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UMo Benchmark Experiment Data Needed to Support Computational and Nuclear Data Validation

J.D. Bess and M.A. Marshall
Nuclear Science & Technology
Idaho National Laboratory, 2525 N Fremont Ave, Idaho Falls, ID 83415 – USA

I. Hill
Division of Nuclear Science
OECD NEA, 46, quai Alphonse Le Gallo, 92100 Boulogne-Billancourt – France

ABSTRACT

Currently there are almost no benchmark experiment data available directly supporting neutronics modeling and simulation of ~20 wt.% ^{235}U, UMo fuel contained within the Organisation for Co-operation and Development Nuclear Energy Agency (OECD NEA) international benchmark handbooks from the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and International Reactor Physics Experiment Evaluation Project (IRPhEP). The benchmarks within these two handbooks represent the international standards used to support computational and nuclear data validation. Recent activities in nuclear data development supporting new neutronics thermal scattering cross sections for UMo fuel indicate the necessity to provide quality benchmark experiment data that can be utilized to support their validation and development. Preparation of high-integrity neutronics benchmarks from UMo experimental data will ensure proper integral testing of these cross sections, as well as serve to support computational validation of contemporary modeling and simulation software.

1 Introduction

The availability of benchmark data available in the Organisation for Co-operation and Development Nuclear Energy Agency (OECD NEA) International Criticality Safety Benchmark Evaluation Project (ICSBEP) [1-2] and International Reactor Physics Experiment Evaluation Project (IRPhEP) [3-4] to support the reduced enrichment campaign were previously discussed [5]. A few specific opportunities to prepare further benchmarks from existing experimental data were also addressed. The benchmark experiment data contained within these handbooks serve as international standards supporting computational and nuclear data validation [6].

Significant efforts are pursued to continually improve upon our existing nuclear data libraries to better sustain modern and future efforts of accurately modeling and simulating various nuclear systems. Most recently, the Collaborative International Evaluation Library Organization (CIELO) project stimulated advances in the neutron cross section data for uranium, plutonium, iron, oxygen, and hydrogen [7]. These improvements, and many others, were included in the latest release of the Evaluated Nuclear Date File ENDF/B-VIII.0, including many new contributions and revisions to neutron thermal scattering data [8]. Thermal scattering data are used in neutron transport codes to account for neutron interactions with bound materials.

Just to aid in the visualization of the difference between various contemporary nuclear data libraries, the incident neutron data for ^{95}Mo (n,tot) cross section is shown in Figure 1. For the most part, these libraries are use very similar cross section values across the neutron energy spectrum. Figure 2 shows a difference of approximately 1 to 2 barns in the total neutron cross section for ^{95}Mo across the energy range of approximately 10 to 40 eV, which can be significant for systems sensitive in that energy region assembled with large quantities of molybdenum material. Some resonance peaks between the different libraries can be significantly different, for example, comparison of JENDL-4.0 with the other libraries in Figure 1. The difference in the total neutron cross section between neutron data libraries appears to be small, within ~1 barn, for the thermal neutron region.

Research to characterize and develop thermal scattering data for uranium metal [9], molybdenum [10], and UMo fuel [11] have been published recently. However, there currently is very limited benchmark data available to support significant validation of these specific nuclear data. This paper summarizes current benchmark handbook content, which indicates a need to evaluate and provide proper benchmark data to support nuclear data validation of UMo-fueled systems.

