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Applicability of Existing Critical Experiments with Beryllium Reflectors to Code Validation for the NASA Fission Surface Power Reactor

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Abstract – *The National Aeronautics and Space Administration is pursuing the design of a fission power system for surface applications. The applicability of existing criticality safety benchmarks with beryllium reflectors was investigated. The similarity of the benchmarks to the current reactor design was assessed using the TSUNAMI-3D sequence in the SCALE5.1 code package. Based on the integral similarity parameters obtained from the analysis, several of the metal-fueled beryllium-reflected benchmarks, all with relative simple geometry, were found to be remarkably good analogues for the much more complicated UO_2-fueled NaK-cooled reactor design.*

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) is pursuing the design of a fission surface power (FSP) system using a nuclear reactor as the heat source. A primary concern in the design of the FSP system is limiting the overall programmatic cost. One avenue of cost savings that is being considered is limiting the scale of the pre-launch ground testing of the FSP system. This includes taking the maximum possible advantage of the existing inventory of critical experiments in [NEA 2008].

The purpose of the work documented here is to determine the applicability of existing beryllium-reflected critical experiments to the validation of the neutronics codes used to design the FSP reactor. The primary advantage of using existing benchmarks is, of course, that the benchmarks are available at no cost to the FSP program. Other advantages are: 1) the benchmark experiment reports have been subjected to a rigorous peer review process, 2) the benchmarks are, in general, simple configurations that are readily modeled, and 3) comparisons between the benchmarks may suggest ways to improve the validity and/or simplify the design of any new benchmarks that might be required in support of the FSP program.

The primary tool for judging the applicability of benchmarks to a particular application is the TSUNAMI sequence of codes that are included in the SCALE5.1 package.[1] The use of the TSUNAMI sequence and the results obtained are reported in the following sections.

II. FSP Reactor Design

II.A. Baseline Design

In a reference reactor design by Los Alamos National Laboratory (LANL) for the Affordable Fission Surface Power System,[2] the reactor is fueled with 85 fuel pins containing highly-enriched UO2 with 1 molar percent gadolinia and is cooled by NaK. The reactor has a thick beryllium reflector that includes rotating control drums.

Figure 1 shows a section through the midplane of an MCNP[3] model of an evolution of the 85-pin design. Characteristics of the reactor are listed in Table II. The 163 fuel pins in the reactor are arranged in a triangular-pitched array in the shape of a hexagon with one element in each corner removed. Like the earlier 85-pin design, the fuel is highly-enriched UO2 but in this case does not include the gadolinia spectral poison. The fuel pins are clad in 316 stainless steel and cooled by NaK. The cross section of the 316 stainless steel reactor vessel is a truncated hexagon. The reactor vessel is surrounded by the beryllium reflector. The reflector is divided into six segments and has six rotating control drums with the absorber sections shown rotated away from the core. The reflector is contained, inside and out, by a 316 stainless steel liner. Each control drum and control drum cavity is lined with 316 stainless steel. The reflector includes six 316 stainless steel lined cavities for the coolant down-comers. The reactor is surrounded by an enriched B4C shield and is buried in lunar regolith.

TABLE I

Characteristics of the FSP Reactor Design

Number of Fuel Pins	163
Fuel	UO_2
Fuel Enrichment	93 atom %
Cladding Material	316 Stainless Steel
Reactor Vessel Material	316 Stainless Steel
Coolant	NaK
Radial Reflector	Beryllium
Fuel Pin Axial Reflector	Beryllium Oxide
Radial Reflector Structure	316 Stainless Steel

