.9968 ± 0.0007	0.0022 ± 0.0010
PNL-32	195	0.870	1	9.322	1.0021	ENDF/B-V	1.0071 ± 0.0007	1.0049 ± 0.0007	0.0022 ± 0.0010
						ENDF/B-VI	0.9995 ± 0.0007	0.9970 ± 0.0007	0.0025 ± 0.0010
PNL-33	761	0.870	1090	9.487	1.0020	ENDF/B-V	1.0130 ± 0.0007	1.0105 ± 0.0007	0.0025 ± 0.0010
						ENDF/B-VI	1.0072 ± 0.0007	1.0042 ± 0.0007	0.0030 ± 0.0010
PNL-34	160	0.990	2	9.842	1.0033	ENDF/B-V	1.0111 ± 0.0007	1.0084 ± 0.0007	0.0027 ± 0.0010
						ENDF/B-VI	1.0036 ± 0.0007	1.0018 ± 0.0007	0.0018 ± 0.0010
PNL-35	689	0.990	767	9.480	1.0026	ENDF/B-V	1.0134 ± 0.0007	1.0118 ± 0.0008	0.0016 ± 0.0011
						ENDF/B-VI	1.0079 ± 0.0007	1.0061 ± 0.0007	0.0018 ± 0.0010

Table II

2D Results for Pin Power Distributions in PNL MOX Lattices

Case	Measured Pins	Library	RMS Difference	Pins with Differences	
				> 1σ	> 2σ
PNL-30	101	ENDF/B-V	0.030	73	20
		ENDF-B/VI	0.018	28	8
PNL-31	117	ENDF/B-V	0.025	52	8
		ENDF/B-VI	0.019	36	12
PNL-32	117	ENDF/B-V			
		ENDF/B-VI			
PNL-33	145	ENDF/B-V			
		ENDF/B-VI			
PNL-34	141	ENDF/B-V			
		ENDF/B-VI			
PNL-35	145	ENDF/B-V	0.023	32	16
		ENDF/B-VI	0.030	48	16