ENCLOSURE 2
ATTACHMENT 1

SHINE MEDICAL TECHNOLOGIES, INC.

SHINE MEDICAL TECHNOLOGIES, INC. APPLICATION FOR CONSTRUCTION PERMIT RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

ATKINS-NS-DAC-SHN-15-03, REVISION 1
MCNP 6.1 VALIDATION WITH CONTINUOUS ENERGY ENDF/B-VII.1 CROSS SECTIONS FOR SHINE MEDICAL TECHNOLOGIES

81 pages follow

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1. Introduction

Nuclear criticality safety analysis is performed for fissile material systems for the SHINE Medical Technologies facility. The nuclear criticality safety analysis establishes the nuclear safety operating limits for the systems and operations. Calculation methods are used to provide an estimate of criticality conditions and the margin of subcriticality (MoS) for the systems and operations under evaluation. The computational methods predict the neutronic behavior of the system and operation. However, certain approximations are inherent in the computer code used including inexact neutron cross section data and statistical uncertainty.

Validation compares the computational method with documented critical experiments to determine any bias that might exist between the calculated reactivity of a given system and the actual conditions. Validation is a process that determines and establishes computational method applicability, adequacy, and uncertainty.

Following the guidance in Reference 10, this report documents the MCNP 6.1 validation. This report includes discussions of input files that model the critical experiments chosen for validation of the MCNP 6.1 computer code system for SHINE Medical Technologies operations, statistical evaluation of the calculation results, and the code bias and bias uncertainty. The validation is conducted using the ENDF/B-VII.1 continuous energy group cross section library. The validation is for use by nuclear criticality safety personnel in performing analysis and evaluation of various facility / site activities involving enriched uranium. Through the selection and validation of appropriate benchmark critical experiments and analysis, this report will validate the computational methods for an entire range of normal and off-normal operating conditions involving heterogeneous and homogeneous fissile material. Toward that end, critical experiments are modeled as reported in NEA/NCS/DOC (95)03 (Reference 1).

1.1. Limits of Applicability

The parameters associated with the critical experiments documented in this report will be used to set the Area of Applicability (AoA) for applications modeling fissile material systems and operations. Applications using the bias and bias uncertainty established for this experiment data set must use the modeling conventions described in Table 1 and the AoA listed in Table 9, or have the Upper Subcritical Limit (USL) reduced. The benchmark calculations were performed on the Atkin's Linux computer cluster (Reference 3); therefore the validation conclusions herein are applicable to this computer cluster. This is a cluster of similar computers utilizing Intel processors that have been demonstrated to accurately reproduce the LANL supplied MCNP 6.1 verification test cases; this is recorded in Reference 10. The configuration control of this cluster is maintained by Reference 11; any hardware or operating system modification to the cluster requires a repeat of the verification tests.

2. MCNP 6.1 Code

The verification of MCNP 6.1 has been completed on the Atkins' Linux computer cluster (Reference 3). All computers have 64-bit hardware and use the 64-bit version of Linux. Distribution of the calculation jobs among the individual CPUs is controlled by the Sun Grid Engine queue software running on the master Linux computer. Additional Linux execution hosts run calculation jobs at the command of the queue master. MCNP 6.1 has been installed in the read only disk area; the installation has been verified with the execution of the sample problems from Reference 2. This disk is shared with the execution hosts. Hardware and software used with the Atkins Linux computer cluster is managed with the Atkins NS System's configuration control.

2.1. MCNP Summary

MCNP is a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, including the capability to calculate eigenvalues for critical systems (Reference 2). The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori.

Pointwise cross-section data are used. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-VII.1) are accounted for. Thermal neutrons are described by both the free gas and $S(\alpha,\beta)$ models.

Important standard features that make MCNP very versatile and easy to use include a powerful general source, criticality source, and surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data.

2.2. ENDF/B-VII.1 Cross Section Library

The ENDF/B-VII.1 cross-section library is used for the critical experiment calculations in this validation analysis. This library contains data for over 300 nuclides. A list of the elements used in this evaluation is provided in Table 1. Where the library does not contain a "natural" mixture of isotopes, the isotopic fractions are included. All of these isotopes were identified with the .80c extension in the cases executed for the validation. The graphite (grph.20t) light water (lwtr.20t) and polyethylene (poly.20t) S(α,β) correction are used for graphite, water and hydrocarbon materials respectively. The lwtr.20t correction is used for water that is found in concrete as well. Both the be-o.20t and o-be.20t corrections are used with the cases containing BeO.

Note that experiment HEU-SOL-THERM-046 included ^{2}H and ^{17}O in an attempt to improve the accuracy of the model. However, the USL calculated with this validation is for applications modeling all oxygen as ^{16}O and all hydrogen as ^{1}H. While this introduced some small bias, it is exactly this bias that is measured herein.

Table 1 - Library Definitions for Various Elements

Element	ZAID	Isotopic Fraction*
Hydrogen	1001	
Boron	5010	0.199
	5011	0.801
Carbon	6000	
Nitrogen	7014	0.99636
	7015	0.00364
Oxygen	8016	
Sodium	11023	
Magnesium	12024	0.7899
	12025	0.100
	12026	0.1101
Aluminum	13027	
Silicon	14028	0.92223
	14029	0.04685
	14030	0.03092
Phosphorus	15031	

Element	**ZAID**	**Isotopic Fraction***
Sulfur	16032	0.9499
	16033	0.0075
	16034	0.0425
	16036	0.0001
Chlorine	17035	0.7576
	17037	0.2424
Potassium	19039	0.932581
	19040	0.000117
	19041	0.067302
Calcium	20040	0.96941
	20042	0.00647
	20043	0.00135
	20044	0.02086
	20046	0.00004
	20048	0.00187
Titanium	22046	0.0825
	22047	0.0744
	22048	0.7372
	22049	0.0541
	22050	0.0518
Chromium	24050	0.04345
	24052	0.83789
	24053	0.09501
	24054	0.02365
Manganese	25055	
Iron	26054	0.05845

Element	ZAID	Isotopic Fraction*
	26056	0.91754
	26057	0.02119
	26058	0.00282
Cobalt	27059	
Nickel	28058	0.68077
	28060	0.26223
	28061	0.011399
	28062	0.036346
	28064	0.009255
Copper	29063	0.6915
	29065	0.3085
Zinc	30064	0.4917
	30066	0.2773
	30067	0.0404
	30068	0.1845
	30070	0.0061
Zirconium	40090	0.5145
	40091	0.1122
	40092	0.1715
	40094	0.1738
	40096	0.0280
Niobium	41093	
Molybdenum	42092	0.1453
	42094	0.0915
	42095	0.1584
	42096	0.1667

Element	ZAID	Isotopic Fraction*
	42097	0.0960
	42098	0.2439
	42100	0.09820
Silver	47107	0.51839
	47109	0.48161
Cadmium	48106	0.0125
	48108	0.0089
	48110	0.1249
	48111	0.1280
	48112	0.2413
	48113	0.1222
	48114	0.2873
	48116	0.0749
Indium	49113	0.0429
	49115	0.9571
Tantalum	73181	
Uranium	92234	Specified by individual experiments.
	92235	
	92236	
	92238	
*From Reference 12.		

3. Validation Methodology

ANSI/ANS-8.1 (Reference 4) requires that calculational methods used for nuclear criticality safety (e.g., determining k_{eff} of a system or deriving subcritical limits) be validated to determine the appropriate biases and uncertainties for the areas of applicability. The bias and uncertainty represent the numerical difference between the results of modeling critical benchmark experiments with a computer code and the experimental k_{eff}. These biases may result in either under- or over-predictions of criticality. The bias may be reported as

either a positive or negative bias. A positive bias occurs when the computations tend to report a higher k_{eff} than the benchmark experiments (i.e., $k_{eff} > 1.0$). A negative bias occurs when the calculated results tend to report a lower k_{eff} than the benchmark experiments (i.e., $k_{eff} < 1.0$).

ANSI/ANS-8.24 (Reference 6) outlines the validation methodology and documentation used herein while NUREG/CR-6698 (Reference 10) details the calculation algorithms. Biases (and their associated uncertainties) are determined through statistical treatment of the calculated results from criticality benchmark experiments. Weighted single sided lower tolerance limits are used for statistical calculations in this validation report when the calculated results data are normally distributed. A non-parametric method is used when the calculated results data are not from a normal statistical distribution.

When performing calculations to assess the subcriticality of a system or operation, a limit must be established on the calculated k_{eff} to ensure that subcriticality is achieved. This limit is defined for the purposes of this validation as the Upper Subcritical Limit (USL). In this validation, the USL is determined by statistical analysis of the calculated k_{effs} from the benchmark critical experiments.

3.1. Establishment of an Upper Subcritical Limit

The purpose of a computer code validation is to determine values of k_{eff} that are demonstrated to be subcritical (at or below the USL) for areas of applicability similar to systems or operations being analyzed. The USL is defined as follows:

$$USL = 1.0 - \text{Bias} - \text{Bias Uncertainty} – \text{Margin of Subcriticality (MoS)}$$

setting $\bar{k}_{eff} = 1.0 – \text{Bias}$ and $K^*S_t = \text{Bias Uncertainty}$

gives: $$USL = \bar{k}_{eff} - K^* S_t - MoS$$

where: USL = Maximum subcritical value of k_{eff}

$\bar{k}_{eff}$ = weighted mean k_{eff} value of the benchmark experiments

K^* = tolerance factor for 95% confidence that 95% of the population is bound

S_t = square root of the pooled variance

MoS = margin of subcriticality

From this, a k_{eff} calculated by the analysis is required to meet the following condition:

$$\text{calculated } k_{eff} + 2\sigma \leq USL$$

where σ is the Monte Carlo statistical uncertainty associated with the analysis.

