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ASSESSMENT OF ZERO POWER CRITICAL EXPERIMENTS AND NEEDS FOR A FISSION SURFACE POWER SYSTEM

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Abstract – *The National Aeronautics and Space Administration (NASA) is providing funding to the Department of Energy to assess, develop, and test nuclear technologies that could provide surface power to a lunar outpost. Sufficient testing of this fission surface power (FSP) system will need to be completed to enable a decision by NASA for flight development. The near-term goal for the FSP work is to conduct the minimum amount of testing needed to validate the system performance within an acceptable risk. This paper provides an assessment of the current modeling capabilities and quantifies a preliminary bias associated with the modeling methods for designing the nuclear reactor. Advanced analysis techniques using Zero Power Plutonium Reactor (ZPPR)-20C data should provide sufficient information to preclude the necessity of a cold critical test of the FSP. Further testing to reduce uncertainties in the beryllium and uranium cross-section data should reduce the overall uncertainty in the computational models.*

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) is providing funding to the Department of Energy (DOE) to assess, develop, and test nuclear technologies that could provide surface power to a lunar outpost. Sufficient testing of this fission surface power (FSP) system will need to be completed to enable a decision by NASA for flight development. In addition to supplying power to a lunar outpost, the FSP needs to be flexible enough in its design that it could also be used to provide surface power for a Mars mission with minimal redesign work. In order for the FSP system to be competitive with other options, it should be cost effective with respect to both flight requirements and system/component cost. The reference system will supply an electrical output of 20-50 kW, and be reliably operated for up to 8 years. This provides an energy-rich environment for mission planning requirements and is based on current calculations and designs for NASA requirements for lunar operation, excluding any *in-situ* resource utilization (ISRU) systems.

The baseline FSP system is a sodium-potassium (NaK) cooled, fast spectrum reactor with 93% ^{235}U enriched Highly Enriched Uranium (HEU)-O_2 fuel, Stainless Steel (SS) 316 cladding, and beryllium reflectors with B_4C control drums. The FSP is to produce approximately 40 kWe net power with a lifetime of up to 8 years at full power. The FSP is to be ready for launch and deployment by 2020.

Although an earth-bound prototype of a scaled or full-scale FSP for testing is not planned, it will be necessary to perform various nuclear experiments/tests (e.g., nuclear criticality). These will be supported by a number of non-nuclear system performance tests to provide an understanding of the steady state and operational transient performance and response of the system. The data generated from such tests will be used to verify and validate both the design and the computer codes that will be used to model the neutronics behavior of the system. Where possible, results from previous criticals as well as criticality benchmarks may be used to validate codes in lieu of specialized FSP experiments.

Expected analyses and testing needed for the FSP include cold and hot critical experiments. The cold criticals include evaluation of critical mass, fission rate, control drum worth, and launch accident scenarios. The hot criticals will be used to evaluate temperature coefficients of reactivity. In addition to the above systems/components, the needs for other generic nuclear data/testing/analysis will be determined at a later date. Given the list of systems and components above that will require critical experiments it should be possible to combine many (if not all) of the system and component tests into several integral cold and/or hot criticals, rather than separate tests for each system or component. Results from the criticals may indicate the need for further nuclear system or component testing.

The near-term goal for the FSP work is to conduct the minimum amount of testing needed to validate the system performance within an acceptable risk. It is desirable that only separate effects tests such as component tests, zero power criticals, other nuclear/hot tests, integral testing, etc., form the basis for a “qualified” reactor system without building and operating a prototype on the earth. The first fully operational FSP nuclear system test would then be performed on the lunar surface (i.e., no earth-based ground test), if the planned testing is deemed to be adequate to meet the requirements of the system. This paper provides a preliminary assessment of the current modeling capabilities and quantifies a preliminary bias associated with the modeling methods for designing the nuclear reactor and associated nuclear physics models. This report also assesses whether a cold critical test can improve the nuclear data or modeling of the FSP.