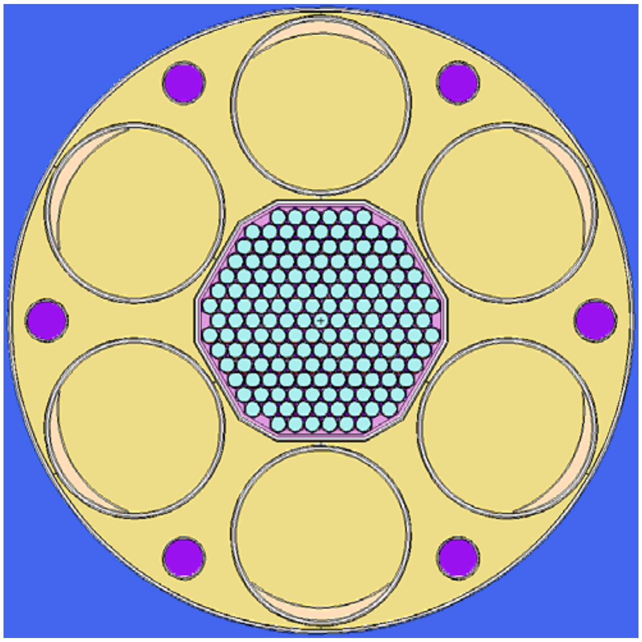

Fig. 1. Horizontal section through the midplane of the FSP reactor MCNP model.

II.B. SCALE5.1 Model

A SCALE5.1 (KENOV.a) model was developed from the MCNP model so that the reactor could be analyzed with the sensitivity/uncertainty code TSUNAMI-3D which is a part of the SCALE5.1 package. The geometry of the fuel pins was replicated with high fidelity. However, the geometry package in KENOV.a is more limited than that in MCNP so the outer boundary of the core vessel could not be modeled exactly in the KENOV.a model. Two goals of the modeling effort were 1) to place the beryllium reflector as close to the outside of the fuel pin array as possible and 2) to minimize the volume of coolant outside the fuel pin array. To achieve the first goal, the core vessel was modeled as a cylinder that was nearly tangent to the outside of the outermost fuel pins in the array (the two pins that flank each of the six corners of the array).

The second goal was achieved by modeling the cylinder that forms the outside of the vessel as filled with the vessel material with the geometric regions that make up the fuel array inserted as “holes” in the vessel material. A section through the reactor at the midplane is shown in Figure 2.

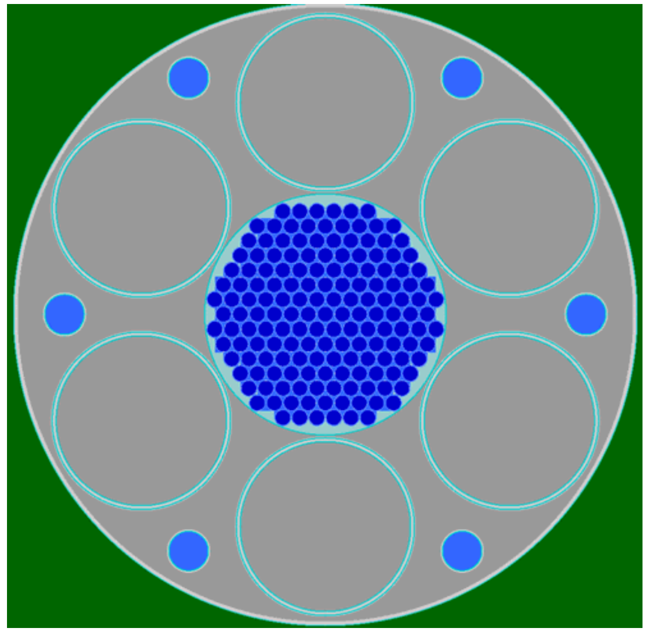

Fig. 2. Section through the midplane of the SCALE5.1 model of the FSP reactor.

III. SYSTEM SENSITIVITIES

The TSUNAMI-3D sequence of the SCALE5.1 package uses perturbation theory to obtain the sensitivity of the k_{eff} of a multiplying system to the myriad of parameters that determine the behavior of keff of the system. The sensitivity S of the system to a given parameter is relative change in k_{eff} that is produced by a small change in the parameter..

TSUNAMI-3D was applied to the SCALE5.1 model of the reactor system. A wide range of sensitivities are available in the output of the code. A sampling is given here. Table II lists the sensitivity for each material in the model with the materials listed from highest to lowest absolute sensitivity. The keff of the model is most sensitive to the UO2 fuel and the beryllium reflector. The sensitivity to the BeO axial reflectors in the fuel pins is nearly a factor of 20 down.