As defined, the USL explicitly incorporates a MoS, which is required per ANSI/ANS-8.1. The MoS is an additional safety factor which is applied to the statistically calculated limit (e.g., a lower tolerance limit).

The bias and its associated uncertainty may be represented by one of several statistical methods:

- a weighted, single sided, lower tolerance limit,
- a weighted confidence interval, or
- a non-parametric statistical analysis.

3.2. Margin of Subcriticality

The MoS is an administrative addition in Δk applied to nuclear criticality safety calculations. The MoS is site specific and usually contained in the fuel facility license or other regulatory authorization basis. The MoS value for SHINE applications is 0.05. This value is typical of uranium processing facilities. All materials and processes within the SHINE facility are established technology and benchmarking against experiments using sufficiently similar materials and enrichments as expected to be used in the SHINE facility is performed herein. This report documents the ability to predict k_{eff} accurately for the SHINE processes. Therefore, it is judged that the proposed margin of subcriticality is acceptable and greater margin is not needed.

For systems which are outside the validation area of applicability, an increased MoS may be warranted, depending on the specific problem being analyzed. The analyst must document any extrapolation beyond the validation area of applicability and justification must be made for no adjustments to the MoS when extrapolations are made.

3.3. Determination of the Area of Applicability

The area of applicability determination quantifies parameters potentially important to the computational calculation of k_{eff}. An area of applicability determination should be performed as a part of every calculation done and compared to the area of applicability of the benchmark experiments used for the code validation. This comparison ensures that appropriate benchmark experiments have been selected to determine the USL for the calculation. The area of applicability determination for the benchmark experiments used in this validation has been performed using guidelines consistent with LA-12683 (Reference 5), specifically Appendix E of that report.

3.4. Discussion of Statistical Analysis

A weighted, single sided lower tolerance limit is a single lower limit above which a defined fraction of the true population of k_{eff} is expected to lie, within a prescribed confidence and with the defined area of applicability. A lower tolerance limit should be used when there are no apparent trends in the benchmark results. Use of this limit requires the benchmark results to have a normal statistical distribution. If the data does not have a normal statistical distribution, a non-parametric statistical treatment must be used. The method used for analysis of data with a non-normal distribution in this validation is taken from NUREG/CR-6698 (Reference 10).

3.4.1. Normality Testing of Data

There are several tests which can be performed to determine if data follows a normal distribution. Depending on the size of the data sets used in establishing the areas of applicability, [Proprietary Information]. The methodology for these tests can be found in NUREG/CR-4604 (Reference 8) and Natrella (Reference 9).

[

Proprietary Information

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Proprietary Information

[Proprietary Information]

3.4.2. *Weighted Single Sided Lower Tolerance Limits*

If the benchmark experiment results are verified to be part of a normal distribution, a weighted, single sided lower tolerance limit technique may be used to construct a USL for criticality. The weighted, single sided lower tolerance limit is calculated with a 95% confidence that 95% of the benchmark data lies above it. Thus, a calculation involving a subcritical system would have a 95% confidence that 95% of all calculations performed on it would yield a result less than the tolerance limit. The weighted, single sided lower tolerance limit is calculated using the method presented in NUREG/CR-6698 (Reference 10). The weighted, single sided lower tolerance limit is adjusted by applying a MoS to define the USL. The USL is defined by the following:

$$USL = \bar{k}_{eff} - K^{*}S_t - MoS$$

where: USL= Maximum subcritical value of k_{eff}

$\bar{k}_{eff}$ = weighted mean k_{eff} value of the benchmark experiments

K^{*} = tolerance factor

S_t = square root of the pooled variance

S^2 = variance about the mean

MoS = margin of subcriticality (0.05)

$$\bar{k}_{eff} = \frac{\sum \frac{1}{\sigma_i^2} k_{eff\,i}}{\sum \frac{1}{\sigma_i^2}}$$

and

$$S^2 = \frac{\left(\frac{1}{n-1}\right)\sum \frac{1}{\sigma_i^2}\left(k_{eff} - \bar{k}_{eff}\right)^2}{\frac{1}{n}\sum \frac{1}{\sigma_i^2}}$$

$$\sigma_i = \sqrt{\left(\sigma_s^2 + \sigma_e^2\right)}$$

$$\bar{\sigma}^2 = \frac{n}{\sum \frac{1}{\sigma_i^2}}$$

$$S_t = \sqrt{\left(s^2 + \bar{\sigma}^2\right)}$$

where: σ_s = Monte Carlo statistical uncertainty associated with the calculation,
σ_e = experimental uncertainty associated with the benchmark experiment,

$\bar{\sigma}^2$ = average uncertainty

The statistical uncertainty, σ_s, is the standard deviation calculated by the code and reported in the output for each benchmark experiment. If available, the experimental uncertainty, σ_e, is determined through rigorous evaluation of each benchmark experiment. NEA/NCS/DOC (95)03 documents such evaluations and thus reports an experimental uncertainty.

The tabulated lower tolerance factors (Reference 10) are listed for a maximum of 50 data items, however the evaluation herein uses more data points. Therefore, the lower tolerance factors (K^*) for data collections greater than 50 items are derived from Reference 9:

$$K^* = \frac{z_P + \sqrt{z_P^2 - ab}}{a}$$

where

$$a = 1 - \frac{z_\gamma^2}{2(N-1)}$$

$$b = z_P^2 - \frac{z_\gamma^2}{N}$$

And z_P and z_γ values are the critical values from the normal distribution that is exceeded with specified probability (P = 95% and γ = 95%) and are both 1.645.

3.4.3. Non-Parametric Analysis

Data that do not follow a normal distribution curve can be analyzed using non-parametric techniques. The method used for this validation is taken from NUREG/CR-6698. As stated previously, this approach is more conservative than other non-parametric techniques available to determine distribution-free confidence

interval (e.g., one based on the sign test as presented in Hollander and Wolfe, Reference 7). This method results in a determination of the degree of confidence that a fraction of the true population of data lies above the smallest observed value. This determination is calculated as follows:

[Proprietary Information]

As stated in NUREG/CR-6698, for a desired population fraction of 95% and a rank order of 1 (the smallest data sample) the equation simplifies to:

$$\beta = 1 - 0.95^{n}$$

For a non-parametric set of data, the USL is determined as follows:

USL = Smallest k_{eff} value in the data set - S_t – NPM - MoS

Where: S_t = standard deviation corresponding to the smallest k_{eff} value in the data set
NPM = non-parametric margin, determined from β
MoS = margin of subcriticality (0.05)

The non-parametric margin is an additional amount subtracted from the lowest data point to account for the small sample size and non-normal distribution of the data. Recommended values for the non-parametric margin are established in NUREG/CR-6698.

4. Benchmark Experiment Descriptions

Reference 10 provides guidance for selecting critical experiment data. This guidance is utilized as follows: the desired range of operating conditions for SHINE is nominally 19.75 wt. % ^{235}U (metal, oxide and solution), thermal neutron energies, sulfate solution, nitrate solution, borated-polyethylene absorber, and concrete reflector. All critical benchmark experiments are taken from Reference 1. One-hundred-forty (140) experiments were selected that include the materials, conditions, and operating parameters to be considered in the SHINE applications. Of these, 30 have 10 wt. % ^{235}U, 54 have between 14.7 and 36 wt. % ^{235}U, and 56 have between 89 and 94 wt. % ^{235}U. Included in these are 9 metal, 66 oxide, and 59 solution experiments. One-hundred-thirty-one (131) experiments have thermal neutron energies. Of the solution experiments, 45 are uranyl nitrate and 14 are uranyl sulfate. Twenty-nine (29) experiments have boron absorbers with 8 of these having borated-polyethylene absorber. Twelve (12) experiments have a concrete reflector. Many additional materials and configurations are also included. Reference 10 provides no minimum number of experiments to produce a rational validation. The guide only states that less than 10 should be accompanied by a technical basis supporting the rationale for acceptability of the validation results. It is judged that the data set herein provides a sufficient number of experiments with varying experimental parameters to ensure a wide area of applicability (AoA) and statistically significant results with no additional justification.

The input files are specifically developed for MCNP 6.1 and the continuous energy ENDF/B-VII.1 cross section library. One-hundred-forty benchmark cases are modeled. The majority are in the thermal neutron

energy range, however some bridge into intermediate and fast energy ranges. The MCNP 6.1 calculated ANECF values range from 0.0027 to 1.46 MeV. The largest group of the experiments have intermediate ^{235}U enrichment; however sufficient low and high enriched experiments are included to evaluate for trends in the bias. The USL is evaluated with and without the LEU and HEU cases, and the more conservative value is chosen. A broad range of chemical forms and metal are included to evaluate potential bias from the chemical form and to encompass the range of expected and potential forms of material at the SHINE facility. Additionally, the cases are fairly evenly split between homogeneous and heterogeneous physical forms. Hydrogen identified in water (including water found in concrete) is modeled with the water lwtr.20t S(α,β) while hydrogen in hydrocarbon materials is modeled with the poly.20t S(α,β). Graphite is modeled with the grph.20t S(α,β). BeO is modeled with both the be-o.20t and o-be.20t.

The descriptions below are taken from Reference 1.

4.1. Low Enriched Uranium

4.1.1. LEU Homogeneous

Uranyl Nitrate Solution with Boron Absorber Rods (LEU-SOL-THERM-006)

A large number of critical experiments with absorber elements of different types in uranyl nitrate solution of different enrichments and concentrations were performed in 1961 - 1963 at the Solution Physical Facility of the Institute of Physics and Power Engineering (IPPE), Obninsk, Russia. The five experiments included in this evaluation were performed with uranium enriched to 10 wt.% ^{235}U. Uranyl nitrate solution with uranium concentration of 420.5 g/l was pumped into the core or inner tank, a stainless steel cylindrical tank with inner diameter 110 cm. One experiment was performed without absorber rods. In each of four experiments a different number of boron carbide absorber rods was inserted in the core tank. The absorber rods were arranged in a hexagonal lattice with different pitches. There was a thick side and bottom water reflector in these experiments.