II. EVALUATION OF EXISTING BENCHMARK DATA

The *International Handbook of Evaluated Criticality Safety Benchmark Experiments*[1] was reviewed for critical benchmarks applicable to the FSP. Additionally, previous work on physics tools qualification for space reactor design was reviewed for applicability to the FSP work. Ideal criticality benchmarks for use in qualification of physics tools for the FSP would consist of fast spectrum, high-enriched uranium oxide fueled, beryllium reflected, sodium-potassium (NaK) cooled systems. However, the ICSBEP fast critical experiment evaluations are limited to bare and reflected uranium metal spheres and cylinders. There were no fast neutron spectra experiments fueled by uranium dioxide. However, the enrichment was ≥ 60 wt% ^{235}U for many of the fast critical experiments, and a significant number of the fast spectrum experiments were performed using reflector and structural materials applicable to the reference FSP reactor, including beryllium and steel.

There may be a benefit to considering other critical experiments in intermediate and thermal neutron spectrums. A significant amount of work was performed on the qualification of physics tools for design of the Jupiter Icy Moons Orbiter (JIMO) reactor in which intermediate spectrum and thermal spectrum experiments were considered.[2,3]

Four important critical experiments from Zero Power Plutonium Reactor (ZPPR)-20 were of particular interest.[4] The ZPPR-20 experiments for the SP-100 program included multiple fuel-enrichment zones, along with seven internal safety rods. The experiments incorporated enriched uranium metal fuel, enriched lithium-7 coolant, B_4C internal safety rods, BeO external radial reflectors, and a lithium-hydride neutron flight shield. This small space reactor mockup incorporated 176 kg ^{235}U. Two of the included ZPPR-20 experiments represent launch accident scenarios: sand burial and water immersion. It is expected that the ZPPR-20 experimental data will provide much of the FSP validation information needed.

II.A. MCNP Biases

Select critical experiments from the handbook were modeled using Monte Carlo N-Particle (MCNP)[5] version 5.1.40 using ENDF/B-V.0, ENDF/B-VI.6, and ENDF/B-VII.0 continuous-energy cross sections evaluated at a temperature of 293 K. The results for different groupings of the benchmark cases are shown in Fig. 1, providing an absolute average bias and standard deviation. These biases represent the difference between the calculated eigenvalues of the benchmark geometry and the actual eigenvalues of the physical experiment. These groupings may give some insight into the effect of different materials used in major components of the experiments. However, since the grouped experiments have other materials which differ, definitive conclusions cannot be drawn from the results of these groupings.

It can be concluded from the benchmark comparisons that the modeling biases generally improve with the ENDF/B-VII cross-section sets except for the Intermediate Enriched Uranium (IEU) fast spectrum experiments and the subcritical experiments. Means must be investigated to reduce the bias uncertainty for subcritical experiments, especially for the validation of launch accident configurations.

II.B. Beryllium Reflector Bias

The effect of beryllium worth on the calculated MCNP eigenvalue bias was investigated using a selection of benchmarks. The results of these analyses are presented in Figs. 2 and 3 for both fast and mixed neutron systems; it is apparent that there is a trend in the bias related to reflector worth. Specifically, the bias increases as the reflector worth increases. This implies that there is a bias in the beryllium

