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Validation of FSP Reactor Design with Sensitivity Studies of Beryllium-Reflected Critical Assemblies

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Abstract. The baseline design for space nuclear power is a fission surface power (FSP) system: sodium-potassium (NaK) cooled, fast spectrum reactor with highly-enriched-uranium (HEU)-O_2 fuel, stainless steel (SS) cladding, and beryllium reflectors with B_4C control drums. Previous studies were performed to evaluate modeling capabilities and quantify uncertainties and biases associated with analysis methods and nuclear data. Comparison of Zero Power Plutonium Reactor (ZPPR)-20 benchmark experiments with the FSP design indicated that further reduction of the total design model uncertainty requires the reduction in uncertainties pertaining to beryllium and uranium cross-section data. Further comparison with three beryllium-reflected HEU-metal benchmark experiments performed at the Oak Ridge Critical Experiments Facility (ORCEF) concluded the requirement that experimental validation data have similar cross section sensitivities to those found in the FSP design. A series of critical experiments was performed at ORCEF in the 1960s to support the Medium Power Reactor Experiment (MPRE) space reactor design. The small, compact critical assembly (SCCA) experiments were graphite- or beryllium-reflected assemblies of SS-clad, HEU-O_2 fuel on a vertical lift machine. All five configurations were evaluated as benchmarks. Two of the five configurations were beryllium reflected, and further evaluated using the sensitivity and uncertainty analysis capabilities of SCALE 6.1. Validation of the example FSP design model was successful in reducing the primary uncertainty constituent, the Be(n,n) reaction, from 0.27 %δk/k to <0.0004 %δk/k. Further assessment of additional reactor physics measurements performed on the SCCA experiments may serve to further validate FSP design and operation.

Keywords: benchmark, beryllium, fission surface power, HEU, TSUNAMI, SCALE.

INTRODUCTION

An initial assessment was performed to evaluate modeling capabilities and quantify biases and uncertainties associated with methods and data utilized in designing a space nuclear reactor system. The evaluated baseline fission surface power (FSP) system was a sodium-potassium (NaK) cooled, fast spectrum reactor with highly-enriched-uranium (HEU)-O_2 fuel, stainless steel (SS) cladding, and beryllium reflectors with B_4C control drums. The conclusion of this initial study was that current capabilities could preclude the necessity of a cold critical test of the FSP; however, additional testing would aid in the reduction of uncertainties in the beryllium and uranium cross-section data, thus reducing the overall uncertainty in the computational design models.[1]

Four important critical experiments from the Zero Power Plutonium Reactor (ZPPR)-20 were initially selected for comparison with the FSP model. These experiments represented mockups of a small space reactor.[2] These experiments were previously evaluated as benchmarks and made available through the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook).[3] Use of the four ZPPR experiments as a validation set in the previous study indicated that the dominant uncertainty in computation of the FSP eigenvalue due to cross section covariance data was the Be(n,n) reaction.[1] A significant amount of work was previously performed on the qualification of physics tools for the design of the Jupiter Icy Moons Orbiter (JIMO) reactor, in which intermediate and thermal spectrum experiments were considered.[4,5]

A more recent study included three additional critical experiments identified as fast-fission configurations of HEU metal reflected by beryllium metal. These experiments had been evaluated for inclusion in the ICSBEP Handbook and further evaluated using the sensitivity and uncertainty analysis capabilities of SCALE 6.[6] Unfortunately, these experiments were not sufficiently sensitive to the beryllium cross sections, due to small reflector worth, to reduce the overall nuclear data uncertainty in the FSP design.[7]

Critical experiments very similar to the FSP design were identified[8] and evaluated as benchmark experiments. Two of the five configurations were beryllium reflected, and further evaluated using SCALE 6.1, similar to the sensitivity and uncertainty analysis studies performed previously.