All five experiments are included in this evaluation. Note that these experiments use the same tank and absorber rods as those used in HEU-SOL-THERM-035, thus the only significant difference is the ^{235}U enrichment. [Proprietary Information]

Uranyl Nitrate Solution with Concrete Reflector (LEU-SOL-THERM-008)

Four critical configurations included in this data set are part of the Static Experiment Critical Facility (STACY) series of experiments. Utilizing the 60-cm diameter cylindrical stainless-steel core tank, a 10% enriched uranyl nitrate solution ($UO_2(NO_3)_2$) was used in these experiments. The uranium concentration and the free nitric-acid concentration were adjusted to approximately 240 g/l and 2.1 mol/l, respectively. Four concrete reflectors of different thicknesses, packed in annular tube-shaped containers, were prepared and arranged against the outer wall of the core tank.

All four experiments are included in this evaluation. This data set is included herein to evaluate uranyl nitrate and concrete reflection.

Uranyl Nitrate Solution with Borated-Concrete Reflector (LEU-SOL-THERM-009)

Three critical configurations included in this data set are part of the Static Experiment Critical Facility (STACY) series of experiments. Utilizing the 60-cm diameter cylindrical stainless-steel core tank, a 10% enriched uranyl nitrate solution ($UO_2(NO_3)_2$) was used in these experiments. The uranium concentration and the free nitric-acid concentration were adjusted to approximately 240 g/l and 2.1 mol/l, respectively. Three borated-concrete reflectors of different boron content, packed in annular tube-shaped containers, were prepared and arranged against the outer wall of the core tank.

All three experiments are included in this evaluation. Note that these experiments differ from those in LEU-SOL-THERM-008 only in the addition of the boron. This data set is included herein to evaluate uranyl nitrate, concrete reflection, and, in conjunction with LEU-SOL-THERM-008, potential sensitivity to boron addition.

4.1.2. LEU Heterogeneous

UO_2 Fuel Rods (LEU-COMP-THERM-022, -023, -024 & -032)

A series of critical experiments with water moderated and reflected lattices of UO_2 fuel rods, (enriched to 10% ^{235}U), was performed over the course of several years (1965-1967) in RRC "Kurchatov Institute." These data sets are included herein to evaluate potential heterogeneous effects, uranium oxide, and to provide a spectrum of $H/^{235}U$ values.

These highly correlated experiments are detailed below.

LEU-COMP-THERM-022

This evaluation describes seven critical experiments for uniform fully flooded hexagonal lattices with pitch values of 0.7, 0.8, 1.0, 1.22, 1.4, 1.83, and 1.852 cm. These configurations have $H/^{235}U$ values between 50 and 629. All seven configurations are included in this validation.

LEU-COMP-THERM-023

This evaluation describes six critical experiments for different levels of water in the active core, which was a hexagonally pitched lattice of fuel rods. The pitch value of the lattice was 1.4 cm. All six configurations are included in this validation.

Note that the submerged portion of these lattices had an $H/^{235}U$ value of 340, but their ANECF values are slightly higher than the near identical configuration of LEU-COMP-THERM-022 because of the contribution of more energetic neutron in the dry portion of the lattice.

LEU-COMP-THERM-024

This evaluation describes critical experiments for two square-pitched lattices of fuel rods. The two studied configurations are arrays of nearly rectangular cross section containing fuel rods with pitches of 0.62 cm and $0.62\times\sqrt{2}$ cm.

LEU-COMP-THERM-032

This evaluation describes nine critical experiments for uniform fully flooded hexagonal lattices with pitch values of 0.7, 1.4, and 1.852 cm at three different temperatures (ranging from 20°C to 274°C) for each lattice. Only the three 20°C configurations are used in this validation. The critical numbers of rods for these configurations differ from those reported in LEU-COMP-THERM-022 because of different assembly support structure and application of steel tubes for safety rods in the present experiments.

4.2. Intermediate Enriched Uranium

4.2.1. IEU Homogeneous

Bare Sphere Enriched Uranium (IEU-MET-FAST-003)

Criticality measurements of bare metal $^{235}U(36\%)$ assemblies were conducted at the Russian federation Nuclear Center VNIIEF's criticality test facility in 1994. The assembly had a core of $^{235}U(36\%)$ incorporating 10 spherical layers of fissile material.

This experiment is modeled using the "simple" model as homogeneous.

Reflected Sphere Enriched Uranium (IEU-MET-FAST-004)

Criticality measurements of a graphite-reflected assembly of $^{235}U(36\%)$ were performed by VNIIEF in September 1977 at its criticality test facility. The assembly core had a central cavity of 2-cm radius and

incorporated 7 spherical layers of fissile material. The graphite reflector was a single spherical layer with an outer radius of 17.2 cm. The value of the uncertainty in reflector radius was 0.2%. Each core and reflector layer consisted of two hemispherical pieces.

This experiment is modeled using the “simple” model as homogeneous.

Reflected Sphere Enriched Uranium (IEU-MET-FAST-006)

Criticality measurements of a Duralumin-reflected assembly of ^{235}U(36%) were conducted by VNIIEF in 1994 at its criticality test facility. The core pieces were manufactured in 1977. As a result of these experiments, two benchmark models, one detailed and one simplified, of a single experiment were developed. The simplified configuration is used herein.

Reflected Sphere Enriched Uranium (IEU-MET-FAST-009)

Criticality measurements of a polyethylene-reflected assembly of ^{235}U(36%) were conducted by VNIIEF in 1977 at its criticality test facility (CTF).

The above metal experiments are included herein to evaluate uranium metal and fast neutron effects.

Hydrocarbon Moderated and Reflected UO_2 (IEU-COMP-THERM-015)

During the late 1950s and 1960s an experimental survey was carried out jointly at Aldermaston and Dounreay of the critical parameters of uranium / hydrogen systems at ~30% ^{235}U enrichment. The Aldermaston phase made use of the solid UO_2/wax compacts had $H/^{235}U$ values between about 8 and 80. This information was obtained primarily as an experimental base for safety calculations in the intermediate enrichment range. The cores were constructed in rectangular geometry from small blocks (mostly 1 in. cubes) to facilitate stacking changes. The proportions of oxide and wax were changed at intervals during the experiment to provide a range of $H/^{235}U$ values.

Experiment nos. 4 – 12 were selected for this evaluation; these are the first nine experiments with the polyethylene reflector and cover the range of $H/^{235}U$ values. However, only eight of these experiments are included in this validation (see note below). While the experiments contained heterogeneous elements, they are modeled as homogeneous.

Note that experiment number 6 has been rejected. While this case calculates low (0.9923) the reason for the rejection is the very high bias in the benchmark k_{eff} (1.0008). Examination of Tables 27 and 28 of the IEU-COMP-THERM-015 section of Reference 1 displays conflicting information for the determination of the experimental bias. In Table 27 a positive bias of 0.0006 is added to the raw experiment value of 1.0000 due to the model simplification of ignoring block/wax impurities and homogenizing the cube lacquer coating. However, this value is not assigned to experiments nos. 1 and 23 using this same material (#16); these are inconsistently assigned bias values of 0.0003 and -0.0001, respectively. Alternately, the bias value of 0.0006 is consistently assigned to experiments nos. 2, 8 & 25 which use material #40. Therefore, it is judged that the experimental bias for experiment nos. 1, 6 & 23 are incorrect, and that the correct values cannot be determined from the information in Reference 1.

This data set is included herein to evaluate uranium oxide, hydrocarbon moderator / reflectors, and to add low $H/^{235}U$ values.

Bare and Water Reflected UO_2F_2 (IEU-SOL-THERM-002)

During the late 1950s and early 1960s an experimental survey was carried out jointly at Aldermaston and Dounreay of the critical parameters of uranium/hydrogen systems at ~ 30% ^{235}U enrichment. The Dounreay phase of this survey was concerned with the criticality of UO_2F_2 aqueous solutions (in cylindrical, slab, and spherical and hemispherical geometries) and covered the $H/^{235}U$ values from about 50 and higher.

Five aluminium spheres of nominal internal diameters 12 in. (30.48 cm), 13.75 in. (34.925 cm), 16 in. (40.64 cm), 22 in. (55.88 cm) and 38 in. (96.52 cm) were used in these experiments with the key objective being to determine the solution concentration necessary for criticality when a sphere was completely filled. This was achieved by measuring critical conditions for a partly filled sphere over a range of fractional volumes and extrapolation to the full spherical volume. Three types of reflection conditions were examined: "bare", partial water-reflected (i.e. with water reflector up to the level of the fuel solution), and fully water-reflected. Critical parameters of full spheres were determined for the following configurations: 12 in. sphere – fully water-reflected; 13.75 in. sphere – bare (at two concentrations) and fully water-reflected; 16 in. sphere – bare, part water-reflected, and fully water reflected; 22 in. sphere – bare, part water-reflected, and fully water-reflected; and 38 in. sphere – bare.

Twelve of the thirteen experimental configurations are evaluated herein; case 6 has been rejected from consideration as its experimental uncertainty is unacceptably high (0.0109) for a criticality safety validation. This data set is included herein to add high $H/^{235}U$ values and unreflected solutions.

BeO Reflected UO_2SO_4 (IEU-SOL-THERM-004)

The experiment was performed at Los Alamos Scientific Laboratory on May 9, 1944. This experiment was to determine the critical mass of ^{235}U in homogenous solutions at various concentrations and moderating media. The experiment was a simple configuration of a hollow sphere containing fissile solution within a beryllium oxide reflector.