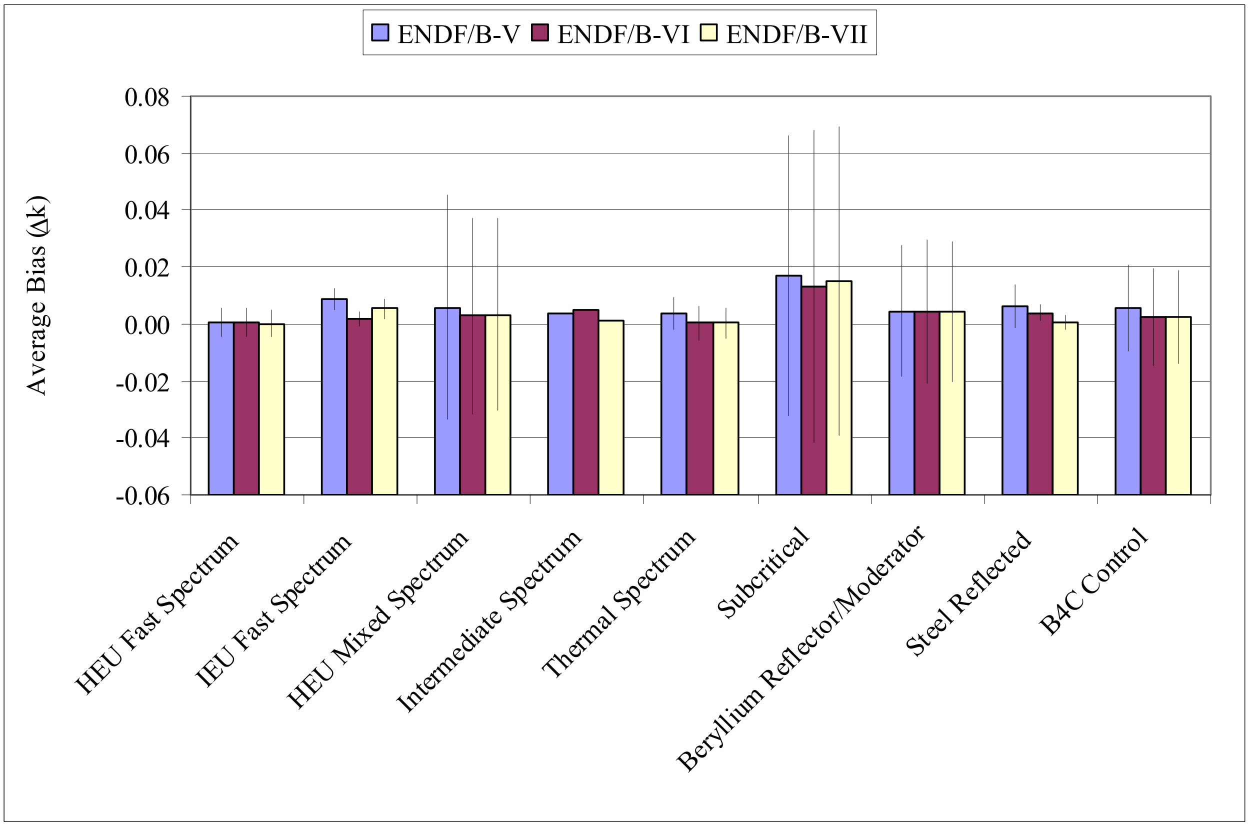

Fig. 1. Absolute average biases and uncertainty (1σ) for the different benchmark groupings and cross-section sets.

