UTILIZING BENCHMARK DATA FROM THE ANL-ZPR DIAGNOSTIC CORES PROGRAM

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ABSTRACT

The support of the criticality safety community is allowing the production of benchmark descriptions of several assemblies from the ZPR Diagnostic Cores Program. The assemblies have high sensitivities to nuclear data for a few isotopes. This can highlight limitations in nuclear data for selected nuclides or in standard methods used to treat these data. The present work extends the use of the simplified model of the U9 benchmark assembly beyond the validation of k_{eff}. Further simplifications have been made to produce a data testing benchmark in the style of the standard CSEWG benchmark specifications. Calculations for this data testing benchmark are compared to results obtained with more detailed models and methods to determine their biases. These biases or "corrections factors" can then be applied in the use of the less refined methods and models. Data testing results using Versions IV, V, and VI of the ENDF/B nuclear data are presented for k_{eff}, f^{28}/f^{25}, c^{28}/f^{25}, and β_{eff}. These limited results demonstrate the importance of studying other integral parameters in addition to k_{eff} in trying to improve nuclear data and methods and the importance of accounting for methods and/or modeling biases when using data testing results to infer the quality of the nuclear data files.

1. INTRODUCTION

The term "benchmark" in a Zero Power Reactor (ZPR) program connotes a particularly simple loading aimed at gaining basic reactor physics insight, as opposed to studying a reactor design. The final series of benchmark experiments conducted on the Argonne National Laboratory (ANL) ZPR critical facilities was the Diagnostic Cores Program.[1] The objective of the Diagnostic Cores Program was to resolve longstanding discrepancies between calculated and measured values for small sample central worths, $ß_{eff}$ and the ^{238}U capture-to- ^{239}Pu fission reaction rate ratio (c^{28}/f^{49}). This program encompassed a wide range of spectra and emphasized strongly the reactor materials of greatest importance to the discrepant parameters.

These assemblies provide excellent systems for criticality safety validation. One assembly of the Diagnostic Cores Program was the U/Fe Benchmark Assembly, whose neutronics characteristics were dominated by ^{235}U and iron. Another was the U9 Benchmark Assembly, whose neutronics characteristics were dominated by ^{235}U and ^{238}U. The U9 assembly (9% ^{235}U) was intended to be a close plate analog of the Los Alamos National Laboratory (LANL) Big Ten assembly – a critical assembly with a cylindrical core of uranium (10% ^{235}U) and a depleted uranium reflector in which the traditional central worth discrepancies had not been observed. Both the U/Fe and U9 Benchmark assemblies have been included in the International Handbook of Evaluated Criticality Safety Benchmark Experiments[2] (as HEU-MET-FAST-035 and IEU-MET-FAST-010, respectively).

The present work will first discuss some of the benefits and caveats of using this type of benchmark assembly in criticality safety validation. It will then focus on the U9 Benchmark Assembly -- first describing the assembly and its features, then presenting the "criticality safety" benchmark model, and finally extending this model to include other integral measurements in a format suitable for data testing.

2. USING BENCHMARK DATA IN CRITICALITY SAFETY VALIDATION

Criticality safety benchmarks derived from the diagnostic cores program can provide sensitive tests of neutron cross section data and processing. The experiences with the U/Fe benchmark illustrate this. Compared to previous experience, initial criticality predictions were inaccurate for the series of uranium-iron diagnostic assemblies to which U/Fe belonged. The resulting investigation led to major revisions of the processing by ANL codes of resonance cross sections for structural isotopes.[3,4] In addition, deficiencies in the then current version of ENDF/B data (Version 4) were observed. Again, when the U/Fe Benchmark was first presented as a criticality safety benchmark, poor predictions of k_{eff} using the SCALE code package led to identification and correction of problems with its treatment of cross sections.

Sensitive benchmarks, such as U/Fe, are a double-edged sword. They provide unique opportunities to identify problems in cross section data and processing. This leads to a general improvement in predictive capability. On the other hand, it can be a misuse of these benchmarks to conclude that errors associated with them are typical of ordinary configurations. For example, the good k_{eff} predictions, made for hundreds of configurations using the same version of SCALE

that produced a 10% overprediction of k_{eff} for the U/Fe Benchmark, show that the SCALE error for U/Fe is not representative of the error for typical configurations. Sensitivity calculations can be used to help clarify and quantify the unique features of these special benchmark assemblies.

3. THE U9 BENCHMARK ASSEMBLY

The U9 Benchmark Assembly was first built in 1980 at the ZPR-9 facility. In 1981 this entire assembly (i.e., every plate and every drawer) was unloaded from the ZPR-9 facility and then reassembled in the ANL ZPR-6 facility. These two identical assemblies are also known by the designations ZPR-9/36, which identifies it as Assembly 36 at the ZPR-9 facility, and ZPR-6/9, which identifies it as Assembly 9 at the ZPR-6 facility. ZPR-9 Assembly 36 actually refers to a series of dozens of critical configurations that are variations designed to accommodate various experiments. By the time ZPR-9/36 was to be disassembled, it had evolved into an especially clean configuration that could be efficiently reassembled as ZPR-6/9. The particular configuration of ZPR-6/9 selected as being most suitable to form a criticality safety benchmark has the designation Loading 11. A description of the ZPR-6 fast critical facility, as well as complete details of the matrix and drawer loading data for Loading 11 of ZPR-6/9, are provided in the benchmark description IEU-MET-FAST-010 of the ICSBEP Handbook.[2] For the convenience of the reader, the map of the core layout and a diagram of the core unit cell are shown in Figures 1 and 2, respectively. The core layout in Figure 1 indicates the front drawer matrix loading of the stationary half.