The critical configuration involved approximately 14.7% enriched uranyl sulfate (UO_2SO_4) solution in a 1-foot (30.48 cm) diameter stainless steel sphere centered in a beryllium oxide pseudo-sphere approximately 3 feet (91.44 cm) in diameter. The $H/^{235}U$ value was 646.

Note that this benchmark model k_{eff} applies to the temperature of 39^oC. However, Reference 1 specifies that a temperature bias of Δ k_{eff} =+0.0072 should be applied to the benchmark model k_{eff} when the benchmark is compared with calculational models whose cross sections are at room temperature (21^oC). As this is the case herein, this temperature bias has been applied.

[Proprietary Information]

4.2.2. IEU Heterogeneous

Reflected Sphere Enriched Uranium (IEU-MET-FAST-005)

Criticality measurements of steel-reflected ^{235}U(36%) assemblies were conducted by VNIIEF in 1994 at its CTF. The assembly core had a central cavity of 2-cm radius and included 6 spherical layers of fissile material. The steel reflector was represented by 5 spherical layers that differed slightly in density. The outermost layer had an outer radius of 21.5 cm. Each of the 5 layers consisted of two hemispherical pieces; the outer 3 steel layers were modeled as one layer and the inner 2 steel layers were modeled as one layer. The value of the uncertainty in the reflector radius, averaged over 5 layers, was 0.15%.

This experiment is modeled using the "simple" model; the hemispherical pieces of the reflector layers were each modeled as continuous spheres. This experiment is included herein to evaluate uranium metal and heterogeneous effects.

Polyethylene-Moderated UF_4-Polyetrafluoroethylene Cubes (IEU-COMP-THERM-001)

One-inch cubes of U(30)F_4 -polytetrafluoroethylene [$(CF_2)_n$] ("U-cubes") were stacked with one-inch cubes and half-cubes of polyethylene ("H-cubes") into cuboid shapes on aluminium platforms. Most critical cores were reflected by paraffin. Twenty-nine ratios and patterns of "U-cubes" and "H-cubes" are included in this benchmark.

Twenty-five experiments are modeled (3 cadmium reflected cases and 1 boron reflected case are not included). This data set is included herein to add a range of H/^{235}U values and to evaluate hydrocarbon moderator / reflectors.

UO_2 Fuel Rods (IEU-COMP-THERM-002)

Critical approach experiments with stainless steel clad UO_2 fuel rods (17 wt. % ^{235}U) in a water filled tank were performed in 1970 - 1973 in the MATR facility at the Institute of Physics and Power Engineering, Obninsk, Russia. The fuel rods were arranged in hexagonal lattices with a pitch of 6.8 cm. Each lattice comprised one of three forms of the fuel rod: without absorber element, with gadolinium absorber element, or with cadmium absorber element in the center of each fuel rod. The lattices were fully reflected on all sides with water. Note that due to the complex geometry of this experiment only case 1 was used and no H/^{235}U value was determined.

This experiment is included herein to evaluate uranium oxide and heterogeneous effects.

U-ZrH Fuel Rods (IEU-COMP-THERM-003)

The benchmark experiments were performed as a part of startup test of the TRIGA Mark II reactor in Ljubljana, Slovenia, after reconstruction and upgrading in 1991, during which all core components (top and bottom grid plates, fuel, control rods, irradiation channels), with the exception of the graphite reflector around the core, were replaced with new ones. The experiments in steady-state operation were performed with completely fresh fuel (including instrumented elements and fuel followers of control rods) in a compact and uniform core (i.e., all elements including the fuel followers of control rods were of the same type with no nonfuel components in the critical core configuration) at well-controlled operating conditions. Standard commercial TRIGA fuel elements of 20 wt.% enrichment and 12 wt.% uranium concentration were used.

This evaluation describes two critical experiments. The core configurations differed only in the position of 7 outermost fuel elements and so are closely correlated. Both cores were critical within 300 pcm (0.3%). The two experiments are included herein to evaluate heterogeneous effects.

4.3. High Enriched Uranium

4.3.1. HEU Homogeneous

Concrete Reflected Arrays of Uranyl Nitrate (HEU-SOL-THERM-007)

Seventeen of the experiments utilized concrete-reflected arrays of uranyl nitrate cylinders. Uranium was enriched to 93.2 wt% ^{235}U and the cylinders were constructed of aluminium with stainless steel sleeves. Arrays of various sizes were placed with a ~10 inch-thick concrete box that was used for the experiments. The inside dimensions of this box formed a rough cube (~122 cm per side).

Experiments nos. 1, 3, 7, 11 & 14 were selected for inclusion in this evaluation. This data set is included herein to evaluate concrete reflectors and potential bias with increasing enrichment.

Water Reflected Oxyfluoride Solution (HEU-SOL-THERM-012)

This water-reflected sphere is part of a series of experiments performed in the 1950's at the Oak Ridge National Laboratory with highly enriched uranium (93.2 wt.% ^{235}U). This measurement was made with a uranium oxyfluoride (UO_2F_2) solution in a 27.9-cm inner radius (91 liters) water-reflected sphere. The sphere was fabricated of 0.20-cm-thick 1100 aluminium and surrounded by an effectively infinite water reflector.

This experiment is included herein to add its high H/^{235}U value (1272).

Uranyl Nitrate Solution with Boron Absorber (HEU-SOL-THERM-027)

A large number of critical experiments with absorber elements of different types in uranyl nitrate solution of different enrichments and concentrations were performed in 1961 - 1963 at the Solution Physical Facility of the IPPE, Obninsk, Russia. The nine experiments included in this evaluation were performed with uranium enriched to 89 wt.% ^{235}U. Uranyl nitrate solution was pumped into the core or inner tank, a stainless steel cylindrical tank with inner diameter 40.07 cm. In eight of the nine experiments, an absorber rod of various diameters with boron or cadmium was inserted in the center of the core tank. There was no outer reflector in these experiments.

Experiment nos. 1 - 5 were selected for inclusion in this evaluation. The first case has no absorber while the next 4 have a boron carbide absorber. This data set is included herein to evaluate uranyl nitrate, boron effects and potential bias with increasing enrichment.

Uranyl Nitrate Solution with Boron Absorber Rods (HEU-SOL-THERM-031)

A large number of critical experiments with absorber elements of different types in uranyl nitrate solution of different enrichments and concentrations were performed in 1961 - 1963 at the Solution Physical Facility of the IPPE, Obninsk, Russia. The four experiments included in this evaluation were performed with uranium enriched to 89 wt.% ^{235}U. Uranyl nitrate solution with uranium concentration of 289 g/l was pumped into the core or inner tank, a stainless steel cylindrical tank with inner diameter 40.07 cm. Eighteen or thirty-six boron carbide absorber rods were inserted in the center of the core tank. The rods were arranged in hexagonal lattices with pitches of 4.0 and 6.0 cm. There was a thick side and bottom water reflector in these experiments.

All four experiments are included herein to evaluate uranyl nitrate, boron effects and potential bias with increasing enrichment.

Uranyl Nitrate Solution with Boron Absorber Rods (HEU-SOL-THERM-035)

A large number of critical experiments with absorber elements of different types in uranyl nitrate solution of different enrichments and concentrations were performed in 1961 - 1963 at the Solution Physical Facility of the Institute of Physics and Power Engineering (IPPE), Obninsk, Russia. The nine experiments included in this evaluation were performed with uranium enriched to 89 wt.% 235U. Uranyl nitrate solution with uranium concentration of 37.51 g/l, 74.87 g/l, or 152.3 g/l was pumped into the core or inner tank, a stainless steel cylindrical tank with inner diameter 110 cm. Three experiments were performed without absorber rods. In six experiments different numbers of boron carbide absorber rods were inserted in the core tank. The absorber rods were arranged in a hexagonal lattice with different pitches. There was a thick side and bottom water reflector in these experiments.

All nine experiments are included in this evaluation. Note that these experiments use the same tank and absorber rods as those used in LEU-SOL-THERM-006, thus the only significant difference is the ^{235}U enrichment. This data set is included herein to evaluate uranyl nitrate, boron effects and potential bias with increasing enrichment.

Uranyl Nitrate Solution with Borated Polyethylene Absorber (HEU-SOL-THERM-038)

Thirty critical experiments involving 93.1%-enriched uranyl nitrate solution were performed in 1988 at the Los Alamos National Laboratory (LANL). The experiments consisted of two thin coaxial slab tanks with various neutron absorber and reflector plates positioned on top of one or both tanks. The reactivity worth (Δk_{eff}) of the neutron absorber and reflector plates was as much as 7.5 %. Three different types of borated polyethylene plates, BP-2, BP-6, and BP-7, were used in the experiments. BP-2 and BP-6 are 5 wt.% borated polyethylene and BP-7 is 30 wt.% borated polyethylene.

Ten experiments (one with no absorber and nine with the borated polyethylene) are included in this evaluation.

Note that the BP-7 borated polyethylene material used in experiments 10, 11 & 17 is nearly identical to the PPC-B material used in the SHINE applications. This data set is included herein to evaluate uranyl nitrate, boron effects and potential bias with increasing enrichment.

Beryllium and Graphite Reflected Uranyl Sulfate Solutions (HEU-SOL-THERM-046)

This evaluation considers thirteen subcritical approaches performed in the early sixty's (1960-1961) at Saclay, France, with homogeneous aqueous solution of uranium (89.84 wt.% ^{235}U) sulfate, containing 0.5 N and 0.1 N excess sulfuric acid respectively. The range of the ^{235}U concentration was 36.588 to 56.51 g/liter. All thirteen experiments are acceptable for use as benchmarks. The estimated experimental uncertainty (1σ) obtained is about 0.3%, mostly due to the outer tank: its thickness, its gap with the inner tank and its gap with the beryllium oxide reflector.