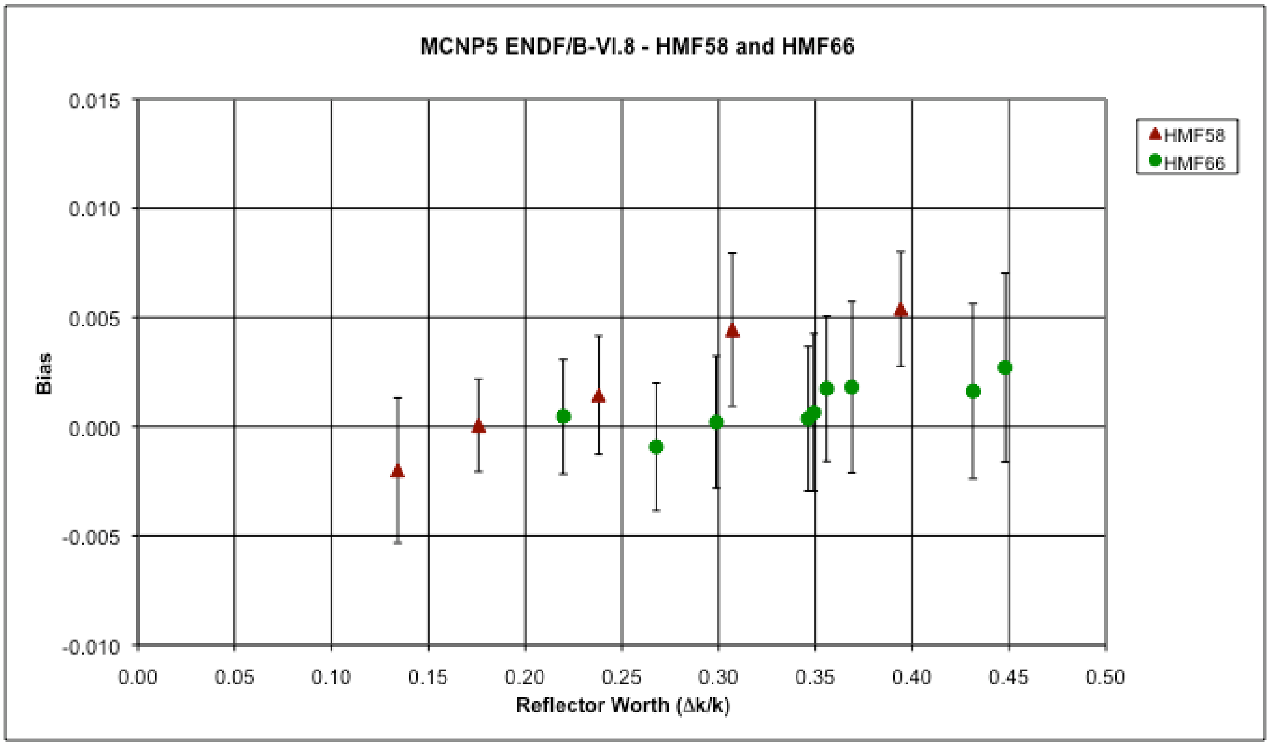

Fig. 2. Beryllium reflector effect results (1σ uncertainty) for benchmarks HEU-MET-FAST-058 and HEU-MET-FAST-066.