SCCA BERYLLIUM-REFLECTED BENCHMARK EXPERIMENTS

A series of critical experiments was performed at the Oak Ridge Critical Experiments Facility (ORCEF) in the early 1960s to support the Medium Power Reactor Experiment (MPRE) space reactor design.[9] These small, compact critical assembly (SCCA) experiments were graphite- or beryllium-reflected assemblies of SS-clad, HEU-O_2 fuel on a vertical lift machine. The delayed critical experiments were a mockup of a small, potassium-cooled space power reactor for validation of reactor calculations and reactor physics methods. All five configurations were evaluated as benchmarks for inclusion in the ICSBEP Handbook and the *International Handbook of Evaluated Reactor Physics Benchmark Experiments* (IRPhEP Handbook).[10]

The core of the experiments contained either 252 or 253 SS-clad UO_2 fuel rods enriched to 93.15 wt.% ^{235}U. The first part of the three-part experimental series included two graphite-reflected tightly-packed arrays (1.27-cm triangular pitch).[11] The second part of the series consisted of a single graphite-reflected critical assembly with a 1.506-cm triangular-pitch array.[12] The third set of experiments consisted of two beryllium-reflected arrays, one with a triangular pitch of 1.506 cm, and the other comprised of multiple seven-rod fuel clusters.[13] Additional measurements such as fission-rate distributions, cadmium ratio distributions, and material worths were also performed on the various assemblies.

Summary of Benchmark Evaluation

Comprehensive evaluation of the two Be-reflected SCCA critical experiments are available in the ICSBEP Handbook in the report identified as HEU-COMP-FAST-004.[3] It should be noted that there were precise measurements of the dimensions and physical properties of the materials used in these experiments, such that the uncertainties in many of the experimental components had a negligible effect and the uncertainty is the reactivity worth measurement was of merit when computing the total uncertainty in the experiment. The majority of the uncertainty in these two experiments comes from uncertainties in the dimensions, mass, and impurity content of the radial beryllium reflectors, indicating a high sensitivity in the worth of the reflector. There is a high correlation between the two beryllium-reflected experiments, as the only difference between the two configurations is the arrangement of the fuel rods, as shown in Figure 1. Comprehensive discussion of the uncertainties and biases evaluated in development of the benchmark models is provided in the benchmark report.

A summary of the calculated results for these two benchmark experiments, compared against the benchmark eigenvalues, is shown in Table 1. Both detailed and simple models were developed for the analysis of these two configurations. Calculations were performed using Monte Carlo N-Particle (MCNP) version 5-1.51[14] with ENDF/B-VII.0 neutron cross section data.[15] Additional calculations using KENO-VI[16] and ENDF/B-VII.0 were also performed using the simple benchmark models, in preparation for sensitivity analysis calculations. Results from both Monte Carlo codes underpredict the benchmark eigenvalues using the same continuous-energy cross section library.

The additional reactor physics experiments, such as fission-rate distributions, cadmium ratio distributions, and material worths, were not utilized in the current study. Their benchmark evaluation are to be documented elsewhere (IRPhEP Handbook report SCCA-SPACE-EXP-003)[10] for availability in future FSP design studies.