The core was comprised of the fissile solution inside a cylindrical tank, of Zircaloy-2. This inner tank was 25 cm in diameter and 30 cm in height, with a conical bottom, surrounded by an outer aluminum-alloy tank, and reflected by a minimum of 27.5 cm of beryllium oxide followed by a layer of at least 50 cm of graphite. The reflectors contained structural plates of aluminum alloy, as well as several penetrations throughout to accommodate the fill tube, experimental channels, control rods, safety rods, etc.

This data set is included herein to evaluate uranyl sulfate and potential bias with increasing enrichment.

This set of experiments overestimated the experimental k_{eff} values by ~1.5% using the APOLLO-MORET code (Reference 1). During the development of the MCNP models, several simplifications in the previous models were identified and corrected. For the MCNP models used herein, material compositions are calculated following the approach used in the benchmark specification. Isotopic number densities are calculated from the supplied weight fraction data using MCNP6 molecular weight data and natural abundance data. For hydrogen and oxygen, ^{1}H is substituted atom-for-atom for ^{2}H, as is common practice. Similarly ^{16}O is substituted for ^{18}O since MCNP6 lacks cross section data for ^{18}O. While the cases still overestimate, the accuracy of the model has been improved.

4.3.2. HEU Heterogeneous

Graphite Reflected UO_2 Rods (HEU-COMP-FAST-002)

A series of small, compact critical assembly (SCCA) experiments were completed in 1962-1965 at Oak Ridge National Laboratory's Critical Experiments Facility. This evaluation had the 253 fuel tubes at a 1.506-cm triangular lattice in a 25.96 cm OD core tank and graphite reflectors on all sides. Note that this fast neutron experiment was modeled with the o2/u.20t, u/02.20t, and al27.20t s(α,β) corrections.

This experiment is included herein to evaluate uranium oxide, heterogeneous effects, and potential biases with fast neutron energies and increasing uranium enrichment.

Reflected Cylinder (HEU-COMP-INTER-003)

The COMET universal critical assembly machine was used to perform a series of seven uranium hydride critical experiments in 1987-88 at Los Alamos National Laboratory. The cylindrical assemblies were disks of canned UH_3 powder, reflected by depleted uranium, beryllium, and iron. Two 2-cm and two 3-cm-thick disks of canned UH_3 compressed powder (6-in. diameter) were used in four of the experiments. These experiments had outer reflectors of depleted uranium and inner reflectors of D38, Be, and Fe. The difference in the next two experiments with Be inner reflectors was that in one experiment one of the 2-cm cans of UH_3 was inverted. The total mass of the UH_3 for each of these experiments was 17.7 kg. Four 3-cm disks were used for two of the three experiments with the outer reflector removed. The total UH_3 mass for the Be and one D38 experiment was 21.3 kg. The total mass for the third D38 experiment was 23.1 kg. This was achieved by using two 2-cm disks and three 3-cm disks.

Only cases 2, 3, 4 and 5, without the depleted uranium inner reflector, are included in this evaluation. Note that cases 2, 3 and 4 have an outer depleted uranium reflector. This data set is included herein to evaluate heterogeneous effects, potential biases with fast neutron energies and increasing uranium enrichment, and potential bias with beryllium reflector.

Bare Sphere (HEU-MET-FAST-001)

One of the experiments performed at Los Alamos in the 1950's to determine the critical mass of a bare, 94 wt.% ^{235}U, sphere of highly enriched uranium (HEU) consisted of two identical sets of nested oralloy hemispheres. This experiment is widely known as ‘Godiva’.

This experiment is included herein to evaluate uranium metal, potential biases with fast neutron energies, increasing uranium enrichment, and potential bias with beryllium reflector.

Graphite Moderated Cylinder (HEU-MET-INTER-006)

The Zeus experiments are a series of on-going critical assemblies at the Los Alamos Critical Experiments Facility (LACEF) at LANL designed to test the adequacy of ^{235}U cross sections in the intermediate-energy range. The three experiments included herein used plates of highly enriched uranium (HEU) metal interspersed with graphite plates in a cylindrical stack that was completely surrounded by copper reflectors.

This data set is included herein to evaluate uranium metal, potential biases with fast neutron energies and increasing uranium enrichment.

4.3.3. Input Summary Tabulation

The characteristics of the benchmark experiments from Reference 1 are tabulated in Table 2. The H/^{235}U values are included in some Reference 1 experiment descriptions. Where these values are not provided they were calculated by the author. Some experiment configurations were too complex to allow this determination. The benchmark k_{eff} and uncertainty are included as k_{exp} and σ.

Table 2 - Critical Benchmark Experiments Summary

Case	wt% ^{235}U	Chem Form	Geometry	Moderator/Reflector	H/^{235}U	Other Materials	k-meas	sigma
HEU-COMP-FAST-02								
02	93.2	UO2	Fuel Pin Array	None/Graphite	n/a	steel, Al	0.9985	0.0006
HEU-COMP-INTER-03								
02	90.5	UH3	Homogeneous Stack of Disks	Hydrogen/Be	3	steel, Al	1.0000	0.0061
03	90.5	UH3		Hydrogen/Be	3	steel, Al	1.0000	0.0056
04	90.5	UH3		Hydrogen/Fe	3	steel, Al	1.0000	0.0055
05	90.5	UH3		Hydrogen/Be	3	steel, Al	1.0000	0.0047
HEU-MET-FAST-001								
01	94.0	Metal	Sphere	None/Bare	n/a	None	1.0000	0.0010
HEU-MET-INTER-006								
01	93.2	Metal	Heterogeneous Cylinder	Graphite/Copper	n/a	Al	0.9977	0.0008
02	93.2	Metal		Graphite/Copper	n/a	Al	1.0001	0.0008
03	93.2	Metal		Graphite/Copper	n/a	Al	1.0015	0.0009
HEU-SOL-THERM-007								
01	93.2	UO2(NO3)2	Homogeneous Cylinders	Water/Concrete	405	SS, Al	1.0000	0.0035
03	93.2	UO2(NO3)2		Water/Concrete	405	SS, Al	1.0000	0.0035
07	93.2	UO2(NO3)2		Water/Concrete	357	SS, Al	1.0000	0.0035
11	93.2	UO2(NO3)2		Water/Concrete	67	SS, Al	1.0000	0.0035
14	93.2	UO2(NO3)2		Water/Concrete	68	SS, Al	1.0000	0.0035
HEU-SOL-THERM-012								
01	93.2	UO2F2	Homogeneous Sphere	Water/Water	1272	Al	0.9999	0.0058
HEU-SOL-THERM-027								

Case	wt%^{235}U	Chem Form	Geometry	Moderator/Reflector	H/^{235}U	Other Materials	k-meas	sigma
01	89	UO2(NO3)2	Homogeneous Cylinders w/ Heterogeneous Absorber Rods	Water/Bare	204	SS	1.0000	0.0046
02	89	UO2(NO3)2			204	SS, B	1.0000	0.0043
03	89	UO2(NO3)2			204	SS, B	1.0000	0.0037
04	89	UO2(NO3)2			204	SS, B	1.0000	0.0037
05	89	UO2(NO3)2			204	SS, B	1.0000	0.0044
HEU-SOL-THERM-031								
01	89	UO2(NO3)2	Homogeneous Cylinders w/ Heterogeneous Absorber Rods	Water/Water	91	SS, B	1.0000	0.0046
02	89	UO2(NO3)2			91	SS, B	1.0000	0.0058
03	89	UO2(NO3)2			91	SS, B	1.0000	0.0058
04	89	UO2(NO3)2			91	SS, B	1.0000	0.0068
HEU-SOL-THERM-035								
01	89	UO2(NO3)2	Homogeneous Cylinders w/ Heterogeneous Absorber Rods	Water/Water	767	SS	1.0000	0.0031
02	89	UO2(NO3)2			767	SS, B, C	1.0000	0.0032
03	89	UO2(NO3)2			767	SS, B, C	1.0000	0.0030
04	89	UO2(NO3)2			767	SS, B, C	1.0000	0.0030
05	89	UO2(NO3)2			379	SS	1.0000	0.0033
06	89	UO2(NO3)2			379	SS, B, C	1.0000	0.0029
07	89	UO2(NO3)2			181	SS	1.0000	0.0035
08	89	UO2(NO3)2			181	SS, B, C	1.0000	0.0038
09	89	UO2(NO3)2			181	SS, B, C	1.0000	0.0041
HEU-SOL-THERM-038								
01	93.1	UO2(NO3)2	Homogeneous Coaxial Slab Tanks	Water/Bare	60	SS, Al	1.0000	0.0025
02	93.1	UO2(NO3)2		Water/Poly	60	SS, Al	1.0000	0.0025
07	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0032
08	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0026
09	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0033
10	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0026
11	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0025
12	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0025
17	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0026
18	93.1	UO2(NO3)2		Water/B-Poly	60	SS, Al, B	1.0000	0.0032
HEU-SOL-THERM-046								
01	89.9	UO2SO4	Homogeneous Cylinders	H2SO4-H2O / BEO & Graphite	708	Al, Zr	1.0011	0.0029
02	89.9	UO2SO4			689	Al, Zr	1.0011	0.0029
03	89.9	UO2SO4			678	Al, Zr	1.0011	0.0029
04	89.9	UO2SO4			661	Al, Zr	1.0011	0.0029
05	89.9	UO2SO4			653	Al, Zr	1.0011	0.0030
06	89.9	UO2SO4			641	Al, Zr	1.0011	0.0029
07	89.9	UO2SO4			622	Al, Zr	1.0011	0.0031
08	89.9	UO2SO4			601	Al, Zr	1.0011	0.0032
09	89.9	UO2SO4			593	Al, Zr	1.0011	0.0037
10	89.9	UO2SO4			561	Al, Zr	1.0011	0.0029
11	89.9	UO2SO4			531	Al, Zr	1.0011	0.0028
12	89.9	UO2SO4			488	Al, Zr	1.0011	0.0029
13	89.9	UO2SO4			457	Al, Zr	1.0011	0.0030
IEU-COMP-THERM-001								
01	30.0	UF4	Heterogeneous Arrays of Cubes	Poly-CF2/Paraffin	8	Al	1.0000	0.0040
02	30.0	UF4		Poly-CF2/Paraffin	16	Al	1.0000	0.0040
03	30.0	UF4		Poly-CF2/Paraffin	32	Al	1.0000	0.0040
04	30.0	UF4		Poly-CF2/Paraffin	64	Al	1.0000	0.0040
05	30.0	UF4		Poly-CF2/Paraffin	222	Al	1.0000	0.0040
06	30.0	UF4		Poly-CF2/Paraffin	32	Al	1.0000	0.0040
07	30.0	UF4		Poly-CF2/Paraffin	32	Al	1.0000	0.0040
08	30.0	UF4		Poly-CF2/Paraffin	32	Al	1.0000	0.0040