The U9 Benchmark Assembly had very uniform core and reflector regions assembled entirely from plates of uranium, except for the matrix tubes, stainless steel drawers, and a few assorted pieces in the control rods. It had a simple core unit cell whose neutronics characteristics were dominated by ^{235}U and ^{238}U. The core half-height was 381 mm (15 in.) and consisted of three 1.6 mm (1/16-in.)-thick columns of 93% enriched uranium distributed between columns of depleted uranium. The only significant compromise in the intended simplicity of the core loading were the "control islands", which were necessitated by operational shutdown requirements. A control island consisted of a nine-fuel-column control rod drawer and five adjacent, stationary core drawers from which the total of six "extra" fuel columns in the control drawer had been removed. The axial and radial reflector drawers were filled entirely with depleted uranium.

A list of experiments performed in the U9 Benchmark Assembly is given below. As noted above, this assembly was part of a program to resolve several long-standing discrepancies between calculated and experimental values for a number of integral parameters. Experiments were done to characterize its neutronics properties as thoroughly as possible. But the main emphasis was on experiments to measure the reactivity associated with small samples of fissile material. None of the listed measurements, other than criticality, was made in Loading 11, but in U9 Benchmark Assembly loadings so similar to Loading 11 that the results are directly applicable to it. References 1, 5 and 6 are open-literature documents that contain information about some of the experiments. Argonne National Laboratory internal memoranda exist that describe all the experiments.

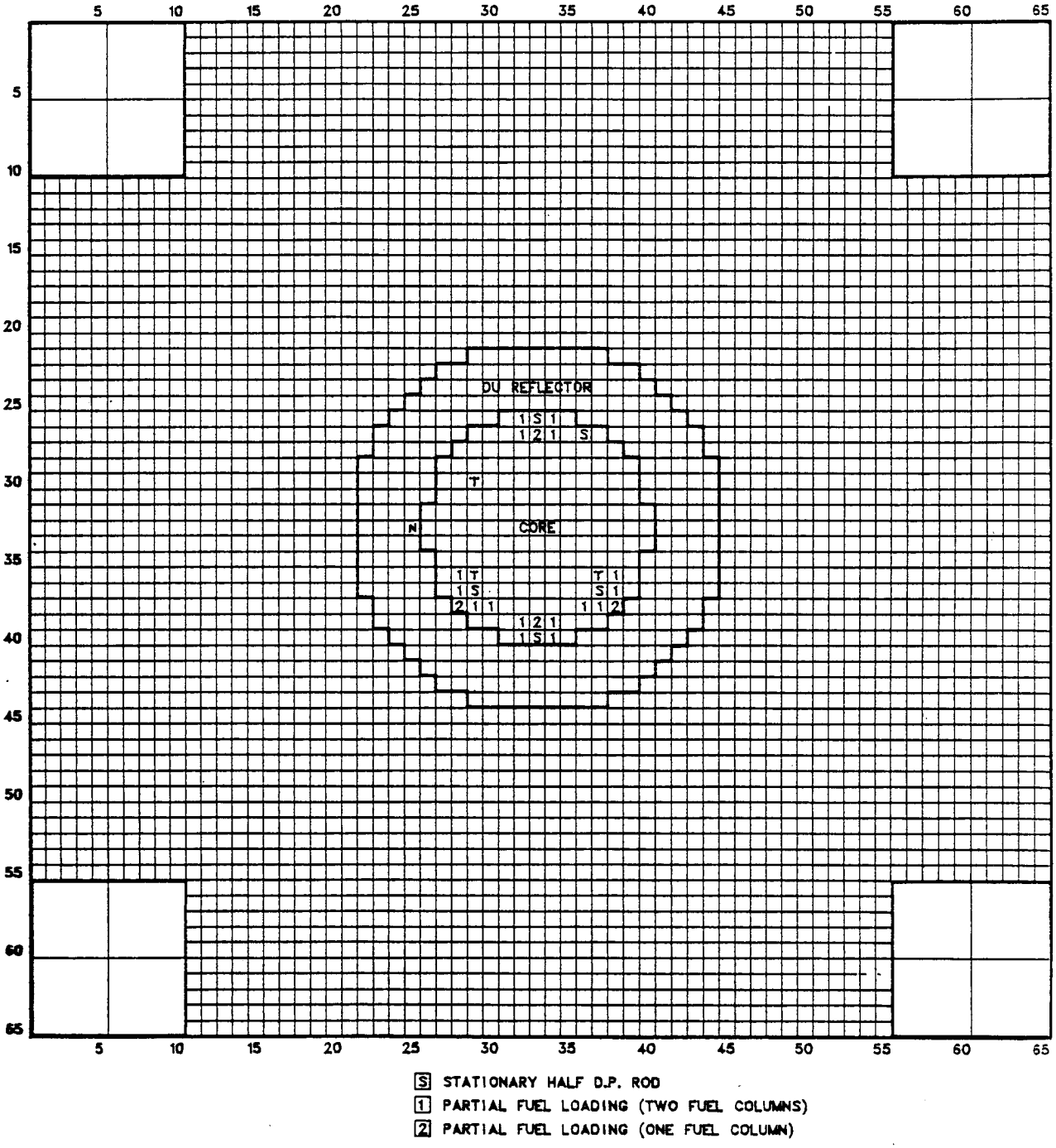

Figure 1. ZPR-6 Assembly 9 Stationary Half Front-Drawer Loading.