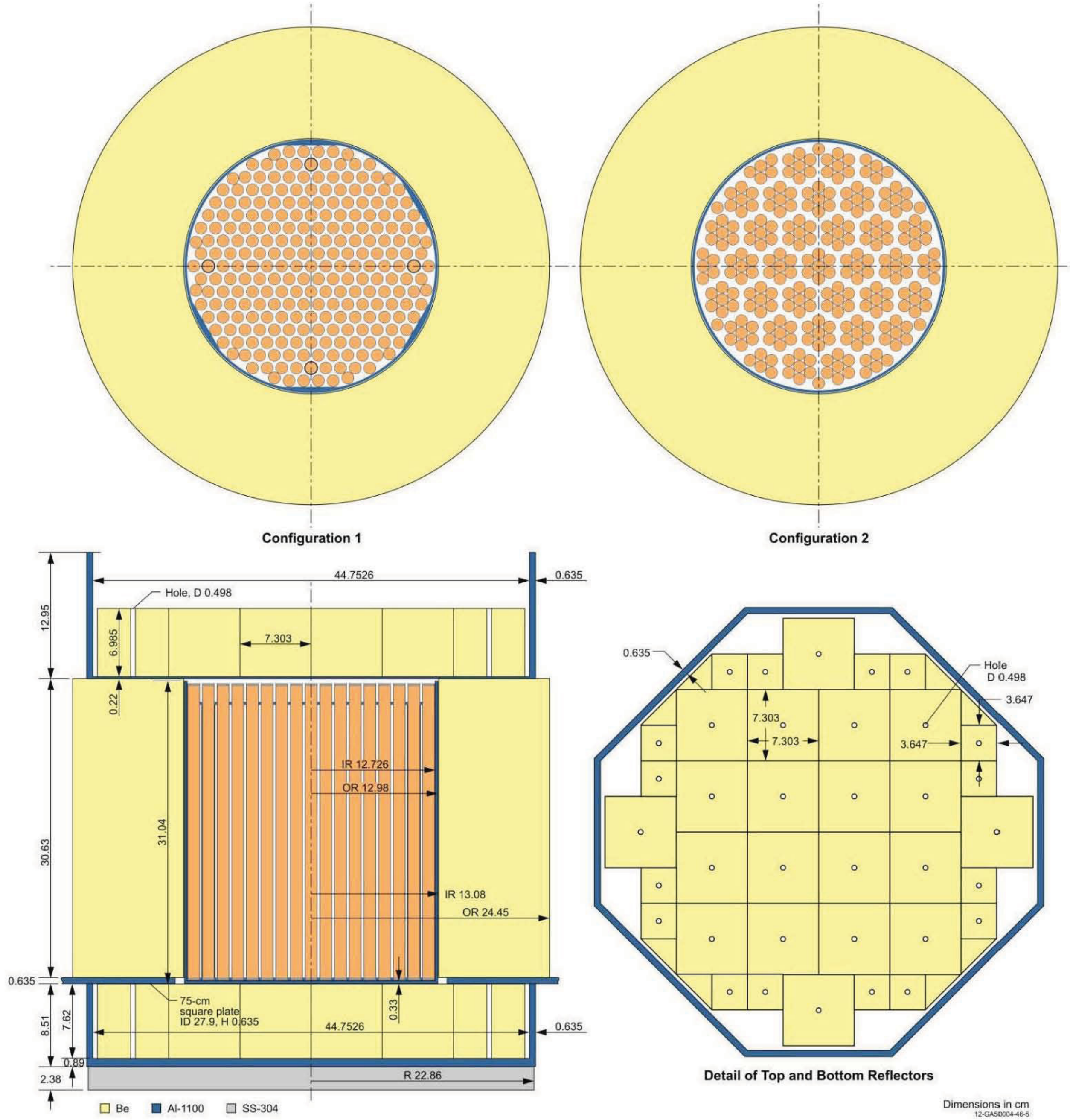

FIGURE 1. Detailed Benchmark Configurations of the Beryllium-Reflected SCCA Experiments.

TABLE 1. Summary of Calculations and Benchmark Analysis of Be-Reflected HEU Experiments.

Benchmark		Analysis	Neutron Cross	Calculated			Benchmark Experiment			$\frac{C-E}{E}(\%)$
Configuration	**Model**	**Code**	**Section Library**	k_{eff}	±	1σ	k_{eff}	±	1σ	
SCCA Be-1	Detailed	MCNP5	ENDF/B-VII.0	0.99435	±	0.00006	1.0003	±	0.0008	-0.60
	Simple	MCNP5	ENDF/B-VII.0	0.99293	±	0.00006	0.9989	±	0.0008	-0.60
		KENO-VI	ENDF/B-VII.0	0.99211	±	0.00009				-0.68
SCCA Be-2	Detailed	MCNP5	ENDF/B-VII.0	0.99615	±	0.00006	1.0011	±	0.0008	-0.50
	Simple	MCNP5	ENDF/B-VII.0	0.99474	±	0.00006	0.9998	±	0.0008	-0.50
		KENO-VI	ENDF/B-VII.0	0.99422	±	0.00009				-0.56

SENSITIVITY ANALYSIS OF CROSS-SECTION COVARIANCE DATA

Oak Ridge National Laboratory developed TSUNAMI-3D (Tools for Sensitivity and Uncertainty Analysis Methodology Implementation in Three Dimensions)[17] as part of their SCALE package to automate the analysis procedure of uncertainties and sensitivities in cross section data for a given model. The core model of an example FSP model was investigated previously.[1] The KENO models of the two Be-reflected SCCA benchmarks were also analyzed using the TSUNAMI-3D code.