Case	wt% ^{235}U	Chem Form	Geometry	Moderator/Reflector	H/ ^{235}U	Other Materials	k-meas	sigma
09	30.0	UF4		Poly-CF2/Paraffin	16	Al	1.0000	0.0040
10	30.0	UF4		Poly-CF2/Paraffin	16	Al	1.0000	0.0040
11	30.0	UF4		Poly-CF2/Paraffin	16	Al	1.0000	0.0040
12	30.0	UF4		Poly-CF2/Paraffin	16	Al	1.0000	0.0040
13	30.0	UF4		Poly-CF2/Paraffin	64	Al	1.0000	0.0040
14	30.0	UF4		Poly-CF2/Paraffin	64	Al	1.0000	0.0040
15	30.0	UF4		Poly-CF2/Paraffin	64	Al	1.0000	0.0040
16	30.0	UF4		Poly -CF2/Paraffin	127	Al	1.0000	0.0040
17	30.0	UF4		Poly -CF2/Bare	16	Al	1.0000	0.0040
18	30.0	UF4		Poly -CF2/Bare	32	Al	1.0000	0.0040
19	30.0	UF4		Poly -CF2/Bare	127	Al	1.0000	0.0040
20	30.0	UF4		Poly -CF2/Paraffin	16	Al	1.0000	0.0040
21	30.0	UF4		Poly-CF2/Paraffin	8	Al	1.0000	0.0040
26	30.0	UF4		Poly-CF2/Paraffin	127	Al	1.0000	0.0040
27	30.0	UF4		Poly-CF2/Paraffin	127	Al	1.0000	0.0040
28	30.0	UF4		Poly-CF2/Paraffin	16	Al	1.0000	0.0040
29	30.0	UF4		Poly-CF2/Paraffin	16	Al	1.0000	0.0040
IEU-COMP-THERM-002								
01	17.0	UO2	Heterogeneous Hexagonally Pitched	Water/Water	n/a	SS, Al	1.0014	0.0039
IEU-COMP-THERM-003								
01	20.0	U-ZrH	Annular Fuel Pin Arrays	Water/Graphite	150	Al, Zr	1.0006	0.0056
02	20.0	U-ZrH		Water/Graphite	150	Al, Zr	1.0046	0.0056
IEU-COMP-THERM-015								
04	30.1	UO2	Homogeneous Cube	Wax/Wax	8	None	0.9982	0.0032
05	30.1	UO2		Wax/Wax	8	None	0.9982	0.0031
07	30.1	UO2		Wax/Wax	16	None	0.9981	0.0036
08	30.1	UO2		Wax/Wax	39	None	0.9990	0.0044
09	30.1	UO2		Wax/Wax	39	None	0.9991	0.0047
10	30.1	UO2		Wax/Wax	39	None	0.9995	0.0045
11	30.1	UO2		Wax/Wax	81	None	0.9985	0.0050
12	30.1	UO2		Wax/Wax	81	None	0.9985	0.0051
IEU-MET-FAST-003								
01	36.0	Metal	Homogeneous Stack of Disks	None/Bare	n/a	None	1.0000	0.0019
IEU-MET-FAST-004								
01	36.0	Metal	Homogeneous Stack of Disks	None/Graphite	n/a	None	1.0000	0.0032
IEU-MET-FAST-005								
01	36.0	Metal	Heterogeneous Stack of Disks	None/Steel	n/a	None	1.0000	0.0023
IEU-MET-FAST-006								
01	36.0	Metal	Sphere	None/Aluminium	n/a	Fe, Cu	1.0000	0.0025
IEU-MET-FAST-009								
01	36.0	Metal	Sphere	None/Polyethylene	n/a	None	1.0000	0.0053
IEU-SOL-THERM-002								
01	30.5	UO2F2	Spheres and Hemispheres	Water/Water	352	Al	1.0004	0.0026
02	30.5	UO2F2		Water/Water	574	Al	1.0003	0.0032
03	30.5	UO2F2		Water/Water	788	Al	1.0003	0.0038
04	30.5	UO2F2		Water/Water	1194	Al	1.0003	0.0046
05	30.5	UO2F2		Water/Bare	218	Al	0.9989	0.0042
07	30.5	UO2F2		Water/Bare	534	Al	0.9991	0.0032
08	30.5	UO2F2		Water/Bare	1039	Al	0.9996	0.0042
09	30.5	UO2F2		Water/Bare	1611	Al	1.0001	0.0054
10	30.5	UO2F2		Water/Water	765	Al	1.0005	0.0038

Case	wt% ^{235}U	Chem Form	Geometry	Moderator/Reflector	H/^{235}U	Other Materials	k-meas	sigma
11	30.5	UO2F2		Water/Water	1178	Al	1.0004	0.0048
12	30.5	UO2F2		Water/Water	729	Al	1.0004	0.0042
13	30.5	UO2F2		Water/Bare	489	Al	0.9984	0.0042
IEU-SOL-THERM-004								
01	14.7	UO2SO4	Sphere	Water/BeO	646	SS	1.0091	0.0041
LEU-COMP-THERM-022								
01	10.0	UO2	Fuel Pin Array	Water/Water	50	SS	1.0000	0.0046
02	10.0	UO2		Water/Water	80	SS	1.0000	0.0046
03	10.0	UO2		Water/Water	151	SS	1.0000	0.0036
04	10.0	UO2		Water/Water	247	SS	1.0000	0.0037
05	10.0	UO2		Water/Water	340	SS	1.0000	0.0038
06	10.0	UO2		Water/Water	613	SS	1.0000	0.0046
07	10.0	UO2		Water/Water	629	SS	1.0000	0.0046
LEU-COMP-THERM-023								
01	10.0	UO2	Fuel Pin Array	Water/Water	340	SS, Al	1.0000	0.0044
02	10.0	UO2		Water/Water	340	SS, Al	1.0000	0.0044
03	10.0	UO2		Water/Water	340	SS, Al	1.0000	0.0044
04	10.0	UO2		Water/Water	340	SS, Al	1.0000	0.0044
05	10.0	UO2		Water/Water	340	SS, Al	1.0000	0.0044
06	10.0	UO2		Water/Water	340	SS, Al	1.0000	0.0044
LEU-COMP-THERM-024								
01	10.0	UO2	Fuel Pin Array	Water/Water	41	SS, Al	1.0000	0.0054
02	10.0	UO2		Water/Water	128	SS, Al	1.0000	0.0040
LEU-COMP-THERM-032								
01	10.0	UO2	Fuel Pin Array	Water/Water	50	SS	1.0000	0.0045
04	10.0	UO2		Water/Water	340	SS	1.0000	0.0037
07	10.0	UO2		Water/Water	629	SS	1.0000	0.0045
LEU-SOL-THERM-06								
01	10.0	UO2(NO3)2	Homogeneous Cylinders w/ Heterogeneous Absorber Rods	Water/Water	532	SS	1.0000	0.0037
02	10.0	UO2(NO3)2		Water/Water	532	SS, B	1.0000	0.0038
03	10.0	UO2(NO3)2		Water/Water	532	SS, B	1.0000	0.0041
04	10.0	UO2(NO3)2		Water/Water	532	SS, B	1.0000	0.0041
05	10.0	UO2(NO3)2		Water/Water	532	SS, B	1.0000	0.0047
LEU-SOL-THERM-08								
72	10.0	UO2(NO3)2	Homogeneous Array of Cylinders	Water/Concrete	956	SS, Al	0.9999	0.0014
74	10.0	UO2(NO3)2		Water/Concrete	955	SS, Al	1.0002	0.0015
76	10.0	UO2(NO3)2		Water/Concrete	952	SS, Al	0.9999	0.0014
78	10.0	UO2(NO3)2		Water/Concrete	951	SS, Al	0.9999	0.0014
LEU-SOL-THERM-09								
92	10.0	UO2(NO3)2	Homogeneous Array of Cylinders	Water/ B-Concrete	936	SS, Al	0.9998	0.0014
93	10.0	UO2(NO3)2		Water/ B-Concrete	934	SS, Al	0.9999	0.0014
94	10.0	UO2(NO3)2		Water/ B-Concrete	933	SS, Al	0.9999	0.0014

5. Evaluation Results

The results for the individual Reference 1 experiment groups are shown in the sections below. The k-normalized values are the MCNP 6.1 calculation k_{eff} results divided by the Reference 1 experimental results shown in Table 3. From this point forward, all references to k_{eff} will reference the normalized value.