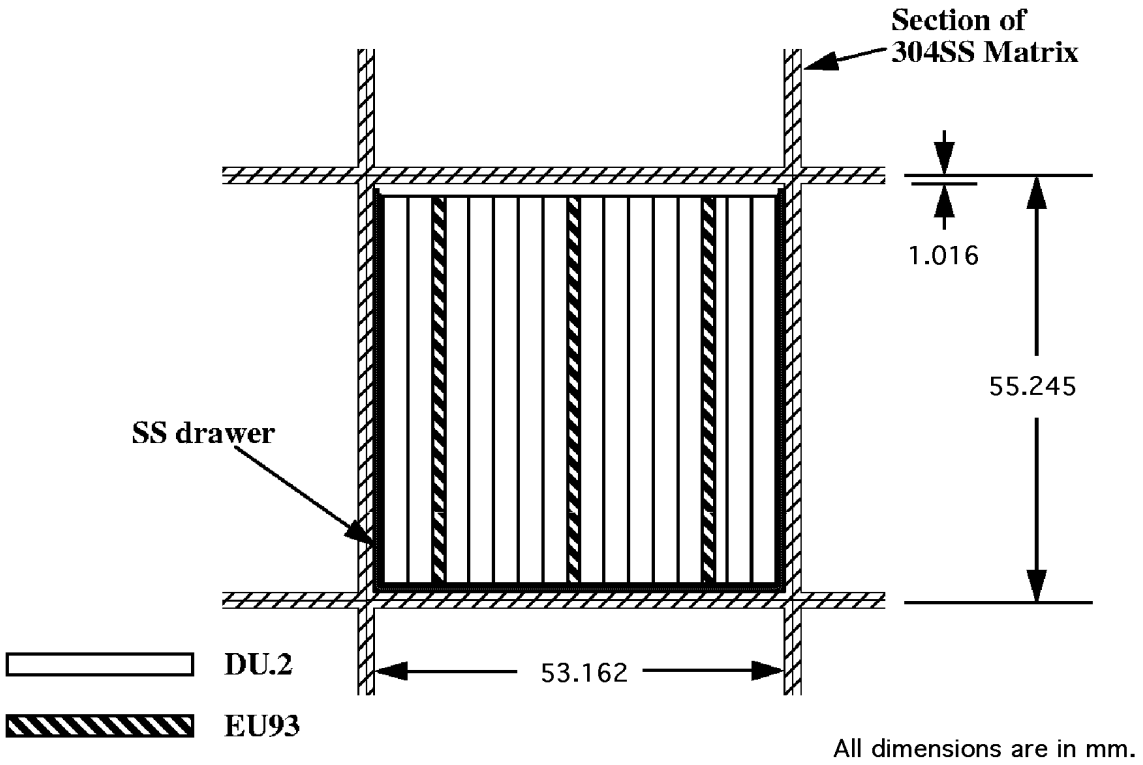

Figure 2. Cross Section of Core Unit-Cell showing Matrix and Plate-Loaded Drawer of ZPR-6 Assembly 9.

Experiments performed in the U9 Benchmark Assembly (ZPR-9/36 and ZPR-6/9) included:

- Criticality.
- Kinetics parameters: $ß_{eff}$, ß/l, and $ß_i$/ß.
- Control rod calibrations (Comparison of Inverse Kinetics and Positive-Period Methods).
- Matrix Interface gap worth.
- Reaction rates in a central cavity.
- Reaction rates in the unit cell (f^{25}, f^{28}, and c^{28}).
- Reaction-rate axial and radial distributions (f^{25}, f^{28}, and c^{28}).
- ANL-East/ANL-West c^{28} comparison measurement.
- Neutron spectrum measurements in core.
- Reaction rates in Proton-Recoil counter environment (f^{25}, f^{28}, f^{49}, and c^{28}).
- Small-sample worth measurements (comparison of Fine Auto Rod and Inverse Kinetics methods).
- Small-sample worth measurements (radial and axial distributions; effect of streaming path; sample cavity size effects).
- Worth of Dispersed-Fuel zone (criticality; small sample worths and distributions; reaction rates and distributions).
- Worth of Clumped-Fuel configuration (ZPR-6 Assembly 9A – criticality; small sample worths and distributions; reaction rates and distributions; prompt temperature coefficient; worth of fuel-thickened zones).

3.1 DETAILED MODEL OF THE U9 ASSEMBLY

This paper discusses a number of neutronics models of the U9 assembly. The first of these models is a fully detailed (plate-by-plate) three-dimensional model of ZPR-6/9 Loading 11. Every plate, drawer, matrix tube, and gap was modeled explicitly. This model includes no significant simplifications or approximations in either geometry or compositions and can be used with a rigorous methodology (such as the continuous-energy Monte Carlo code VIM[7]) to produce reference values for the assembly. That is, biases produced by the introduction of simplified models or methods can be determined by comparison with the VIM results for this fully detailed model.

A description and complete listing of this model is given in Reference 2. A subset of the experimental results are presented in Table 1 together with results obtained using the VIM code with this detailed model. The results with ENDF/B-IV data were obtained in the original analysis of these measurements (in the early 1980's). The ENDF/B-IV data overpredict the eigenvalue by ~0.6%. Subsequent "improvements" in the evaluated data files each increase this eigenvalue bias an additional 0.5%. The threshold fission rate ratio (f^{28}/f^{25}) is overpredicted by ~7% with the ENDF/B-IV data, and worsens significantly with the newer data. This (~10-12%) bias with ENDF/B-V and -VI data is larger than the error in the ratio of these fission cross sections. Considered together with the large overprediction of the eigenvalue with the ENDF/B-V and -VI data, these results suggest the calculated flux spectra for the U9 core is too hard. (Unfortunately, the neutron spectrum measurement mentioned above does not shed much light on the f^{28}/f^{25} error because only a small fraction of the spectrum contributing to the f^{28} threshold reaction was measured.) Given the extreme sensitivity of calculated results for the U9 assembly to the ^{238}U data, these results indicate the modern evaluated files for ^{238}U should be reviewed with particular attention to the scattering cross sections. No discrepancies are observed for predictions of the ratio of ^{238}U capture to ^{235}U fission.