A comprehensive sensitivity study of each model determined the relative standard deviation in k_{eff} due to cross-sections in the neutron library. A summary of the uncertainty in k_{eff} and major sources of uncertainty is provided for each of the Be-reflected benchmarks in Table 2. Sensitivity data for the ZPPR-20 and FSP models were recalculated using SCALE 6.1 and are also provided in Table 2 for comparison. Only uncertainty components greater than 0.1 $\%\Delta k/k_{eff}$ are included in this report. As cross-section errors, as bounded by their uncertainties, are the most significant sources of computational bias, the data shown in Table 2 represent a ranked list of the most likely bias sources. The component uncertainty from the (n,γ) reactions in ^{235}U are greater than the uncertainty in the (n,f) reactions. Although the FSP is more sensitive to the (n,f) reaction, the uncertainty of the (n,γ) cross section far exceeds that of (n,f), especially at fast energies, leading to a greater uncertainty in k_{eff} due to (n,γ) than for (n,f). The contribution to the total covariance uncertainty due to beryllium reactions is similar between the Be-reflected benchmark experiments and the FSP model. Where cross-section uncertainties are not available, a uniform uncertainty of 5% was used. Note that some uncertainties are represented as a negative $\Delta k/k$. These values represent anticorrelations between two reactions that are present in the covariance data. As some component of the uncertainty is shared between the two reactions, the presence of both sources of uncertainty together represent a net *decrease* in the system uncertainty relative to what would be observed if the system were sensitive to one reaction but not the other.

Correlation Analysis and Data Adjustment

The sensitivity data generated by the TSUNAMI-3D analyses for the various experiment models and the core model can be compared using TSUNAMI-IP (Tools for Sensitivity and Uncertainty Analysis Methodology Implementation – Indices and Parameters).[17] The TSUNAMI-IP code uses the sensitivity data generated by the TSUNAMI-3D analysis with the cross-section covariance data to compute various relational parameters and indices. The parameters can be used to determine the degree of similarity between two systems. Where two systems show a high degree of similarity in terms of uncertainties due to cross-section-covariance data, the systems are expected to have similar computational biases.

The primary global integral indices generated in TSUNAMI-IP include the correlation coefficient index, c_k, which measures the similarity of two systems in terms of related uncertainty.[17] The integral index c_k can be used as a trending parameter in criticality safety analysis validation studies to determine computational uncertainties and biases.[18] Utility of this application in the analysis of space power reactor design has been previously discussed and demonstrated.[1]

The FSP model was compared against the two SCCA beryllium-reflected benchmark models using SCALE 6.1 ENDF/B-VII cross-section covariance data. A summary of the correlation coefficient and cross-section uncertainties for both libraries is provided in Table 3. General guidance is that c_k values greater than 0.9 demonstrate similarity between two experiments or models, and c_k values between 0.8 and 0.9 demonstrate moderate similarity. Values closer to zero indicate systems that are totally dissimilar. Both SCCA beryllium-reflected benchmark models have c_k values greater than 0.99 and thus exhibit high similarity with the FSP model; these c_k values are greater than those found for the ZPPR benchmark series used in previous assessments (also shown in Table 3).

TABLE 2. Cross-Section Covariance Uncertainty in TSUNAMI-3D Analysis.