Table 3 - MCNP 6.1 Results Summary

	MCNP 6.1 Calculation			Benchmark Values		Normalized Results	
Exp Name	k-calc	σ-calc	ANECF MeV	k-meas	σ-exp	k-norm	σ-tot
Maximum	1.0139	0.0008	1.4585	1.0091	0.0068	1.0128	0.0068
Minimum	0.9934	0.0001	0.0027	0.9977	0.0006	0.9952	0.0007
Average	1.0027	0.0003	0.1318	1.0001	0.0037	1.0026	0.0037
HEU-COMP-FAST-002	1.0001	0.0003	0.771	0.9985	0.0006	1.0016	0.0007
HEU-COMP-INTER-003-02	1.0051	0.0003	0.649	1.0000	0.0061	1.0051	0.0061
HEU-COMP-INTER-003-03	1.0048	0.0003	0.652	1.0000	0.0056	1.0048	0.0056
HEU-COMP-INTER-003-04	1.0028	0.0003	0.677	1.0000	0.0055	1.0028	0.0055
HEU-COMP-INTER-003-05	0.9979	0.0003	0.542	1.0000	0.0047	0.9979	0.0047
HEU-MET-FAST-001-01	0.9996	0.0002	1.459	1.0000	0.0010	0.9996	0.0010
HEU-MET-INTER-006-01	0.9934	0.0003	0.334	0.9977	0.0008	0.9956	0.0009
HEU-MET-INTER-006-02	0.9965	0.0003	0.377	1.0001	0.0008	0.9964	0.0009
HEU-MET-INTER-006-03	1.0000	0.0004	0.447	1.0015	0.0009	0.9985	0.0010
HEU-SOL-THERM-007-01	1.0110	0.0005	0.007	1.0000	0.0035	1.0110	0.0035
HEU-SOL-THERM-007-03	1.0060	0.0005	0.007	1.0000	0.0035	1.0060	0.0035
HEU-SOL-THERM-007-07	1.0031	0.0005	0.008	1.0000	0.0035	1.0031	0.0035
HEU-SOL-THERM-007-11	1.0072	0.0006	0.035	1.0000	0.0035	1.0072	0.0035
HEU-SOL-THERM-007-14	1.0069	0.0006	0.035	1.0000	0.0035	1.0069	0.0035
HEU-SOL-THERM-012-01	1.0009	0.0004	0.003	0.9999	0.0058	1.0010	0.0058
HEU-SOL-THERM-027-01	0.9968	0.0004	0.015	1.0000	0.0046	0.9968	0.0046
HEU-SOL-THERM-027-02	0.9967	0.0004	0.015	1.0000	0.0043	0.9967	0.0043
HEU-SOL-THERM-027-03	0.9975	0.0004	0.015	1.0000	0.0037	0.9975	0.0037
HEU-SOL-THERM-027-04	0.9983	0.0004	0.015	1.0000	0.0037	0.9983	0.0037
HEU-SOL-THERM-027-05	0.9962	0.0004	0.015	1.0000	0.0044	0.9962	0.0044
HEU-SOL-THERM-031-01	0.9970	0.0004	0.028	1.0000	0.0046	0.9970	0.0046
HEU-SOL-THERM-031-02	1.0080	0.0004	0.029	1.0000	0.0058	1.0080	0.0058
HEU-SOL-THERM-031-03	0.9970	0.0004	0.029	1.0000	0.0058	0.9970	0.0058
HEU-SOL-THERM-031-04	1.0015	0.0004	0.030	1.0000	0.0068	1.0015	0.0068
HEU-SOL-THERM-035-01	1.0005	0.0004	0.004	1.0000	0.0031	1.0005	0.0031
HEU-SOL-THERM-035-02	1.0034	0.0004	0.004	1.0000	0.0032	1.0034	0.0032
HEU-SOL-THERM-035-03	1.0043	0.0004	0.004	1.0000	0.0030	1.0043	0.0030
HEU-SOL-THERM-035-04	1.0037	0.0004	0.004	1.0000	0.0030	1.0037	0.0030
HEU-SOL-THERM-035-05	1.0023	0.0004	0.008	1.0000	0.0033	1.0023	0.0033
HEU-SOL-THERM-035-06	1.0037	0.0004	0.008	1.0000	0.0029	1.0037	0.0029
HEU-SOL-THERM-035-07	1.0051	0.0005	0.015	1.0000	0.0035	1.0051	0.0035
HEU-SOL-THERM-035-08	0.9987	0.0005	0.016	1.0000	0.0038	0.9987	0.0038
HEU-SOL-THERM-035-09	0.9997	0.0005	0.016	1.0000	0.0041	0.9997	0.0041

	MCNP 6.1 Calculation			Benchmark Values		Normalized Results	
Exp Name	k-calc	σ-calc	ANECF MeV	k-meas	σ-exp	k-norm	σ-tot
HEU-SOL-THERM-038-01	0.9955	0.0002	0.043	1.0000	0.0025	0.9955	0.0025
HEU-SOL-THERM-038-02	0.9970	0.0002	0.040	1.0000	0.0025	0.9970	0.0025
HEU-SOL-THERM-038-07	0.9979	0.0002	0.042	1.0000	0.0032	0.9979	0.0032
HEU-SOL-THERM-038-08	0.9986	0.0002	0.041	1.0000	0.0026	0.9986	0.0026
HEU-SOL-THERM-038-09	0.9985	0.0002	0.041	1.0000	0.0033	0.9985	0.0033
HEU-SOL-THERM-038-10	0.9970	0.0002	0.042	1.0000	0.0026	0.9970	0.0026
HEU-SOL-THERM-038-11	0.9966	0.0002	0.043	1.0000	0.0025	0.9966	0.0026
HEU-SOL-THERM-038-12	0.9963	0.0002	0.043	1.0000	0.0025	0.9963	0.0025
HEU-SOL-THERM-038-17	0.9969	0.0002	0.043	1.0000	0.0026	0.9969	0.0026
HEU-SOL-THERM-038-18	0.9974	0.0002	0.043	1.0000	0.0032	0.9974	0.0032
HEU-SOL-THERM-046-01	1.0139	0.0003	0.004	1.0011	0.0029	1.0128	0.0029
HEU-SOL-THERM-046-02	1.0105	0.0003	0.004	1.0011	0.0029	1.0094	0.0029
HEU-SOL-THERM-046-03	1.0110	0.0003	0.004	1.0011	0.0029	1.0099	0.0029
HEU-SOL-THERM-046-04	1.0119	0.0003	0.004	1.0011	0.0029	1.0108	0.0029
HEU-SOL-THERM-046-05	1.0098	0.0003	0.004	1.0011	0.0030	1.0087	0.0030
HEU-SOL-THERM-046-06	1.0111	0.0003	0.004	1.0011	0.0029	1.0100	0.0029
HEU-SOL-THERM-046-07	1.0120	0.0003	0.004	1.0011	0.0031	1.0109	0.0031
HEU-SOL-THERM-046-08	1.0113	0.0003	0.004	1.0011	0.0032	1.0102	0.0032
HEU-SOL-THERM-046-09	1.0107	0.0003	0.004	1.0011	0.0037	1.0096	0.0037
HEU-SOL-THERM-046-10	1.0086	0.0003	0.004	1.0011	0.0029	1.0075	0.0029
HEU-SOL-THERM-046-11	1.0114	0.0003	0.005	1.0011	0.0028	1.0103	0.0028
HEU-SOL-THERM-046-12	1.0105	0.0003	0.005	1.0011	0.0029	1.0094	0.0029
HEU-SOL-THERM-046-13	1.0100	0.0003	0.005	1.0011	0.0030	1.0089	0.0030
IEU-COMP-THERM-001-01	1.0021	0.0007	0.210	1.0000	0.0040	1.0021	0.0041
IEU-COMP-THERM-001-02	1.0047	0.0007	0.155	1.0000	0.0040	1.0047	0.0041
IEU-COMP-THERM-001-03	0.9987	0.0007	0.103	1.0000	0.0040	0.9987	0.0041
IEU-COMP-THERM-001-04	1.0000	0.0007	0.073	1.0000	0.0040	1.0000	0.0041
IEU-COMP-THERM-001-05	1.0053	0.0006	0.045	1.0000	0.0040	1.0053	0.0040
IEU-COMP-THERM-001-06	1.0034	0.0007	0.105	1.0000	0.0040	1.0034	0.0041
IEU-COMP-THERM-001-07	1.0015	0.0007	0.109	1.0000	0.0040	1.0015	0.0041
IEU-COMP-THERM-001-08	0.9998	0.0007	0.117	1.0000	0.0040	0.9998	0.0041
IEU-COMP-THERM-001-09	1.0084	0.0007	0.164	1.0000	0.0040	1.0084	0.0041
IEU-COMP-THERM-001-10	1.0014	0.0007	0.154	1.0000	0.0040	1.0014	0.0041
IEU-COMP-THERM-001-11	1.0006	0.0007	0.154	1.0000	0.0040	1.0006	0.0041
IEU-COMP-THERM-001-12	1.0011	0.0006	0.153	1.0000	0.0040	1.0011	0.0040
IEU-COMP-THERM-001-13	0.9999	0.0007	0.073	1.0000	0.0040	0.9999	0.0041
IEU-COMP-THERM-001-14	0.9998	0.0007	0.073	1.0000	0.0040	0.9998	0.0041
IEU-COMP-THERM-001-15	1.0023	0.0007	0.073	1.0000	0.0040	1.0023	0.0041
IEU-COMP-THERM-001-16	1.0033	0.0007	0.054	1.0000	0.0040	1.0033	0.0041
IEU-COMP-THERM-001-17	1.0042	0.0008	0.202	1.0000	0.0040	1.0042	0.0041