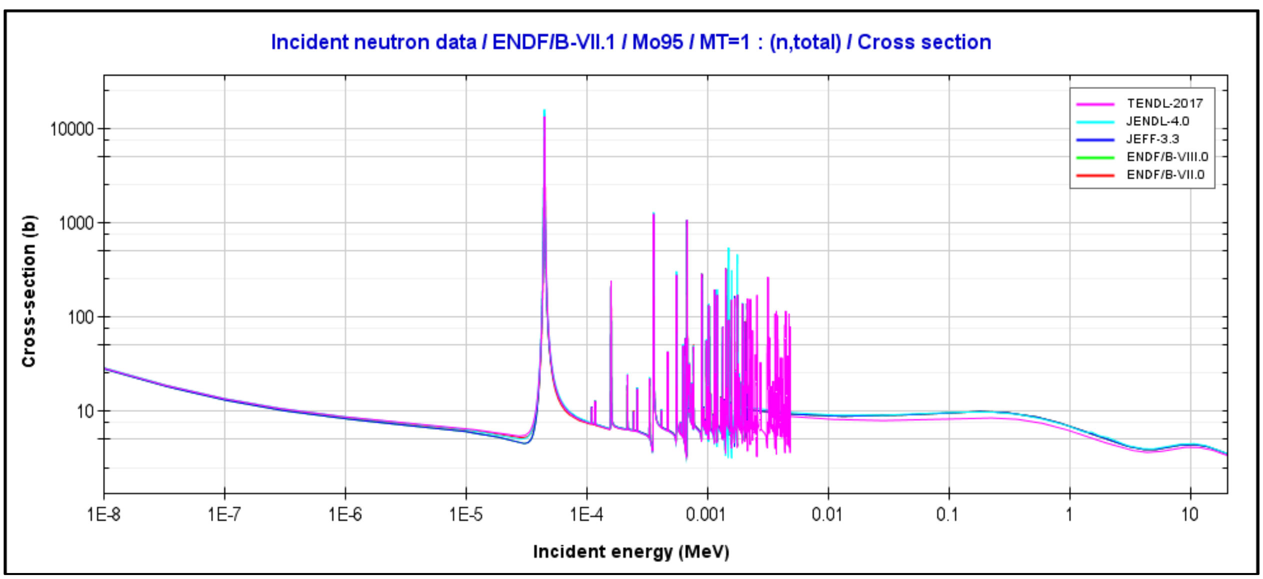

Figure 1. ^{95}Mo (n,tot) Incident Neutron Data for Example Nuclear Data Libraries.

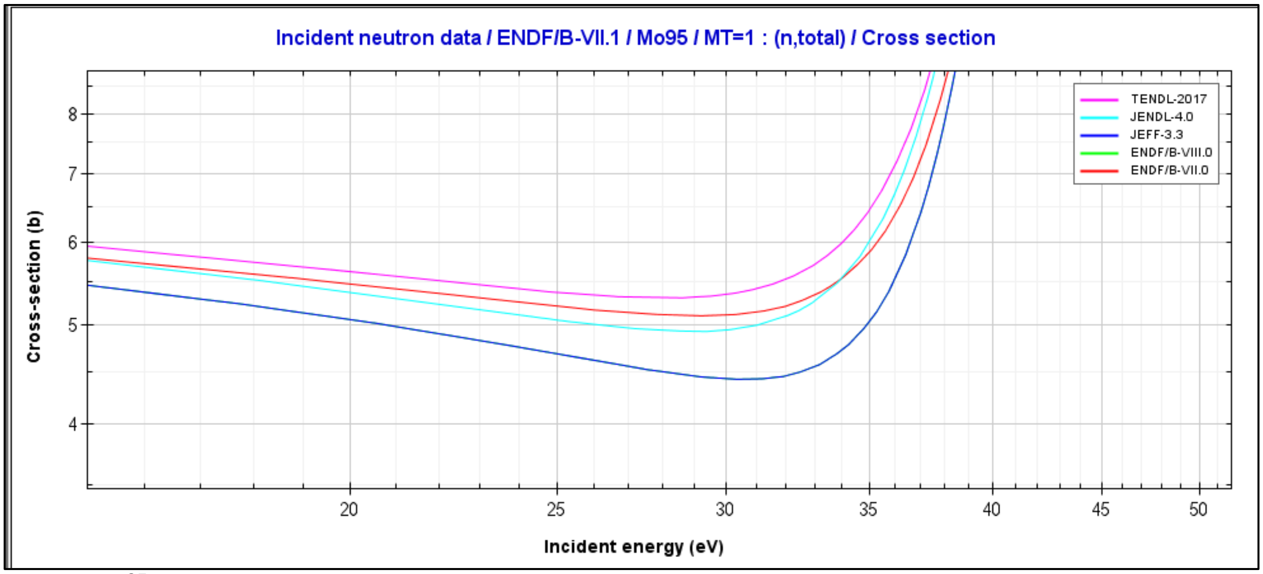

Figure 2. ^{95}Mo (n,tot) Incident Neutron Data from ~10 to 40 eV.

2 Evaluation of Currently Available Benchmarks

The Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) is instrumental in the irradiation campaign supporting UMo fuel plate qualification for U.S. High Performance Research Reactor (USHPRR) conversion [12-13]. Criticality safety validation supporting Reduced Enriched Research Test Reactors (RERTR) full size demonstration fuel element placement in the ATR indicated not only limited benchmark data to support validation of 20 wt.% ^{235}U fueled reactor systems, but unavailability of applicable UMo benchmark data [14].