Model	Total Uncertainty (%Δk/k_{eff})	Major Components	Component Uncertainty (%Δk/k_{eff})
SCCA Be-1	2.042	^{235}U(n,γ)	1.948
		Be(n,n)	0.507
		^{235}U(n,n')	0.248
		^{235}U(n,f)	0.186
		^{235}U(ν-bar)	0.133
		^{235}U(n,n) to ^{235}U(n,n')	-0.130
		Be(n,2n)	0.129
		^{235}U(n,n) to ^{235}U(n,γ)	-0.127
SCCA Be-2	2.031	^{235}U(n,γ)	1.939
		Be(n,n)	0.498
		^{235}U(n,n')	0.257
		^{235}U(n,f)	0.187
		^{235}U(ν-bar)	0.133
		^{235}U(n,n) to ^{235}U(n,n')	-0.129
		Be(n,2n)	0.127
		^{235}U(n,n) to ^{235}U(n,γ)	-0.124
ZPPR-20C(105)	2.025	^{235}U(n,γ)	1.947
		^{235}U(n,n) to ^{235}U(n,γ)	0.270
		^{235}U(n,f)	0.230
		^{187}Re(n,γ)	0.191
		^{93}Nb(n,γ)	0.165
		^{93}Nb(n,n)	0.161
		^{235}U(n,n')	0.161
		^{185}Re(n,γ)	0.146
		^{235}U(ν-bar)	0.143
		^{235}U(n,n) to ^{235}U(n,n')	-0.131
		^{16}O(n,n)	0.113
ZPPR-20D(129)	1.613	^{235}U(n,γ)	1.532
		^{187}Re(n,γ)	0.248
		^{185}Re(n,γ)	0.213
		^{93}Nb(n,γ)	0.213
		^{235}U(n,f)	0.181
		^{235}U(n,n) to ^{235}U(n,γ)	0.141
		^{235}U(ν-bar)	0.136
ZPPR-20D(136)	1.516	^{235}U(n,γ)	1.437
		^{187}Re(n,γ)	0.232
		^{93}Nb(n,γ)	0.216
		^{185}Re(n,γ)	0.201
		^{235}U(n,f)	0.185
		^{235}U(ν-bar)	0.135
		^{235}U(n,n) to ^{235}U(n,γ)	0.120
ZPPR-20E(160)	1.424	^{235}U(n,γ)	1.356
		^{235}U(n,f)	0.246
		^{187}Re(n,γ)	0.142
		^{235}U(ν-bar)	0.141
		^{93}Nb(n,γ)	0.121
		^{235}U(n,n) to ^{235}U(n,γ)	0.119
		^{185}Re(n,γ)	0.117
FSP	2.010	^{235}U(n,γ)	1.950
		Be(n,n)	0.364
		^{235}U(n,n')	0.224
		^{235}U(n,f)	0.188
		^{235}U(ν-bar)	0.134
		^{235}U(n,n) to ^{235}U(n,n')	-0.125

TABLE 3. Correlation Coefficient and Cross-Section Uncertainties Comparison.

Model	C_k	Cross-Section Uncertainty (%)
SCCA Be-1	0.9967	2.042
SCCA Be-2	0.9969	2.031
ZPPR-20C(105)	0.9733	2.025
ZPPR-20D(129)	0.9467	1.613
ZPPR-20D(136)	0.9421	1.516
ZPPR-20E(160)	0.9605	1.424

The reassessment of uncertainty in the FSP model using the four ZPPR benchmarks yielded an uncertainty of 2.011% δk/k. TSUNAMI-IP was then used to develop a penalty assessment for the model, which provides additional margins of uncertainty where sufficient experimental information is unavailable. This additional uncertainty component can be included with the calculated k_{eff} of the system to provide an added measure of safety where validation coverage might be lacking. An analysis of the nuclides that make important contributions to this penalty can also help to identify what benchmark problems could be added to the analysis to potentially reduce the uncertainty. This initial penalty was calculated to be 0.293% δk/k. Of this, 0.273% δk/k resulted from the Be(n,n) reaction, indicating that this reaction was not covered sufficiently by the four ZPPR benchmarks.