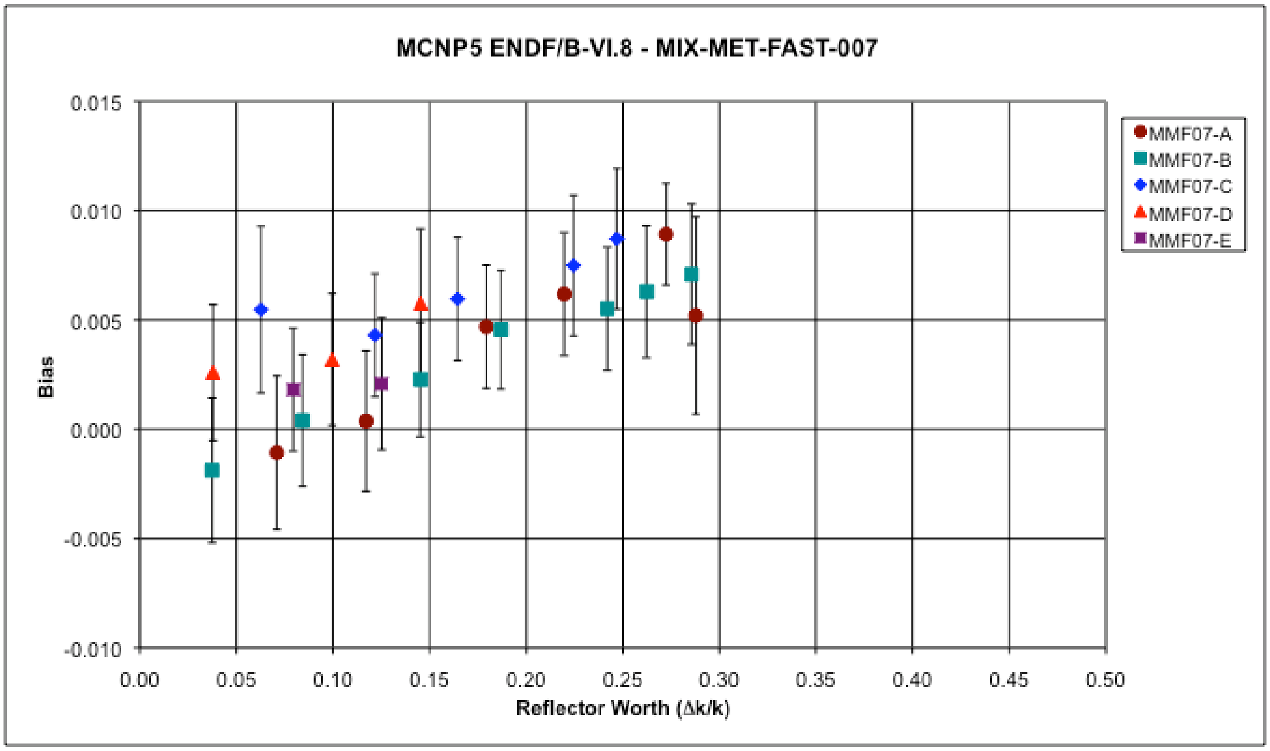

Fig. 3. Beryllium reflector effect results (1σ uncertainty) for benchmarks MIX-MET-FAST-007.

cross section that will affect the modeling results of the FSP. Though the bias is about 0.5% or less for HEU systems, improved cross sections for beryllium may improve the MCNP modeling capabilities for the FSP.

II.C. TSUNAMI Analysis with ZPPR-20 Benchmarks

Oak Ridge National Laboratory developed TSUNAMI-3D (Tools for Sensitivity and Uncertainty Analysis Methodology Implementation in Three Dimensions)[6] to automate the analysis procedure of uncertainties and sensitivities in cross section data for a given model. Only a small selection of the ZPPR-20 configurations[7] is currently available as benchmark in the ICSBEP Handbook[1] for potential analysis with the TSUNAMI-3D code. Models were converted from MCNP format into KENO-V.a[8] and analyzed using the ENDF/B-VI.7 238-group neutron cross-section libraries. The effective multiplication factor, k_{eff}, calculated using both MCNP and KENO models were approximately equivalent.

A comprehensive sensitivity analysis of each model in TSUNAMI-3D determined the relative standard deviation in k_{eff} due to cross-section covariance data, as the square root of the sum of the squares of the various constituents in the cross-sections in the neutron library. It should be noted that the component uncertainty from the (n, γ) reactions in ^{235}U are greater than the uncertainty in the (n, fission) reactions. Although the FSP is more sensitive to the (n, fission) reaction, the uncertainty of the (n, γ) cross section far exceeds that of (n, fission), especially at fast energies, leading to a greater uncertainty in k_{eff} due to (n, γ) than for (n, fission).

For this analysis, pre-release SCALE 6 cross-section-covariance data were used in the TSUNAMI-3D code of SCALE 5.1 to generate the uncertainty information. Where cross-section uncertainties were not available, a uniform uncertainty of 5% was assumed.