Table 1. VIM Results with the Detailed As-Built Model.

Integral Parameter	Experimental Value ± 1σ	VIM Calc. ± 1σ ENDF/B-IV	VIM Calc. ± 1σ ENDF/B-V	VIM Calc. ± 1σ ENDF/B-VI
k_{eff}	1.0014 ± 0.0016	1.0076 ± 0.0005 (C-E): 0.0062	1.0118 ± 0.0002 (C-E): 0.0104	1.0175 ± 0.0003 (C-E): 0.0161
f^{28}/f^{25}	0.02931 ± 2.2%	0.03134 ± 0.52% (C/E): 1.069	0.03284 ± 0.46% (C/E): 1.120	0.03234 ± 0.32% (C/E): 1.103
c^{28}/f^{25}	0.1097 ± 1.8%	0.1115 ± 0.40% (C/E): 1.016	0.1114 ± 0.40% (C/E): 1.015	0.1085 ± 0.27% (C/E): 0.989
β_{eff}	0.007061 ± 1.3%	---	---	---

3.2 A SIMPLIFIED BENCHMARK MODEL OF THE U9 ASSEMBLY

A very accurate transformation to a simplified model is needed to make any of the ZPR assemblies a practical criticality-safety benchmark. There is simply too much geometric detail in an exact model of a ZPR assembly – even for a clean benchmark such as U9. The

transformation must reduce the detail to a practical level without masking any of the important features of the criticality experiment. And it must do this without increasing the total uncertainty far beyond that of the original experiment. Such a transformation was made for the U9 Benchmark Assembly using a pair of VIM continuous-energy Monte Carlo calculations.

The key features retained in the benchmark model are the region-averaged compositions, region volumes, and the global RZ geometry. The radial dimensions of the benchmark model are determined by the total cross-sectional area of the matrix positions included in each region, i.e., radii of cylindrical boundaries conserve cross-sectional areas of the corresponding regions in the detailed model. Axial dimensions of each region conserve the region volume. Note that since axial regions in the as-built model core have been taken at fuel plate boundaries (which may vary with matrix position), the axial extent that conserves the region volume may be "non-physical", i.e., it may not correspond to any actual fuel-plate boundary. Masses of the constituents within these regions are then homogenized to produce the region-averaged compositions, thereby conserving material masses within each region. The VIM output edits for the as-built model included the region-average compositions, which were extracted to construct the criticality safety benchmark model. This simple cylindrical model contains only nine homogeneous regions and nine compositions. These nine compositions include: four core regions, two depleted uranium axial reflector regions, one depleted uranium radial reflector region, and two empty matrix tube regions. Details of this simple model, including dimensions and atom densities, are provided in Reference 2.

As described above, the assembly was first modeled in full detail – every plate, drawer, matrix tube, and air gap was modeled explicitly. Then the regionwise compositions and volumes from this model were used as a homogeneous, two-dimensional (RZ) model. This simple model is the criticality-safety benchmark reported in Reference 2. The difference in k_{eff} values from the two models ($k_{simplified} - k_{detailed}$) is -0.0066 ± 0.0003. (Note that this value as well as the values given in the following table have been changed slightly from the values reported in Reference 2. This was the result of running additional Monte Carlo histories for several of the models and combining the results. None of these changes impact the results or conclusions given in Reference 2.) This difference in k_{eff} represents a bias in the eigenvalue due to the Monte Carlo transformation of the model. This transformation of the model is, of course, a composite of a number of simplifications, including homogenization of the unit cell (i.e., matrix tubes, drawers, and plates), the homogenization of different unit cells (i.e., smearing of the control islands), and the "edge-smoothing" (i.e., XYZ $\rightarrow$ RZ). Because each of these effects had been considered in the design of this critical assembly, each of these effects and their sum were minimized. Each of these effects can be modeled precisely with the VIM code and pairs of "intermediate" models were also generated to isolate and quantify these effects. These results are shown in Table 2. Each of the four representations of the U9 assembly was calculated with the VIM code using ENDF/B-V nuclear data.

Note that Configuration A and Configuration D are the modeling "end points" used to derive the transformation Δk for the benchmark. That is, the transformation $\Delta k = (k_D - k_A) = -0.0066 \pm 0.0003$.

Table 2. VIM Calculations of "Modeling" Effects in the U9 Assembly.

Configuration or Representation	K-effective
A. XYZ Heterogeneous "As-Built"	1.0118 ± 0.0002
B. XYZ "Smeared" Matrix Locations	1.0084 ± 0.0002
C. XYZ "Smeared" XY-Plane	1.0053 ± 0.0005
D. RZ Homogeneous Benchmark	1.0052 ± 0.0002

In Configuration B, all of the materials in a matrix location (i.e., plates, drawers, matrix tubes, gaps) have been homogenized within that matrix location and within the axial (Z) ranges of the RZ benchmark model. That is, the eigenvalue difference ($k_A - k_B$) = +0.0034 ± 0.0003 represents the unit-cell heterogeneity effect (which has been eliminated from the RZ benchmark model).