Since beryllium was not sufficiently assessed by the initial calculations, it was determined that adding the two SCCA beryllium-reflected benchmark experiments would potentially reduce the overall uncertainty of the FSP model. It was discovered that these benchmarks also do sufficiently cover the Be(n,n) reaction. This is illustrated in Figure 2, which plots the sensitivity of the FSP model and the two SCCA beryllium-reflected benchmark models to the Be(n,n) reactions. Using all seven benchmarks, overall uncertainty of the FSP model was calculated to be 2.011%, with the penalty reduced to 0.021% δk/k with the dominant portion of 0.015% δk/k contributed from the ^{56}Fe(n,n) reaction. The contribution from the Be(n,n) reaction was reduced to 0.0004% δk/k. Utility of only the SCCA beryllium-reflected benchmark models without ZPPR data would reduce the penalty to 0.108% δk/k. Further reduction of the small penalty would require sensitivity data from similar experiments more sensitive to the ^{56}Fe(n,n) reaction at fission neutron energies (see Figure 3).

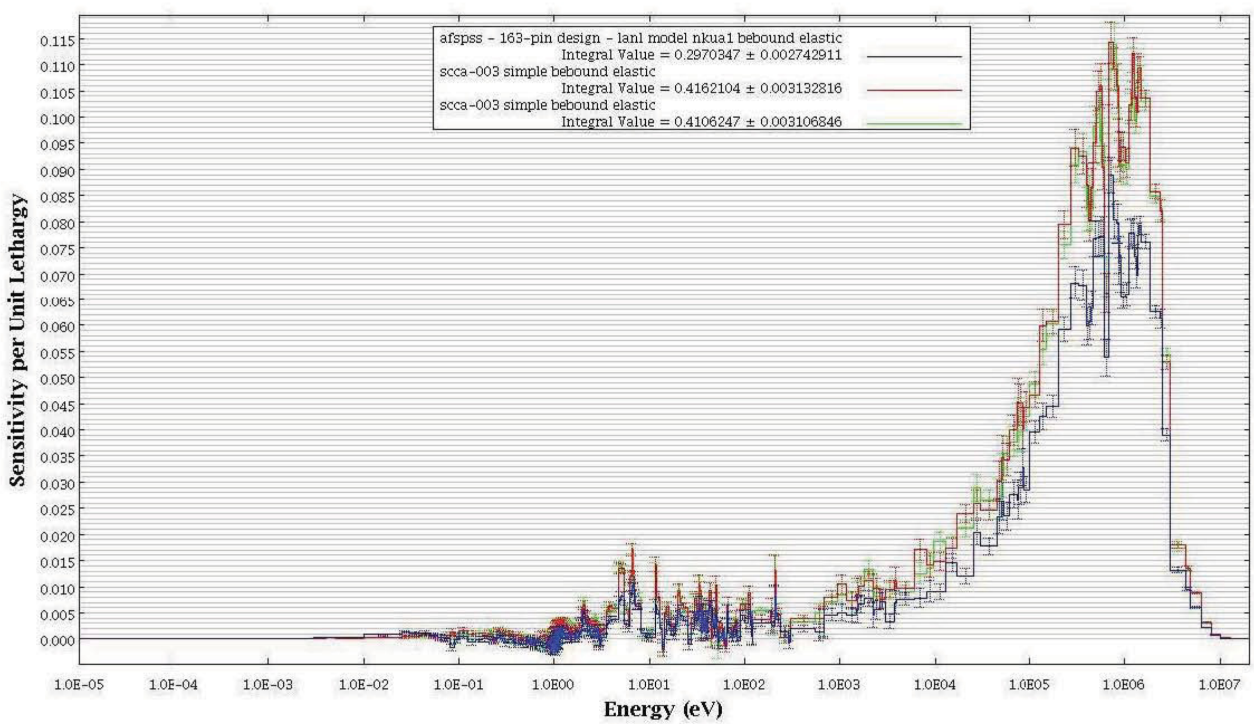

FIGURE 2. Be(n,n) Sensitivity Profiles of the FSP Model and the Two SCCA Beryllium-Reflected Benchmark Models.