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).[8] 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.[9] The integral index c_k can be used as a trending parameter in criticality safety analysis validation studies to determine computational uncertainties and biases.[10] The application of TSUNAMI for benchmark design, interpretation and estimation of biases and uncertainties in space power reactor design and safety analyses has been previously proposed.[11]

Determination of the c_k index involves a rigorous uncertainty analysis that propagates the tabulated cross-section uncertainty information to the calculated k_{eff} value of a given system via the energy-dependent sensitivity coefficients. Mathematically, the system uncertainty is computed with a quadratic product of the group-wise sensitivity profile vectors by nuclide and reaction type with the group-wise cross-section uncertainty matrices by nuclide and reaction type. The result is not just an estimate of the uncertainty in the system k_{eff} due to cross sections, but also an estimate of the correlated uncertainty between systems. Therefore the c_k index not only uses a single value to relate two systems, but to also measure the similarity of the systems in terms of related uncertainty.

The FSP model was compared against the four ZPPR models using both the SCALE 5.1 and pre-release SCALE 6 ENDF/B-VI cross-section covariance data. Note that the SCALE 6 covariance library contains several ENDF/B-VII evaluations for important nuclides such as ^{235}U and improved evaluations for many light elements, such as Be. A summary of the correlation coefficient and cross-section uncertainties for both libraries is provided in Table I. 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. The differences in the SCALE 5.1 and SCALE 6 results arise from improved uncertainty estimations for the cross section data; SCALE 5.1 results were underestimating the true uncertainty in the model.

TABLE I

Correlation coefficient and cross-section uncertainties comparison between FSP and ZPPR-20 models.

Model	SCALE 5.1 Covariance Data		SCALE 6 Covariance Data	
	c_k	Cross-Section Uncertainty (%)	c_k	Cross-Section Uncertainty (%)
ZPPR-20C(105)	0.6494 ± 0.0292	0.5821	0.9753 ± 0.0036	2.0684
ZPPR-20D(129)	0.3751 ± 0.0089	0.6881	0.9453 ± 0.0021	1.7137
ZPPR-20D(136)	0.2749 ± 0.0050	0.6652	0.9327 ± 0.0020	1.6520
ZPPR-20E(160)	0.5241 ± 0.0342	0.4551	0.9323 ± 0.0041	1.5943

The dominant uncertainty in the cross-section data is derived from uncertainties in the uranium and beryllium. Thus, with experiments that provide similar sensitivities to uranium and beryllium, any bias observed in the experiments could be projected to a bias in the FSP. With sufficient numbers of similar experiments, it may be possible to obtain the target subcritical safety margin of approximately 1.5% (k_{eff} of 0.985).[12]

The uncertainty from oxygen isotopes in the ZPPR-20 benchmark models and the FSP model are 0.1 %Δk/k or smaller. Because the ^{235}U(n, fission) sensitivity correlation between the models is approximately 0.8 or greater, it is expected that a critical experiment, if deemed necessary, could be performed with uranium metal fuel with oxygen equivalent components instead of UO_2. Furthermore, a plate-and-drawer mockup of the reactor would be sufficient in modeling a critical system, where bulk effects from fuel and reflector represent the dominant uncertainty. Further evaluation and comparison against additional benchmark data might be necessary to confirm this conclusion.

The TSUNAMI-IP code allows for a penalty assessment that determines additional margins of uncertainty where sufficient experimental information is unavailable. This additional uncertainty component could be included with the calculated k_{eff} of a system to provide added measure of safety where validation coverage might be lacking. Criteria for the penalty assessment are based upon the results of the g index computed with TSUNAMI-IP.[8] Using only the four ZPPR experiments as the validation set, the uncertainty of the FSP with SCALE 6 covariance data is reduced from 2.09 to 0.29 %Δk/k. The only remaining uncertainty component above 0.1 %Δk/k is Be(n,n), with a value of 0.28 %Δk/k. If a statistically significant number of similar experiments were available to quantify the bias and bias uncertainty due to all other components of the FSP, this penalty could be used to quantify an additional margin to subcriticality to account for the lack of experimental coverage for beryllium.

TABLE II

Primary sources of covariance uncertainty in the FSP model.