In Configuration C, all of the "smeared" matrix locations of Configuration B have been homogenized in the XY-plane while maintaining the outer XY boundaries of the core and reflector regions and also maintaining the axial ranges of Configuration B (and of the RZ benchmark model). The transformation between Configurations B and C removed the variation of the drawer loadings within the core and reflector regions, i.e., eliminated the control islands, etc. The eigenvalue difference ($k_B - k_C$) = +0.0031 ± 0.0005 represents the "control-island" effect (which also has been eliminated from the RZ benchmark model).

In Configuration D, all of the "smeared" matrix locations of Configuration C have been homogenized within (volume-equivalent) cylindrical radial boundaries of the core and reflector regions, yielding the final RZ benchmark model. The transformation between Configurations C and D replaces the "stepped" outer boundaries of the XYZ model with the cylindrical outer boundaries of the RZ model. The eigenvalue difference ($k_C - k_D$) = +0.0001 ± 0.0006 represents the "edge-smoothing" effect (which also has been eliminated from the RZ benchmark).

None of the above effects is large. Furthermore, none of these modeling effects is beyond the rigor of continuous-energy Monte Carlo methods. Therefore, the calculation of the transformation Δk for this benchmark = ($k_D - k_A$) = -0.0066 ± 0.0003 is adequate. In the discussion of this bias factor in Reference 2, an attempt was made to account for the uncertainty in this correction due to its dependence on the evaluated nuclear data. Based on estimated sensitivities of the eigenvalue to nuclear data errors, an additional ±0.002 uncertainty was combined with the statistical uncertainty of the Monte Carlo calculations of this transformation Δk to yield ±0.0021. The present study has also calculated these "end points" using ENDF/B-VI nuclear data. Using the ENDF/B-VI values, the transformation Δk for this benchmark = ($k_D - k_A$) = -0.0056 ± 0.0004. The variation of this bias factor by 0.1% Δk is well within with the "conservative" uncertainty estimate provided in Reference 2.

In addition to the above modeling simplifications between the detailed three-dimensional plate model of the assembly and the cylindrical homogeneous model, two other modeling simplifications relative to the as-built experiment can be identified. The matrix interface gap effect (+0.00013 ± 0.00006 Δk) and the room return (-0.00003 ± 0.00003 Δk), although both small enough to neglected, can be combined with the transformation Δk for the simplified

benchmark to adjust the measured excess reactivity of the as-built loading to yield a result appropriate for the benchmark model, as shown in Table 3.

Table 3. Experimental and Benchmark-Model Eigenvalues.

Experimental k_{eff}	1.0014 ± 0.0016
Remove matrix interface gap	+0.00013 ± 0.00006
Remove room return	-0.00003 ± 0.00003
Monte Carlo transformation of model	-0.0066 ± 0.0021
Benchmark-Model k_{eff}	0.9949 ± 0.0026

3.3 INTEGRAL DATA TESTING WITH A SIMPLIFIED MODEL

As mentioned above, there were many measurements in the U9 Benchmark Assembly in addition to the excess reactivity of a clean reference configuration. Many of these integral measurements can be useful in testing nuclear data and methods. In fact, the very limited set of Monte Carlo results (k_{eff} and two reaction rate ratios) given in Section 3.1 illustrate how important the inclusion of integral data in addition to k_{eff} can be to drawing inferences on the quality of the nuclear data files. However, their use with the simplified benchmark model requires a set of "correction factors" to account for the transformation from the detailed plate environment of the critical assembly to the homogenized model of the benchmark.

The present work has produced a set of "correction factors" for a limited set of integral measurements from the U9 assembly; namely, for the integral measurements included in Table 1 (k_{eff}, f^{28}/f^{25}, c^{28}/f^{25}, and β_{eff}). These factors will also be obtained for select calculations based on multigroup cross sections and standard deterministic methods. Various sets of multigroup constants were obtained using the ETOE-2/MC^2-2/SDX code system[3] with both ENDF/B-V and ENDF/B-VI nuclear data. The multigroup libraries were generated with 20 broad energy groups (E_{top} ~ 14.19 MeV and varying Δu ~ 0.5). Furthermore, this variety of multigroup libraries were of two types: (1) one treatment included the cell heterogeneity and the spatial variation of the neutron energy spectrum in generation of "cell-average" cross sections and (2) a second treatment considering only the homogeneous cell compositions and fundamental mode spectra. Multigroup calculations using the former libraries (i.e., heterogeneous cell-average constants) were performed for XYZ and RZ models using fine mesh finite difference diffusion theory (FDDT), coarse mesh nodal diffusion theory (NDT) and nodal transport theory (NTT). Diffusion theory calculations were performed both with and without the use of Gelbard diffusion coefficient modifiers, which account for neutron streaming in the plate cells and the P1-to-B1 transport effect. In this assembly there is no significant streaming effect. These methods, described in many references, e.g., References 1 and 3, represent standard treatment for the typical plate-type ZPR critical assemblies. Multigroup calculations using the latter libraries (i.e., homogeneous fundamental mode collapse) were also performed for XYZ and RZ models using FDDT and NDT methods. Data testing results and sensitivity analyses typically employ methods and libraries such as these.