The current contents of the ICSBEP Handbook [2] were interrogated using the Database for International Criticality safety benchmark Evaluation project (DICE) [15] to assess which benchmark data demonstrate sensitivity to UMo or Mo. No additional benchmark data are available on the IRPhEP Handbook [4], with the exception of a ^{95}Mo reactivity worth measurement in MINERVE, that does not duplicate existing ICSBEP Handbook data for these materials. A summary of the results is provided in Table I.

Eigenvalue sensitivities have been computed for most of the configurations tabulated in Table I. The most sensitive configuration to molybdenum cross section data is HEU-MET-FAST-005, which is a highly enriched UMo fuel space reactor mockup, with a k_{eff} sensitivity of up to an absolute magnitude of 0.058 %Δk/%Σ (58 pcm/%Σ. However, the sensitivity is across the entire energy range and not just in the thermal neutron spectrum. Greater thermal spectrum sensitivity is demonstrated in highly enriched UO_2 fueled space reactor benchmarks HEU-COMP-MIXED-003 and -004. The low enriched UO_2 fueled research reactor benchmark with molybdenum metal rod insertions, LEU-COMP-THERM-067, is less sensitive to molybdenum but is sensitive mostly in the thermal neutron spectra. Sensitivity calculations for the UMo plate experiment performed in the same research reactor have not yet been computed and included in DICE. Sensitivity calculations for HEU-COMP-INTER-005 and MINERVE-FUND-RESR-001 have also not yet been performed.

ICSBEP Benchmarks with Sensitivity to Molybdenum Cross Section Data.

Evaluation ID	**Fuel (wt.%)**	**Molybdenum Details**	**k_{eff} Sensitivity (| %Δk/%Σ |)**	
			Thermal (< 0.625 eV)	**Total (0 - 20 MeV)**
LEU-COMP-THERM-067	UO_2 (4.35 ^{235}U)	Mo Rods in Research Reactor	< 0.011	< 0.013
LEU-COMP-THERM-103	UMo (19.8 ^{235}U) UO_2 (4.35 ^{235}U)	UMo Plate Experiment in Research Reactor	Unavailable	Unavailable
HEU-COMP-INTER-005	UO_2 (90.11 ^{235}U)	Mo Pellets Between UO_2 Fuel	Unavailable	Unavailable
HEU-COMP-MIXED-003	UO_2 (95.92 ^{235}U)	Mo Tubes in Space Reactor Mockup	< 0.030	<0.044
HEU-COMP-MIXED-004	UO_2 (95.92 ^{235}U)	Mo Tubes in Space Reactor Mockup	< 0.030	<0.044
HEU-MET-FAST-005	UMo (90 ^{235}U)	Be & Mo Reflected Space Reactor Mockup	< 0.001	< 0.058
HEU-MET-FAST-084	U metal (93.3 ^{235}U)	Mo & Mo_2C Reflected Cylinder	0	< 0.036
HEU-MET-FAST-092	U metal (96 ^{235}U)	Mo Reflected Cylinder	0	< 0.029
HEU-MET-FAST-093	U metal (96 ^{235}U)	Mo Diluted Cylinder	0	< 0.031
HEU-MET-FAST-094	U metal (96 ^{235}U)	Be & Mo Diluted Cylinder	0	< 0.005
HEU-MET-MIXED-020	U metal (96 ^{235}U)	Mo & CH_2 Diluted Cylinder	< 0.025	< 0.031
PU-MET-FAST-044	Pu metal (5.1 ^{240}Pu)	Mo Reflected Sphere	< 0.004	< 0.018
MINERVE-FUND-RESR-001	UAl (90-93 ^{235}U)	^{95}Mo Pellet in Oscillation Measurement	Unavailable	Unavailable

Basic visualization of uranium and molybdenum sensitivities as a function of neutron spectra are shown in Figure 3 for LEU-COMP-THERM-067. As expected, the uranium fuel sensitivity is much greater than that of molybdenum. A comparison of the sensitivities to the total neutron cross section data for seven molybdenum isotopes is shown in Figure 4. The isotope with greatest sensitivity in this benchmark is ^{95}Mo. The sensitivities to molybdenum are slightly more pronounced in the thermal spectra for the HEU-COMP-THERM-003 benchmark, as shown in Figure 5.