Covariance Library	Total Uncertainty (%Δk/k)	Major Components	Component Uncertainty (%Δk/k)[a]
SCALE 5.1	1.0675	Be(n, n)	0.9456 ± 0.0050
		^{235}U(n, n’)	0.3268 ± 0.0016
		^{235}U(n, γ)	0.3095 ± 0.0001
		^{235}U(n, fission)	0.1832 ± 0.0001
		^{235}U(n, n) to ^{235}U(n, n’)	-0.1793 ± 0.0009
		^{235}U(ν-bar)	0.1343 ± 0.0000
		Be(n, 2n)	0.1112 ± 0.0003
SCALE 6	2.0872	^{235}U(n, γ)	1.9576 ± 0.0006
		^{235}U(ν-bar)	0.5651 ± 0.0000
		Be(n, n)	0.3559 ± 0.0023
		^{235}U(n, n’)	0.2261 ± 0.0009
		^{235}U(n, fission)	0.1864 ± 0.0000
		^{235}U(n, n) to ^{235}U(n, γ)	-0.1297 ± 0.0003

[a] Negative values represent anticorrelations between two reactions in the covariance data.

III. FUTURE EFFORTS

As only four critical experiments have been analyzed with TSUNAMI in this work, it will be useful to generate TSUNAMI data for the remaining benchmark experiments. The generation of c_k values for these remaining benchmarks relative to the FSP should yield a statistically significant number of sufficiently similar ($c_k > 0.8$) benchmarks and allow the use of trending analysis techniques for the quantification of computational biases and uncertainties in terms of k_{eff}. The coverage provided by the entire benchmark suite previously analyzed using MCNP will only be known when the TSUNAMI analysis is completed. Advanced bias determination techniques, such as the data adjustment methods employed in the SCALE 6 TSURFER code,[13] could also prove useful with such a benchmark suite.

A more comprehensive analysis of the ZPPR-20C benchmark model might provide sufficient information for confirming the computational model of the FSP and thus eliminate the need for a cold critical experiment. Some of the parameters from the ZPPR-20 benchmarks, which could be used to confirm the computational model of the FSP are: control rod worths, material worth measurements, reflector worth measurements, temperature effects and reaction rate measurements. Although TSUNAMI in SCALE 5.1 only assesses eigenvalue uncertainty, other reactor parameters would also be affected by this cross-section uncertainty. SCALE 6 TSUNAMI techniques implemented in TSAR (Tools for Sensitivity Analysis of Reactivities)[13] can compute reactivity sensitivities and uncertainties such as control rod, material, coolant, reflector, and temperature worths.[14] Where sufficient experimental data are available for reactivity measurements, TSAR data can be used with TSUNAMI-IP to determine similarities, biases and penalties in terms of reactivity sensitivities. Generalized perturbation theory TSUNAMI techniques currently under development will be able to compute the sensitivities of reaction rates and reaction rate ratios to the cross-section data to determine uncertainties, similarities, biases and penalties for the FSP for these important quantities. Confirmation of available reaction rate data[7] would verify modeling capabilities of the ZPPR-20C benchmark and validate modeling capabilities for the FSP.

The cold critical of the FSP could be carefully designed to confirm reaction rate data should the ZPPR-20C analysis be insufficient. Should the penalty due to lack of sufficient experimental coverage for beryllium prove limiting, a FSP cold critical could confirm beryllium-reflector worth and edge effects between the uranium and beryllium. In essence there might be an improvement in the modeling uncertainty of the entire reactor system, but if a collection of other experiments can together yield sufficient coverage, an FSP cold-critical evaluation would just become an additional data point in the benchmark library.

It will be necessary to identify specific manufacturing and operational parameters with their respective margins for the FSP design. Utilization of parameterization analysis software such as MC^2-2[15] with perturbation techniques can help in understanding the computational uncertainty and relative systematic effects of these parameters. Once select parameters of interest have been identified, select benchmarks of existing critical experiments need to be generated to assess and reduce uncertainties in margin prediction.