In considering the data testing calculations with the simplified cylindrical model discussed above, it was realized that this simple model could have (or perhaps should have) been simplified even further. For example, two types of core compositions in the criticality safety benchmark model arise because the front drawers (which contain the core plate loadings) contain different piece sizes in the first nine inches than in the following six inches. This produces slightly different fuel concentrations in these axial zones – a difference that is worth retaining even though it has little effect on the eigenvalue. However, the variation of these two core compositions between the stationary and moveable halves of the assembly is extremely slight and use of an average of these pairs of atom densities has a negligible effect on calculated integral parameters. It was decided to produce a further simplified model, which would be symmetric axially across the assembly midplane, would exclude the empty matrix tube regions beyond the radial and axial reflectors, and retain only four compositions, namely the two axial regions of the core and the radial and axial depletion uranium reflectors. This simplified cylindrical model, described fully in Table 4 and Figure 2, will be referred to as the data testing benchmark model.

Table 4. Dimensions and Compositions for the Simplified Data Testing Benchmark Model of the U9 Assembly.

	Core 1 (3-inch Fuel)	Core 2 (2-inch Fuel)	Axial Reflector	Radial Reflector
Region Boundaries (cm)				
R_{lower}	0.000	0.000	0.000	40.996
R_{upper}	40.996	40.996	40.996	65.157
Z_{lower}	0.00	22.941	38.181	0.000
Z_{upper}	22.941	38.181	120.461	120.461
Atom Densities (atoms/barn-cm)				
^{235}U	3.48543×10^{-3}	3.47666×10^{-3}	8.27868×10^{-5}	8.56868×10^{-5}
^{238}U	3.52633×10^{-2}	3.53869×10^{-2}	3.70703×10^{-2}	3.83747×10^{-2}
^{234}U	3.34211×10^{-5}	3.33328×10^{-5}	0.0	0.0
^{236}U	1.60227×10^{-5}	1.59801×10^{-5}	0.0	0.0
Cr	1.86067×10^{-3}	1.87418×10^{-3}	1.72627×10^{-3}	1.69502×10^{-3}
Ni	7.49053×10^{-4}	7.54654×10^{-4}	7.03836×10^{-4}	6.86302×10^{-4}
Fe	6.65688×10^{-3}	6.70752×10^{-3}	6.26631×10^{-3}	6.13244×10^{-3}
Al	0.0	0.0	4.16747×10^{-4}	0.0
C	9.62798×10^{-5}	9.63974×10^{-5}	3.98412×10^{-5}	3.77935×10^{-5}
Mo	1.18327×10^{-5}	1.19799×10^{-5}	1.12206×10^{-5}	1.07671×10^{-5}
Mn	1.63509×10^{-4}	1.64823×10^{-4}	1.46859×10^{-4}	1.46803×10^{-4}
Cu	2.38833×10^{-5}	2.42329×10^{-5}	2.13537×10^{-5}	2.16820×10^{-5}
H	1.94526×10^{-5}	1.94443×10^{-5}	2.83602×10^{-6}	2.53803×10^{-6}
Si	7.16001×10^{-5}	7.42038×10^{-5}	8.31237×10^{-5}	7.69676×10^{-5}
Cl	3.33410×10^{-5}	3.34590×10^{-5}	4.90256×10^{-6}	4.39454×10^{-6}
F	9.90935×10^{-5}	9.94440×10^{-5}	1.45178×10^{-5}	1.30132×10^{-5}

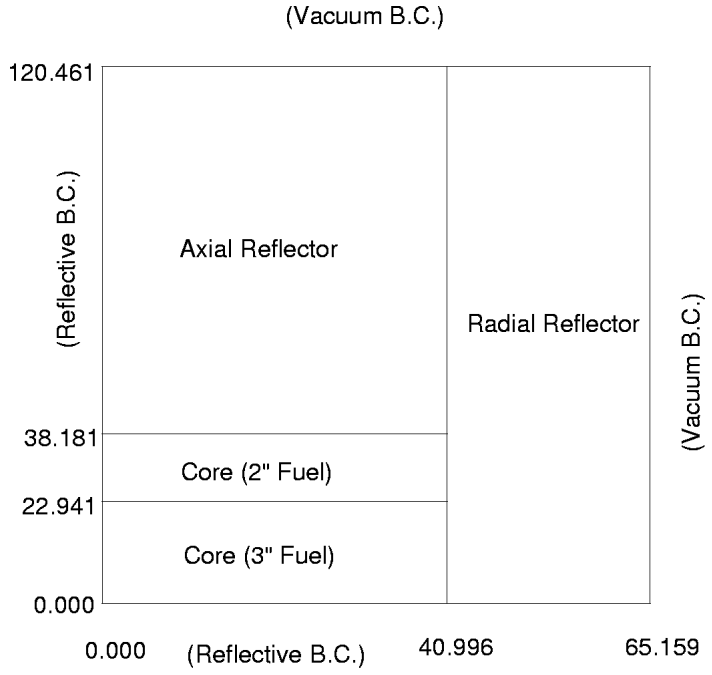

Figure 2. Cylindrical Representation of Simplified Data Testing Benchmark Model of the U9 Assembly (dimensions in cm).

ENDF/B-V data testing results obtained with an XYZ model are shown in Table 5, together with the measured values and the VIM results for the detailed "as-built" model. As mentioned above, the VIM results with ENDF/B-V data overpredict the eigenvalue by 1.1% Δk, overpredict the ^{238}U to ^{235}U fission rate ratio by 12%, and agree (within experimental uncertainty) with the capture in ^{238}U relative to the ^{235}U fission rate. Eigenvalue results using the heterogeneous cross sections are somewhat higher (~0.3-0.4% Δk) than the Monte Carlo values. The biases for the reaction rate ratios based on the heterogeneous cross sections differ only slightly (within ~1%) from the Monte Carlo values, and the prediction of β_{eff} is within the 1^{+}% uncertainty. The homogeneous cross sections lower k_{eff} by ~0.4-0.5% Δk (which is slightly larger than the heterogeneity effect determined by Monte Carlo) and raise the reaction rate ratios by ~1-2%. Of course, the reduced C/E for the homogeneous case is misleading, as this eigenvalue should be compared with an "adjusted" excess reactivity (to correspond to a fictitious homogeneous assembly). This difference, as well as the ~1-2% change in the reaction rate ratios, highlights the necessity for accounting for biases which result from methods and/or modeling approximations whenever using C/E comparisons (e.g., in data testing or sensitivity analyses).