Looking closer at the results shown in Figures 3 through 5, these benchmarks are most sensitive to the ^{95}Mo isotope around 0.1 eV, where the total neutron cross section is approximately 30 barn. Some resonance sensitivities also exist in the 10 to 100 eV portion of the neutron spectra shown in Figures 1 and 2.

Although there are some benchmarks in the ICSBEP Handbook demonstrating sensitivity to molybdenum cross sections, the selection is rather limited in application. Benchmarks simulating nuclear systems containing significant quantities of UMo fuel (~20 wt.% ^{235}U) are not currently available.

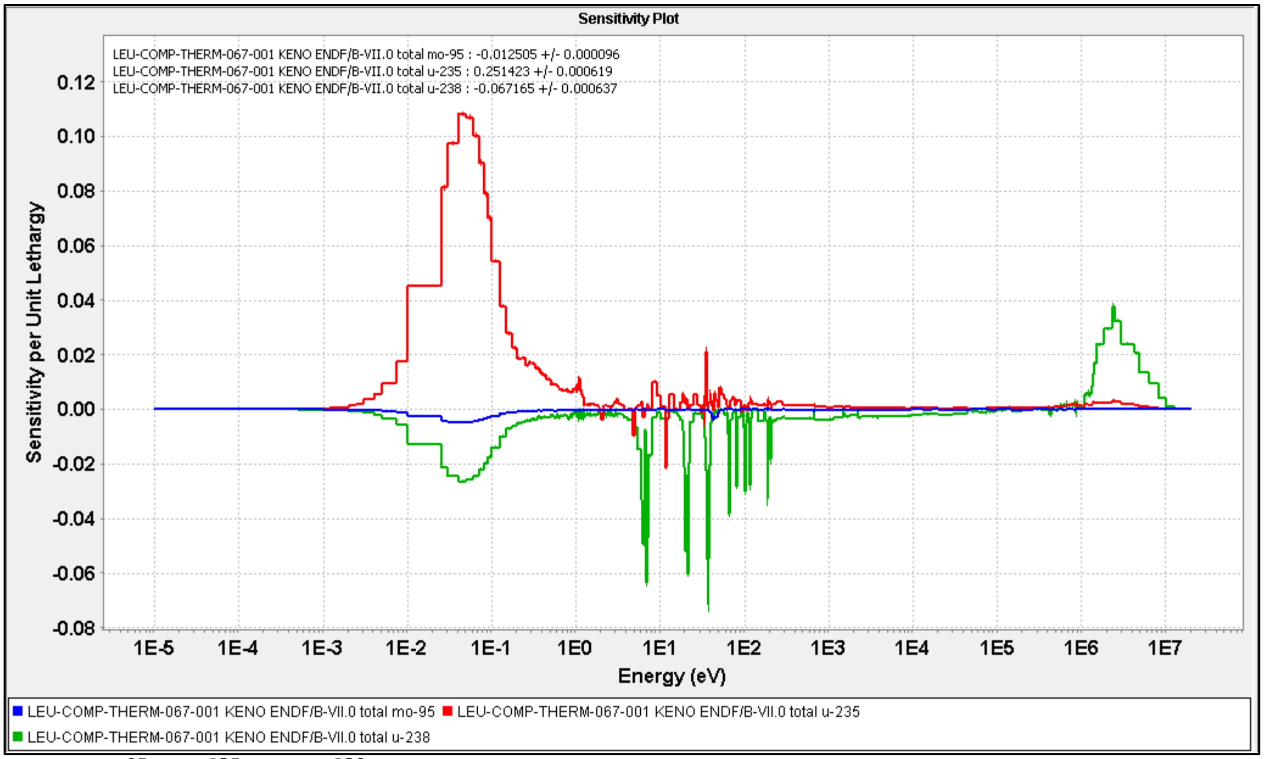

Figure 3. ^{95}Mo, ^{235}U, and ^{238}U Sensitivities for LEU-COMP-THERM-067.