Improvement in the cross-section covariance data for uranium and beryllium would improve the certainty of the models. Uranium cross-section data analyses are part of the current Global Nuclear Energy Partnership priorities. The present analyses have identified the beryllium cross-section data as a likely concern. The design and implementation of tests to specifically develop and reduce uncertainties in the beryllium cross-section data would be necessary for further reduction in the overall uncertainty. Collaboration with Brookhaven National Laboratory to improve this data would be necessary, so as to capitalize on their expertise in cross-section generation and refinement. As further analyses are performed through the parameterization studies, additional cross sections might be identified for necessary improvement.

It is clear that more work needs to be done in verifying the FSP modeling capabilities. The decision on whether or not a cold critical test is necessary will become clear with additional modeling efforts. The work needed to reach a definitive decision is as follows:

- Generate TSUNAMI data for the remaining experiments utilized in the MCNP analysis.
- Use TSAR on the FSP model and the benchmark experiments to compute the sensitivities and uncertainties of specific parameters of the FSP including control rod, material, coolant, reflector, and temperature worths.
- Using MC^2-2, determine the parameters of the FSP which are most critical to the safe operation of the FSP. Once the parameters are determined, focus on decreasing the uncertainty associated with the critical parameters using advanced data analysis techniques.
- Compare specific parameters (control rod worths, material worth measurements, reflector worth measurements, temperature effects and reaction rate measurements) measured in the ZPPR-20 experiments with results from the ZPPR-20 models to verify the modeling capability for these specific FSP parameters.

IV. CONCLUSIONS

From the analysis of the criticality safety benchmark experiments considered, in most cases MCNP version 5.1.40 with the ENDF/B-VII cross sections produced equivalent or reduced eigenvalue biases when compared to ENDF/B-V and ENDF/B-VI. The two areas where the ENDF/B-VII cross-section data did not outperform the ENDF/B-VI cross sections were the subcritical benchmarks and the intermediate enrichment benchmarks. The ENDF/B-VII cross-section data showed significant improvement over the ENDF/B-VI cross-section data in the intermediate spectrum benchmarks and the steel reflected benchmarks. The subcritical experiments showed the largest bias (1.3 – 1.7%) of all the analyzed benchmarks. There may be better analytical tools or cross section sets for analyzing subcritical configurations.

The beryllium reflector analysis shows a trend in bias with increasing reflector worth. This is most evident in Figs. 2 and 3. This indicates desired cross section improvements for beryllium. Using different ENDF cross section sets does not appear to be able to provide any significant improvement in the beryllium cross sections as shown in Fig. 1.

The TSUNAMI uncertainty and sensitivity study demonstrated high correlation between the ZPPR-20 experiments and the current FSP model. The correlation coefficient index is above 0.93 for all experiments using the ENDF/B-VI cross-section-covariance data from SCALE 6 with an overall cross-section uncertainty between 1.6 and 2.1 %Δk/k. A preliminary penalty assessment was performed using the four ZPPR-20 experiments to validate the FSP; the uncertainty in the FSP model was reduced from 2.09 to 0.29 %Δk/k, leaving beryllium as the only major nuclide without sufficient validation coverage and a need for improvement in the ^{235}U(n,γ) data. It is recommended that TSUNAMI data be generated for all utilized benchmarks to develop a more comprehensive analysis of the FSP, such that computational biases and their uncertainties can be defensibly quantified.

The final conclusion from this report is that a cold critical evaluation of the FSP is not necessary. An actual cold-critical experiment would provide data that might be more readily obtained from more comprehensive benchmark analyses of available ZPPR data. Additional comparison with benchmark data should increase certainty in the computational validation and analysis of the FSP design. A worst-case accident criticality analysis would still be needed to validate the computational modeling capabilities and the FSP design in regards to subcritical submersion into additional reflector and/or moderator medium.

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