ENDF/B-V data testing results obtained with the simplified RZ data testing benchmark model are shown in Table 6 (again displayed with the measured values and the VIM results for the detailed "as-built" model). The agreement between results with the heterogeneous cross sections (with FDDT and Gelbard Ds) and the Monte Carlo results is slightly better using the RZ model (than with the XYZ model). The biases for the reaction rate ratios based on the heterogeneous cross sections are close to the Monte Carlo values, and the prediction of β_{eff} is again within the 1^{+}% uncertainty. As observed with the XYZ calculations, the homogeneous cross sections

Table 5. ENDF/B-V Data Testing Results Obtained with XYZ Model.

Integral Parameter	Experimental Value ± 1σ	Detailed "As-Built" VIM Calc. ± 1σ	XYZ, NDT, Heter. σ's, w/ Gelbard Ds	XYZ, NDT, Homog. σ's, w Gelbard Ds	XYZ, NTT, Heter. σ's, ---
k_{eff}	1.0014 ± 0.0016	1.0118 ± 0.0002 (C-E): 0.0114	1.0149 (C-E): 0.0135	1.0104 (C-E): 0.0090	1.0166 (C-E): 0.0152
f^{28}/f^{25}	0.02931 ± 2.2%	0.03284 ± 0.46% (C/E): 1.120	0.03270 (C/E): 1.116	0.03327 (C/E): 1.135	---
c^{28}/f^{25}	0.1097 ± 1.8%	0.1114 ± 0.40% (C/E): 1.015	0.1124 (C/E): 1.025	0.1135 (C/E): 1.035	---
β_{eff}	0.007061 ± 1.3%	---	0.007006 (C/E): 0.992	0.007037 (C/E): 0.997	---

Table 6. ENDF/B-V Data Testing Results obtained with RZ Model.

Integral Parameter	Experimental Value ± 1σ	Detailed "As-Built" VIM Calc. ± 1σ	RZ, FDDT, Heter. σ's, w/ Gelbard Ds	RZ, FDDT, Heter. σ's, w/o Gelbard Ds	RZ, FDDT, Homog. σ's, w/o Gelbard Ds
k_{eff}	1.0014 ± 0.0016	1.0118 ± 0.0002 (C-E): 0.0114	1.0126 (C-E): 0.0112	1.0115 (C-E): 0.0101	1.0067 (C-E): 0.0053
f^{28}/f^{25}	0.02931 ± 2.2%	0.03284 ± 0.46% (C/E): 1.120	0.03277 (C/E): 1.118	0.03278 (C/E): 1.118	0.03337 (C/E): 1.139
c^{28}/f^{25}	0.1097 ± 1.8%	0.1114 ± 0.40% (C/E): 1.015	0.1124 (C/E): 1.025	0.1124 (C/E): 1.025	0.1135 (C/E): 1.035
β_{eff}	0.007061 ± 1.3%	---	0.007009 (C/E): 0.993	0.007011 (C/E): 0.993	---

lower k_{eff} by ~0.5% Δk (which is slightly larger than the heterogeneity effect determined by Monte Carlo) and raise the reaction rate ratios by ~1-2%. The comparison of results between the XYZ model and the RZ indicate the eigenvalue for the cylindrical model is lower by ~0.3% Δk, with only slight changes for the reaction rate ratios.

ENDF/B-VI data testing results obtained with an XYZ model are shown in Table 7, together with the measured values and the VIM results for the detailed "as-built" model. As mentioned above, the VIM results with ENDF/B-VI data overpredict the eigenvalue by ~1.6% Δk (i.e., even 0.5 Δk higher than the ENDF/B-V result), overpredict the ^{238}U to ^{235}U fission rate ratio by 10%, and agree (within experimental uncertainty) with the capture in ^{238}U relative to the ^{235}U fission rate. Eigenvalue results using the heterogeneous cross sections are somewhat higher (~0.3-0.5% Δk) than the Monte Carlo values. The biases for the reaction rate ratios based on the heterogeneous cross sections change slightly (within ~1%) from the Monte Carlo values, and the prediction of β_{eff} is between one and two standard deviations larger than the experimental

uncertainty. The homogeneous cross sections lower k_{eff} by ~0.2-0.3% Δk (which is slightly smaller than the heterogeneity effect observed with the Version V data) and raise the reaction rate ratios by ~1-2%. As stated above, the reduced C/E for the homogeneous case is misleading, as this eigenvalue should be compared with an "adjusted" excess reactivity (to correspond to a fictitious homogeneous assembly).

ENDF/B-VI data testing results using the simplified RZ data testing benchmark model (shown in Table 8) were obtained only with FDDT and homogeneous cross sections. The eigenvalue bias between the XYZ and RZ model obtained with these cross sections is ~0.3% Δk, as observed using the Version V data. The VIM result with ENDF/B-VI nuclear data for the homogeneous RZ model is also given in Table 8. The difference between these VIM eigenvalues (+0.56 % Δk) was quoted previously in reference to the transformation Δk for the simplified benchmark and its variation between ENDF/B-V and -VI.