The sensitivity to each of the four nuclides included in the model fuel is shown in Table III. The primary sensitivity is to the ^{235}U with the sensitivity to the ^{16}O more than an order of magnitude lower.

Table II

Material Sensitivities in the Model of the Reactor

Material	Sensitivity	Uncertainty
UO_2 Fuel	0.461	0.06%
Radial Reflector	0.256	0.32%
BeO Axial Reflector	0.0137	0.49%
Cladding (SS316)	0.0086	0.42%
Core Vessel	-0.0035	1.73%
Reflector Drum Structure (SS316)	-0.00121	2.68%
Shield Liner (SS316)	0.00101	0.12%
Radial Reflector Liner (SS316)	-0.00070	2.86%
B_4C Shield	0.00068	1.68%
NaK Coolant (in Core Vessel)	0.00045	2.79%
NaK Coolant (Downcomers)	0.00040	0.86%
NaK Coolant (Plena)	0.00026	0.47%
Plenum Structure (SS316)	0.000177	0.55%
Burial Material (Lunar Regolith)	0.000010	0.91%

TABLE III

Fuel Sensitivities Listed by Nuclide

Nuclide	Sensitivity	Uncertainty
^{235}U	0.421	0.04%
^{16}O	0.0351	0.59%
^{238}U	0.0028	0.30%
^{234}U	0.0012	0.18%

The sensitivities for each of the 32 nuclides present in the model of the FSP reactor are shown in Table IV.

TABLE IV

Nuclide Sensitivities in the Model of the FSP Reactor

Nuclide	Sensitivity	Nuclide	Sensitivity
^{235}U	0.421	^{57}Fe	0.00044
^{9}Be	0.263	^{62}Ni	-0.00040
^{16}O	0.041	K	0.00038
^{52}Cr	0.0057	^{54}Cr	0.00018
^{56}Fe	0.0039	^{11}B	0.00016
^{238}U	0.0028	^{58}Fe	-5.8E-05
^{58}Ni	-0.0021	^{64}Ni	4.4E-05
^{53}Cr	-0.0020	^{61}Ni	2.9E-05
^{10}B	-0.0017	Si	1.9E-06
^{234}U	0.0012	^{27}Al	1.0E-06
^{50}Cr	-0.00078	Ca	8.5E-07
C	0.00077	Mg	3.2E-07
^{23}Na	0.00073	Ti	3.5E-08
^{54}Fe	0.00068	^{55}Mn	1.1E-08
^{60}Ni	0.00060	^{31}P	4.4E-09
Mo	-0.00051	S	4.3E-09

IV. BERYLLIUM-REFLECTED BENCHMARKS

The FSP reactor is most sensitive to the ^{235}U in the fuel and the beryllium in the radial reflector. For this reason, a set of benchmarks with beryllium reflectors from the International Handbook of Evaluated Criticality Safety Benchmark Evaluations[4] (IHECSBE) was selected for investigation here. The benchmarks were chosen for: 1) a significant presence of beryllium in the configuration and 2) the simplicity of the benchmark configuration. The selected benchmarks are listed in Table V.

TABLE V

Benchmarks with Beryllium Reflectors

Designator*	Cases	Configuration
HCI-03	3	UH_3 Cylinders, Be inner reflector, D38 or void outer reflector
HMF-16	1	HEU cylinder, Be reflector
HMF-17	1	HEU cylinder, Be moderator and reflector
HMF-41	2	HEU sphere, Be reflector
HMF-58	5	HEU spheres, Be reflector
HMF-66	9	HEU spherical shell, Be moderator and reflector
HMF-84	4	HEU cylinder, Be reflector
MMF-07	23	Pu sphere, HEU spherical shell, Be reflector

*The designator used here is an abbreviation of the designator from the IHECSBE. For the first letter, H=HEU and M=MIX. For the second letter, C=COMP and M=MET. For the third letter, I=INTER and F=FAST.