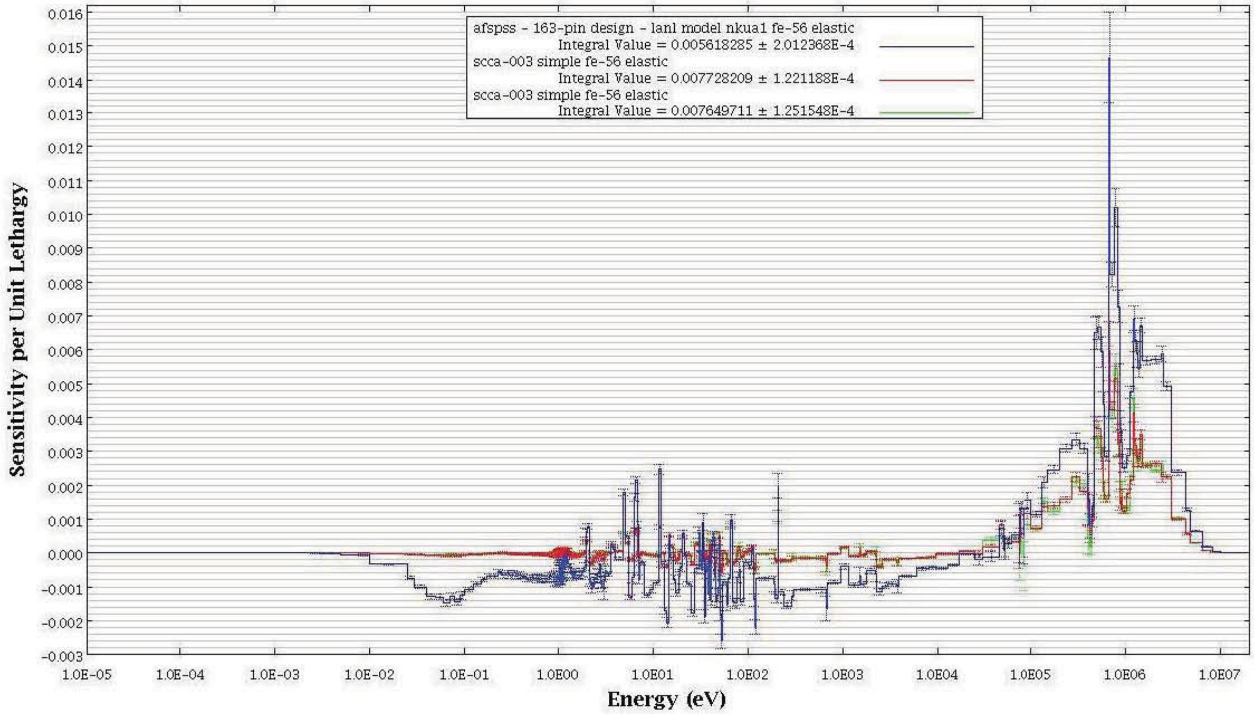

FIGURE 3. ^{56}Fe(n,n) Sensitivity Profiles of the FSP Model and the Two SCCA Beryllium-Reflected Benchmark Models.

CONCLUSION

An uncertainty analysis of the fission surface power (FSP) system was recently performed using a comparison to four ZPPR benchmark experiments. While this study indicated that current capabilities could preclude the necessity of a cold critical test of the FSP, a reduction in the uncertainty of beryllium and uranium cross-section data, which would reduce the overall uncertainty in the computed FSP design model, is still desired. In an effort to reduce these uncertainties, two more critical benchmark experiments, both containing SS-clad HEU-O_2 fuel rods with beryllium reflectors, were added to the FSP analysis. A TSUNAMI-IP analysis indicated that the sensitivity of the benchmarks to the beryllium elastic scatter cross section (the dominant contributor to overall uncertainty) was much larger than the sensitivity of the FSP model. Utility of all seven benchmark models reduced the penalty in the FSP model design from 0.293% δk/k to 0.021% δk/k. The contribution from the Be(n,n) reaction is negligible. The remaining dominant portion of the penalty comes from the ^{56}Fe(n,n) reaction, which contributes 0.015% δk/k. Further reduction of the remaining small penalty would require analysis of experiments sensitive to the ^{56}Fe(n,n) reaction at fission neutron energies. Additional reactor physics measurements from the SCCA beryllium-reflected experiments can be used in future FSP design studies.

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