Table 7. ENDF/B-VI Data Testing Results obtained with XYZ Model.

Integral Parameter	Experimental Value ± 1σ	Detailed "As-Built" VIM Calc. ± 1σ	XYZ, NDT, Heter. σ's, w/ Gelbard Ds	XYZ, NDT, Homog. σ's, w/ Gelbard Ds	XYZ, NTT, Heter. σ's, ---
k_{eff}	1.0014 ± 0.0016	1.0175 ± 0.0003 (C-E): 0.0161	1.0206 (C-E): 0.0192	1.0182 (C-E): 0.0168	1.0224 (C-E): 0.0210
f^{28}/f^{25}	0.02931 ± 2.2%	0.03234 ± 0.32% (C/E): 1.101	0.03251 (C/E): 1.109	0.03320 (C/E): 1.133	---
c^{28}/f^{25}	0.1097 ± 1.8%	0.1085 ± 0.27% (C/E): 0.989	0.1104 (C/E): 1.006	0.1112 (C/E): 1.014	---
β_{eff}	0.007061 ± 1.3%	---	0.007192 (C/E): 1.019	0.007214 (C/E): 1.022	---

Table 8. ENDF/B-VI Data Testing Results obtained with RZ Model.

Integral Parameter	Experimental Value ± 1σ	Detailed "As-Built" VIM Calc. ± 1σ	Homog. RZ VIM Calc. ± 1σ	RZ, FDDT, Homog. σ's, w/o Gelbard Ds
k_{eff}	1.0014 ± 0.0016	1.0175 ± 0.0003 (C-E): 0.0161	1.0119 ± 0.0002 (C-E): 0.0105	1.0146 (C-E): 0.0132
f^{28}/f^{25}	0.02931 ± 2.2%	0.03234 ± 0.32% (C/E): 1.101	---	0.03329 (C/E): 1.136
c^{28}/f^{25}	0.1097 ± 1.8%	0.1085 ± 0.27% (C/E): 0.989	---	0.1111 (C/E): 1.013
β_{eff}	0.007061 ± 1.3%	---	---	0.007222 (C/E): 1.023

The calculational results presented above for the U9 Assembly have utilized a variety of methods, models and evaluated nuclear data files. These sets of numbers can be further compared to produce two additional sets of useful results. First, the availability of results with a rigorous method (continuous-energy Monte Carlo) using a fully detailed representation of the assembly allows determination of "correction factors" appropriate to the application of simpler methods and/or models. Determination of these bias factors was, in fact, a principle motivation for undertaking these calculations. Second, some of these correction factors can be determined based on either ENDF/B Version V or VI data. Comparison of these different results provides some estimate of their sensitivity to the particular nuclear data evaluation. The sensitivity to nuclear data is often a matter of speculation.

Correction factors for the use of the simplified data testing benchmark model of the U9 Assembly have been calculated for the integral parameters k_{eff}, f^{28}/f^{25}, c^{28}/f^{25}, and β_{eff}. For the first three of these parameters, the correction factors were derived as the difference between the calculated parameter obtained from the detailed VIM calculation and the value obtained using the homogeneous cross sections with the homogeneous RZ benchmark model. For β_{eff} the correction factor was derived as the difference between β_{eff} calculated using heterogeneous cross sections with NDT and the XYZ model and the value obtained using the homogeneous cross sections with the homogeneous RZ benchmark model. Correction factors derived from the ENDF/B Version V and Version VI results are shown in Table 9. For k_{eff} and β_{eff} , there is approximately factor of 2 difference between the correction factors obtained with the two data evaluations. The dependence on nuclear data for the remaining correction factors is weaker.

Table 9. Correction Factors for the Simplified Data Testing Benchmark Model of the U9 Assembly.

Parameter	Correction Factor		Uncertainty in Correction Factor
	with ENDF/B-V	with ENDF/B-VI	
k_{eff}	+0.0061	+0.0029	±0.002
f^{28}/f^{25}	-1.9%	-3.5%	±1%
c^{28}/f^{25}	-2.0%	-2.4%	±0.5%
β_{eff}	-0.6%	-0.4%	±0.2%

The values in Table 9 indicate it is important to account for the effect of the simplification in methods and models. Furthermore, the differences between the ENDF/B-V and -VI values are also significant, indicating the appropriate values should be used. Also shown in Table 9 are "estimated" uncertainties in these correction factors. These values are based on differences observed between the Version V and VI results and appear to be consistent with "engineering judgment" of (1) the sensitivities of these parameters to the methods employed in these calculations and in standard benchmark data validation calculations and (2) the sensitivities to nuclear data uncertainties. Clearly, these correction factors and the estimated uncertainties would be inappropriate if either the methods or some sensitive portion of the nuclear data were greatly different than those used in this study.

SUMMARY

The support of the criticality safety community is allowing the production of benchmark descriptions of several assemblies from the ZPR Diagnostic Cores Program. These assemblies have high sensitivities to nuclear data for a few isotopes. This can highlight limitations in nuclear data for selected nuclides or in standard methods used to treat these data. The present work extends the use of the simplified model of the U9 benchmark assembly beyond the validation of k_{eff} and presents calculated results for a limited set of measured integral parameters based on both higher order methods/models (continuous energy Monte Carlo with a fully detailed model) and simplified methods/models (multigroup methods with homogeneous models). Consideration of these additional parameters not only enhances the usefulness of the benchmark for data testing, but is equally important in many applications of sensitivity analyses, such as studies of the range of applicability in criticality safety. This work also illustrates the need to account for calculational biases due to methods and/or modeling approximations when trying to infer the quality of the nuclear data files.

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