The benchmark configurations were modeled with MCNP5 version 1.50 and analyzed using the cross section sets included with the code that were based on ENDF/B-VI.8 and ENDF/B-VII.0. Comparisons of a sampling of the results are shown in Figures 3 and 4. The data are plotted as the bias – k_{eff}(calculated) minus k_{eff}(benchmark) – versus the reflector worth defined by Eq. 1.

$$\frac{\Delta k}{k} = \frac{k_{with\ reflector} - k_{without\ reflector}}{k_{with\ reflector}} \tag{1}$$

This sample of the results indicates that the bias obtained for the ENDF/B-VI.8 cross sections has a dependence on the reflector worth. The bias obtained with the ENDF/B-VII.0 cross sections show a smaller, but still possibly significant, dependence on the reflector worth. Similar tendencies are visible in the results for several of the other benchmark configurations.

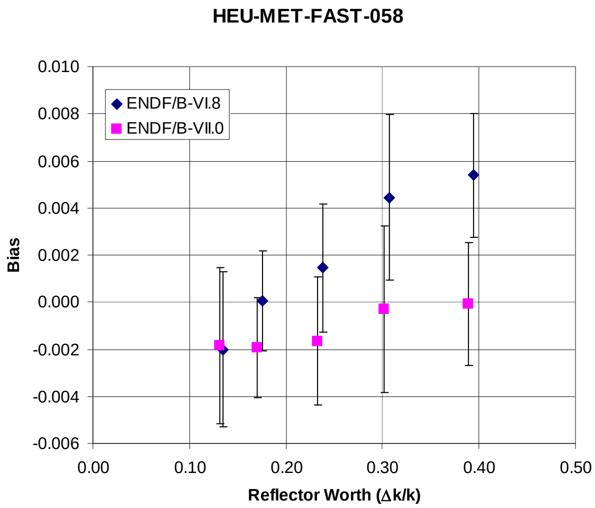

Fig. 3. Bias as a function of reflector worth for HEU-MET-FAST-058 benchmark configurations.

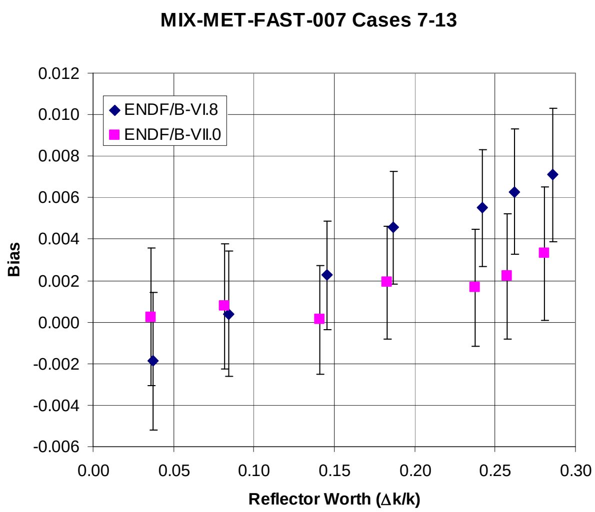

Fig. 4. Bias as a function of reflector worth for MIX-MET-FAST-007 benchmark configurations

The uncertainties shown in the figures are the combination of the uncertainty in the Monte Carlo results and the reported uncertainties in the benchmark k_{eff}. The benchmark uncertainties represent the uncertainties in the experiments for comparison with any other benchmark experiment. These values certainly bound the uncertainties when comparing configurations in the same benchmark series. When comparing configurations in a benchmark series, it should be possible to reduce the configuration-to-configuration uncertainty because many of the uncertainty components will be correlated. This effect was not investigated as part of this work.