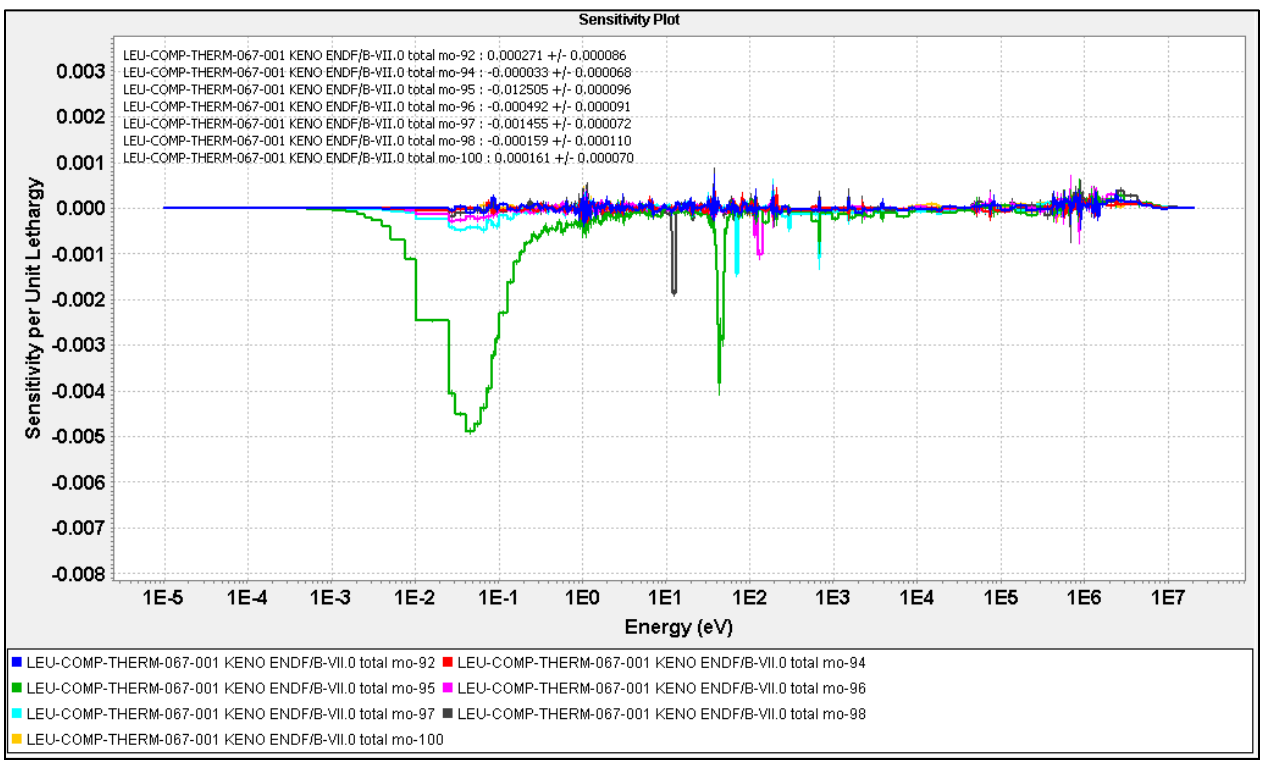

Figure 4. Molybdenum Isotope Sensitivities for LEU-COMP-THERM-067

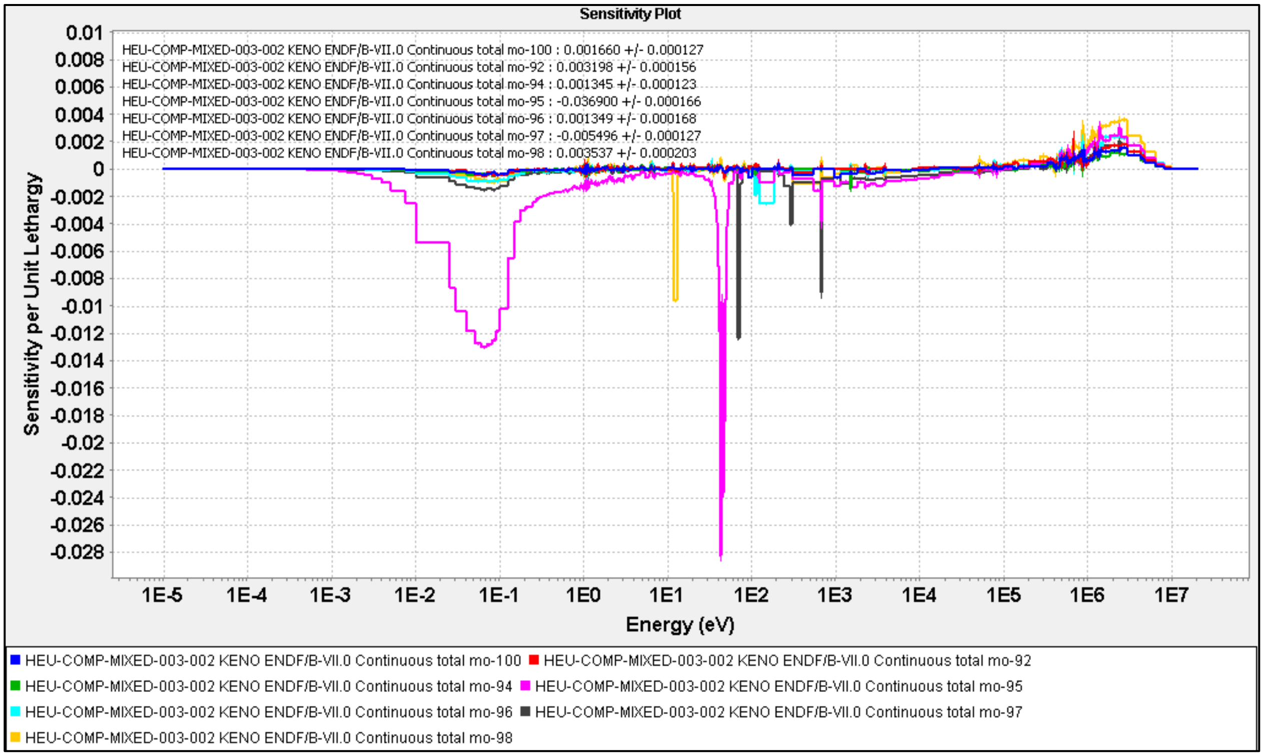

Figure 5. Molybdenum Isotope Uncertainties for HEU-COMP-MIXED-003.

3 Future Work

Significant efforts have gone into experiments designed to test material properties and irradiation effects upon UMo fuel for nuclear research and test reactors [16-17] for both UMo dispersion [18] and monolithic fuel types [19]. Neutronics characterization prior to irradiation and as a component of post irradiation analyses are integral to many of the safety, operations, and evaluation of these irradiation experiments. Identification of key experiments from which integral benchmark models can be evaluated and developed would serve to provide validation data compatible with the materials characterization data obtained from these irradiation experiments.

As experiments are performed in ATR to support HPRR efforts using UMo plate demonstration elements, the neutronics component of these efforts should be evaluated as benchmark data, providing understanding in key uncertainties and biases most relevant to future converted reactors using this fuel type.

Experiments performed at the Joint Institute for Power and Nuclear Research – Sosny of the National Academy of Sciences of Belarus are also of benchmark interest [20]. While these experiments were performed with UO_2 fuel and ZrH moderator, instead of UMo fuel, the enrichment of the fuel for the experiments are 21, 36, and 45 wt.% ^{235}U. These experiments serve to further validate low-enriched uranium (LEU) reactors and associated fuel-cycle computations while also bridging the validation data gap between LEU and highly enriched uranium (HEU) systems.