V. COMPARISONS BETWEEN THE FSP AND BENCHMARK MODELS

The purpose of developing the KENOV.a model of the FSP reactor was to allow the comparison of the reactor with existing critical benchmarks through the use of the sensitivity/uncertainty module TSUNAMI-3D in SCALE5.1. Having TSUNAMI-3D results for the reactor and the benchmarks allows comparisons through integral parameters using the SCALE5.1 module TSUNAMI-IP. For details of the methods, refer to the TSUNAMI-IP documentation in the SCALE5.1 manual.[1]

The results for four integral parameters are shown in Figures 5 and 6. The integral parameters shown are c_k, E_{sum}, g (Be Scatter) and g(^{235}U total). The first, c_k, assesses the similarity of two systems based on the sensitivities of the systems to the myriad of reactions occurring in the models and the cross section covariances within and among the reactions. Guidance from the SCALE5.1 developers is that benchmarks giving values of c_k above 0.9 are applicable for method validation for the design system. Benchmarks that give values between 0.8 and 0.9 are of some, but perhaps marginal, value.

The integral index E_{sum} is similar to c_k except that the similarity is assessed based only of the sensitivities of the systems. E_{sum} does not depend on the cross section covariances. The two g indices assess the similarity of the systems based of the energy-dependent sensitivities for specific reactions. The g value indicates the energy dependent coverage of the design system by the benchmark for the particular reaction.

All of the integral indices are normalized so that perfect similarity or coverage is indicated by the maximum value of 1. Reduced perfection is indicated by lower values.

Table VI summarizes the integral index results for the 48 benchmark configurations considered.

TABLE VI

Summary of the Integral Index Results

Index	**Range**		
	>0.8	**>0.9**	**>0.95**
c_k	22	19	17
E_{sum}	22	21	11
g (Be Scatter)	24	19	4
g (^{235}U Total)	25	22	6

A summary of the high values of the integral index values is as follows:

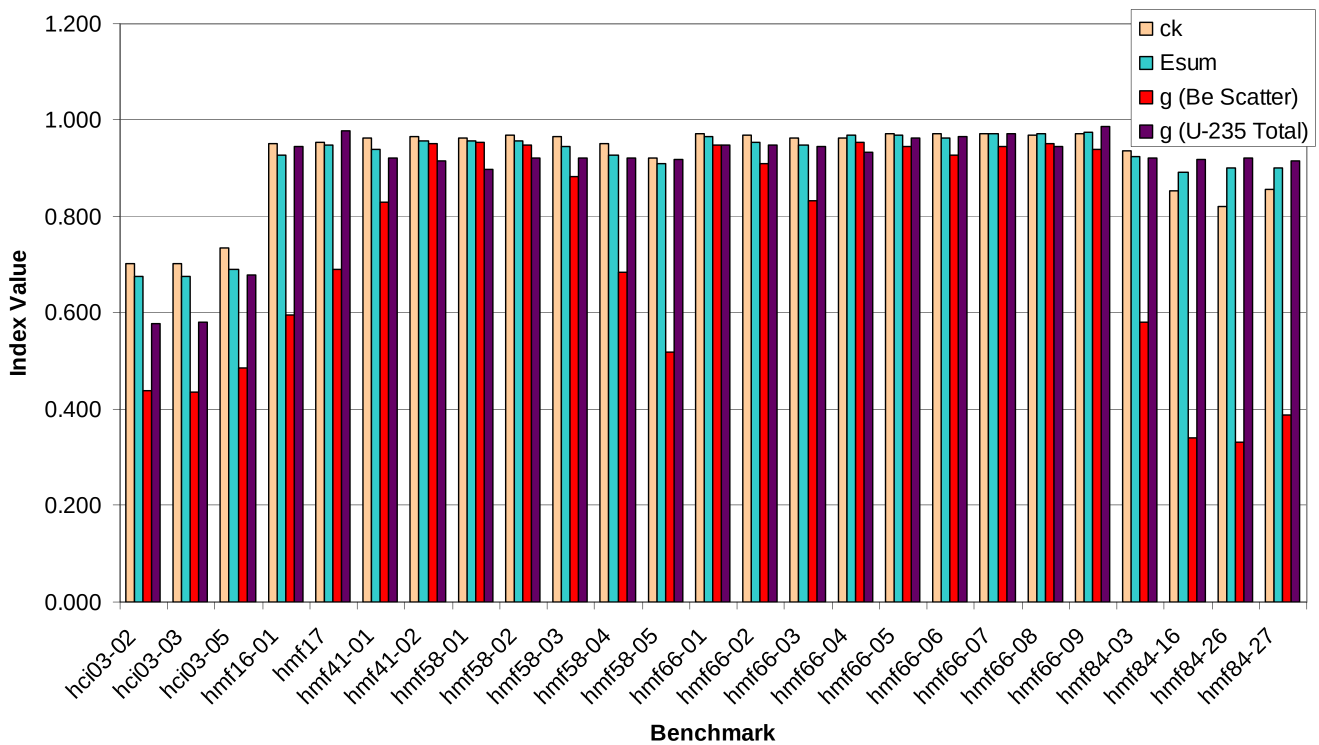

Fig. 5. Integral index results for the HEU benchmarks.

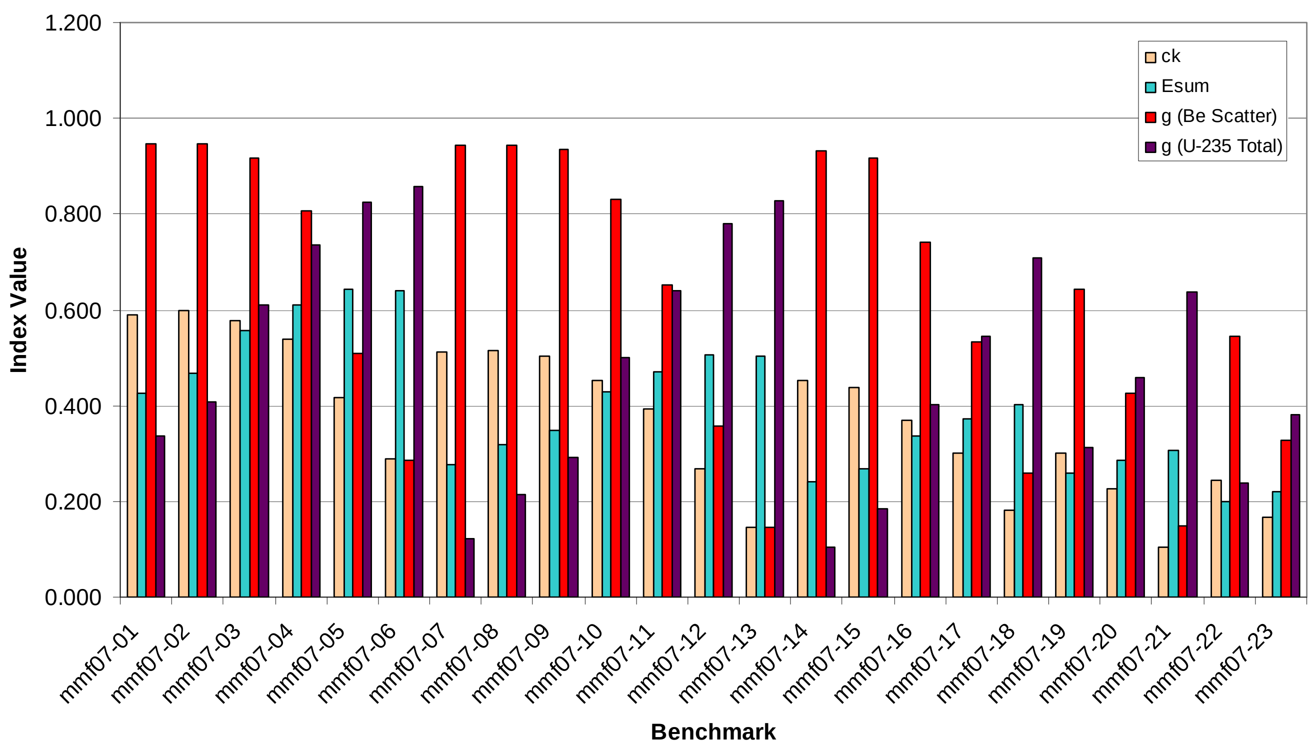

Fig. 6. Integral index results for the MMF benchmarks

c_k: The experiments with at least one configuration that gave a c_k value greater than 0.95 were HMF16 (1), HMF17 (1), HMF41 (2), HMF58 (4), and HMF66 (9). All configurations of HMF16, HMF17, HMF41, HMF58, and HMF66 and one configuration of HMF84 gave c_k values greater than 0.9.