Experimental data have been collected in the IRPhEP archive of STEK experiments [21], which contains measurements of small Mo samples [22]. The STEK reactor (ECN Petten/ Netherlands) was a fast-thermal coupled facility of zero power. The annular thermal drivers were filled by fuel assemblies and moderated by water. The inner insertion lattices were loaded with pellets of fuel and other materials producing the fast neutron flux. The characteristics of the neutron and adjoint spectra were obtained by special arrangements of these pellets in unit cells. In this way, hard or soft neutron spectrum or a special energy behavior of the adjoint function could be reached. The samples were moved by means of tubes to the central position (pile-oscillation technique). These experiments are good candidates for future evaluation.

Computation of the sensitivities to Mo for LEU-COMP-THERM-103 can be performed and included into DICE to compliment the data available on the ICSBEP Handbook. However, as the UMo experiment itself is small compared to the full core compliment of UO_2 fuel rods, the results will be limited in applicability to support the validation of full core reactor simulations using UMo fuel. Sensitivity calculations for HEU-COMP-INTER-005 and MINERVE-FUND-RESR-001 could also be performed to provide some additional information regarding these experiments. However, these experiments use HEU fuel, which do not sufficiently represent the LEU fuel plates desired for HPRRs.

4 Conclusions

The currently available benchmark data regarding systems sensitive to UMo fuel and/or Mo on the ICSBEP Handbook was collated and summarized herein. Available benchmark experiment data, especially for 20 wt.% ^{235}U enriched systems, is very limited. It is recommended that neutronics experiment data be evaluated as benchmarks to provide suitable validation data to support validation of LEU UMo reactors and fuel cycle modeling and simulation activities.

5 Acknowledgements

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