E_{sum}: HMF41, HMF58, and HMF66 had configurations that gave E_{sum} values greater than 0.95. All configurations of these benchmarks as well as HMF16 and HMF17 as well as three configurations of HMF84 gave E_{sum} values greater than 0.9.

g (Be Scatter): HMF41, HMF58, and HMF66 had at least one configuration that gave values greater than 0.95. Eleven configurations of these benchmarks and eight configurations of MMF07 gave values greater than 0.9.

g (^{235}U Total): Configurations from HMF17 and HMF66 gave values greater than 0.95. All of the configurations of the HMF benchmarks gave values greater than 0.9.

Under the guidance given by the TSUNAMI-3D developers, the following benchmarks will be of value for the current reactor design: HMF16, HMF17, HMF41, HMF58, and HMF66. Each of these benchmarks has one or more configurations that had c_k values above 0.9.

The results for beryllium scattering indicate that, in addition to the benchmarks noted above, several of the MMF07 configurations could have value in testing the treatment of beryllium in the analytical methods.

The g values for the ^{235}U total cross section were above 0.9 for all of the HMF benchmark configurations indicating that these configurations provide good tests of the ^{235}U cross section. The g values for the HCI and MMF benchmarks were all less than 0.8.

The set of benchmark experiments investigated here was chosen primarily for the presence of the beryllium reflector in the hope that good coverage of the beryllium scattering in the reflector could be obtained. As it turns out, some of these experiments – HMF41, HMF58, and HMF66 in particular – are remarkably good analogues to the current reactor design as evidenced by the number of c_k values above 0.95. This is despite the fact that the benchmarks were simple arrangements of HEU metal and beryllium shells and spheres while the reactor design has NaK-cooled pin-type HEU oxide fuel in a triangular-pitched array with an annular beryllium reflector.

SUMMARY

A SCALE5.1 model of the current design of the FSP reactor was constructed from information provided by LANL on the current reactor design. The model was used in the TSUNAMI-3D sequence in SCALE5.1 to obtain the sensitivities of the reactor design to the materials in the reactor. The highest sensitivities in the SCALE5.1 model were to the highly-enriched uranium dioxide fuel and to the beryllium reflector. The sensitivity to the BeO axial reflector was in third place but more than an order of magnitude down from the first two. The nuclides with the highest sensitivities were the ^{235}U in the fuel and the ^{9}Be in the reflector.

Knowing the primary sensitivities of the reactor, a set of benchmarks was chosen for analysis. The chief characteristic guiding the selection was the presence of a beryllium metal reflector in the benchmarks. The benchmarks were analyzed with MCNP5.1.50 using ENDF/B-VI.8 and ENDF/B-VII.0 cross sections. When the bias was examined as a function of the worth of the beryllium reflector in the benchmarks, the bias for the ENDF/B-VI cross sections appeared to be affected by the reflector worth with higher worth values giving higher biases. When ENDF/B-VII cross sections were used, this dependence was much smaller. The conclusion is that the ENDF/B-VII cross sections perform better for beryllium-reflected systems.

A sensitivity analysis was done for each of the selected benchmarks so that these sensitivities could be compared with those of the reactor model. It was found that some of the selected benchmarks were remarkably good analogues, in terms of sensitivities, to the reactor system. This was evidenced by the high values of the global integral parameter c_k obtained for some of the benchmarks and despite the significant differences in the geometry of the reactor and benchmarks.

ACKNOWLEDGMENTS

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