	MCNP 6.1 Calculation			Benchmark Values		Normalized Results	
Exp Name	k-calc	σ-calc	ANECF MeV	k-meas	σ-exp	k-norm	σ-tot
IEU-COMP-THERM-001-18	1.0053	0.0008	0.131	1.0000	0.0040	1.0053	0.0041
IEU-COMP-THERM-001-19	1.0051	0.0007	0.060	1.0000	0.0040	1.0051	0.0041
IEU-COMP-THERM-001-20	1.0088	0.0007	0.151	1.0000	0.0040	1.0088	0.0041
IEU-COMP-THERM-001-21	1.0031	0.0007	0.207	1.0000	0.0040	1.0031	0.0041
IEU-COMP-THERM-001-26	1.0077	0.0006	0.055	1.0000	0.0040	1.0077	0.0041
IEU-COMP-THERM-001-27	1.0021	0.0007	0.056	1.0000	0.0040	1.0021	0.0041
IEU-COMP-THERM-001-28	1.0111	0.0007	0.154	1.0000	0.0040	1.0111	0.0041
IEU-COMP-THERM-001-29	1.0077	0.0007	0.148	1.0000	0.0040	1.0077	0.0041
IEU-COMP-THERM-002-01	1.0001	0.0005	0.044	1.0014	0.0039	0.9987	0.0039
IEU-COMP-THERM-003-01	1.0043	0.0003	0.023	1.0006	0.0056	1.0037	0.0056
IEU-COMP-THERM-003-02	1.0087	0.0003	0.023	1.0046	0.0056	1.0040	0.0056
IEU-COMP-THERM-015-04	0.9954	0.0001	0.283	0.9982	0.0032	0.9972	0.0032
IEU-COMP-THERM-015-05	0.9947	0.0001	0.283	0.9982	0.0031	0.9964	0.0031
IEU-COMP-THERM-015-07	0.9941	0.0001	0.179	0.9981	0.0036	0.9960	0.0036
IEU-COMP-THERM-015-08	0.9980	0.0001	0.089	0.9990	0.0044	0.9990	0.0044
IEU-COMP-THERM-015-09	0.9976	0.0001	0.090	0.9991	0.0047	0.9985	0.0047
IEU-COMP-THERM-015-10	0.9977	0.0001	0.089	0.9995	0.0045	0.9982	0.0045
IEU-COMP-THERM-015-11	1.0005	0.0001	0.047	0.9985	0.0050	1.0020	0.0050
IEU-COMP-THERM-015-12	1.0010	0.0001	0.047	0.9985	0.0051	1.0025	0.0051
IEU-MET-FAST-003-01	1.0031	0.0003	1.262	1.0000	0.0019	1.0031	0.0019
IEU-MET-FAST-004-01	1.0076	0.0003	1.222	1.0000	0.0032	1.0076	0.0032
IEU-MET-FAST-005-01	1.0016	0.0003	1.208	1.0000	0.0023	1.0016	0.0023
IEU-MET-FAST-006-01	0.9965	0.0003	1.205	1.0000	0.0025	0.9965	0.0025
IEU-MET-FAST-009-01	1.0110	0.0003	0.946	1.0000	0.0053	1.0110	0.0053
IEU-SOL-THERM-002-01	1.0095	0.0001	0.013	1.0004	0.0026	1.0091	0.0026
IEU-SOL-THERM-002-02	1.0000	0.0001	0.009	1.0003	0.0032	0.9997	0.0032
IEU-SOL-THERM-002-03	1.0005	0.0001	0.007	1.0003	0.0038	1.0002	0.0038
IEU-SOL-THERM-002-04	1.0020	0.0001	0.005	1.0003	0.0046	1.0016	0.0046
IEU-SOL-THERM-002-05	1.0045	0.0002	0.024	0.9989	0.0042	1.0056	0.0042
IEU-SOL-THERM-002-07	1.0005	0.0001	0.011	0.9991	0.0032	1.0014	0.0032
IEU-SOL-THERM-002-08	1.0039	0.0001	0.006	0.9996	0.0042	1.0043	0.0042
IEU-SOL-THERM-002-09	1.0085	0.0001	0.004	1.0001	0.0054	1.0084	0.0054
IEU-SOL-THERM-002-10	1.0024	0.0001	0.007	1.0005	0.0038	1.0019	0.0038
IEU-SOL-THERM-002-11	1.0050	0.0001	0.005	1.0004	0.0048	1.0046	0.0048
IEU-SOL-THERM-002-12	1.0043	0.0001	0.007	1.0004	0.0042	1.0039	0.0042
IEU-SOL-THERM-002-13	1.0051	0.0001	0.012	0.9984	0.0042	1.0068	0.0042
IEU-SOL-THERM-004-01	1.0094	0.0002	0.013	1.0091	0.0041	1.0003	0.0041
LEU-COMP-THERM-022-01	1.0032	0.0001	0.157	1.0000	0.0046	1.0032	0.0046
LEU-COMP-THERM-022-02	1.0065	0.0003	0.115	1.0000	0.0046	1.0065	0.0046
LEU-COMP-THERM-022-03	1.0069	0.0003	0.074	1.0000	0.0036	1.0069	0.0036

	MCNP 6.1 Calculation			Benchmark Values		Normalized Results	
Exp Name	k-calc	σ-calc	ANECF MeV	k-meas	σ-exp	k-norm	σ-tot
LEU-COMP-THERM-022-04	1.0081	0.0003	0.054	1.0000	0.0037	1.0081	0.0037
LEU-COMP-THERM-022-05	1.0031	0.0003	0.045	1.0000	0.0038	1.0031	0.0038
LEU-COMP-THERM-022-06	1.0015	0.0002	0.035	1.0000	0.0046	1.0015	0.0046
LEU-COMP-THERM-022-07	1.0046	0.0003	0.034	1.0000	0.0046	1.0046	0.0046
LEU-COMP-THERM-023-01	0.9952	0.0003	0.059	1.0000	0.0044	0.9952	0.0044
LEU-COMP-THERM-023-02	0.9980	0.0003	0.053	1.0000	0.0044	0.9980	0.0044
LEU-COMP-THERM-023-03	0.9995	0.0003	0.051	1.0000	0.0044	0.9995	0.0044
LEU-COMP-THERM-023-04	1.0012	0.0003	0.050	1.0000	0.0044	1.0012	0.0044
LEU-COMP-THERM-023-05	1.0024	0.0003	0.048	1.0000	0.0044	1.0024	0.0044
LEU-COMP-THERM-023-06	1.0024	0.0003	0.047	1.0000	0.0044	1.0024	0.0044
LEU-COMP-THERM-024-01	1.0007	0.0003	0.178	1.0000	0.0054	1.0007	0.0054
LEU-COMP-THERM-024-02	1.0081	0.0003	0.081	1.0000	0.0040	1.0081	0.0040
LEU-COMP-THERM-032-01	1.0016	0.0003	0.158	1.0000	0.0045	1.0016	0.0045
LEU-COMP-THERM-032-04	1.0029	0.0003	0.046	1.0000	0.0037	1.0029	0.0037
LEU-COMP-THERM-032-07	1.0045	0.0002	0.034	1.0000	0.0045	1.0045	0.0045
LEU-SOL-THERM-006-01	0.9978	0.0003	0.025	1.0000	0.0037	0.9978	0.0037
LEU-SOL-THERM-006-02	1.0034	0.0003	0.025	1.0000	0.0038	1.0034	0.0038
LEU-SOL-THERM-006-03	0.9978	0.0003	0.025	1.0000	0.0041	0.9978	0.0041
LEU-SOL-THERM-006-04	0.9992	0.0003	0.025	1.0000	0.0041	0.9992	0.0041
LEU-SOL-THERM-006-05	1.0008	0.0003	0.026	1.0000	0.0047	1.0008	0.0047
LEU-SOL-THERM-008-72	1.0021	0.0002	0.015	0.9999	0.0014	1.0022	0.0014
LEU-SOL-THERM-008-74	1.0011	0.0002	0.015	1.0002	0.0015	1.0009	0.0015
LEU-SOL-THERM-008-76	1.0014	0.0002	0.015	0.9999	0.0014	1.0015	0.0014
LEU-SOL-THERM-008-78	1.0021	0.0002	0.015	0.9999	0.0014	1.0022	0.0014
LEU-SOL-THERM-009-92	0.9998	0.0002	0.016	0.9998	0.0014	1.0000	0.0014
LEU-SOL-THERM-009-93	1.0008	0.0002	0.016	0.9999	0.0014	1.0009	0.0014
LEU-SOL-THERM-009-94	1.0013	0.0002	0.016	0.9999	0.0014	1.0014	0.0014

The results of each enrichment group are examined for normality. The null hypothesis is that the data are normally distributed, and 95% confidence is required to reject this assumption herein. The hypothesis of normality is accepted for all subgroups. The results of the normality testing are shown in Section 5.2.

5.1. Trend Evaluation

The k_{eff} results are also analyzed to determine if a trend exists with important validation parameters. A calculational methodology should have a bias that neither has dependence on a characteristic nor is a smooth function of a parameter. If a trend exists, the bias will vary as a function of that trend over the parameter range. If no trend exists, then the bias will be constant over the area of applicability. Critical experiment parameters examined include the hydrogen to fissile material ratio (H/X), the Average Neutron Energy Causing Fission (ANECF), the ^{235}U enrichment, the moderator material, the reflector material and the chemical form of the fissile material. Graphs of the validation results versus these parameters are shown. Where appropriate, the graphs of the results and the trending parameters also include a plotted trend line and the coefficient of determination value (R^2) for the trend line. Note, an R^2 value less than 0.3 is

considered to indicate no data correlation, while an R^2 value of 0.8 or greater is indicative of data correlation. It is concluded that no trend in the bias is observed.

5.1.1. Average Neutron Energy Causing Fission (ANECF)

The ANECF value is a MCNP calculated value used to characterize the system neutron energy. Consistent with the purpose of this validation, the majority of the experiments evaluated are in the thermal neutron range with ANECF values between 0.005 and 0.10 MeV. However, sufficient higher energy experiments are included with ANECF values up to 1.46 MeV to demonstrate that there is no trend in the k_{eff} values relative to the ANECF value. Figure 1 presents the MCNP 6.1 data.

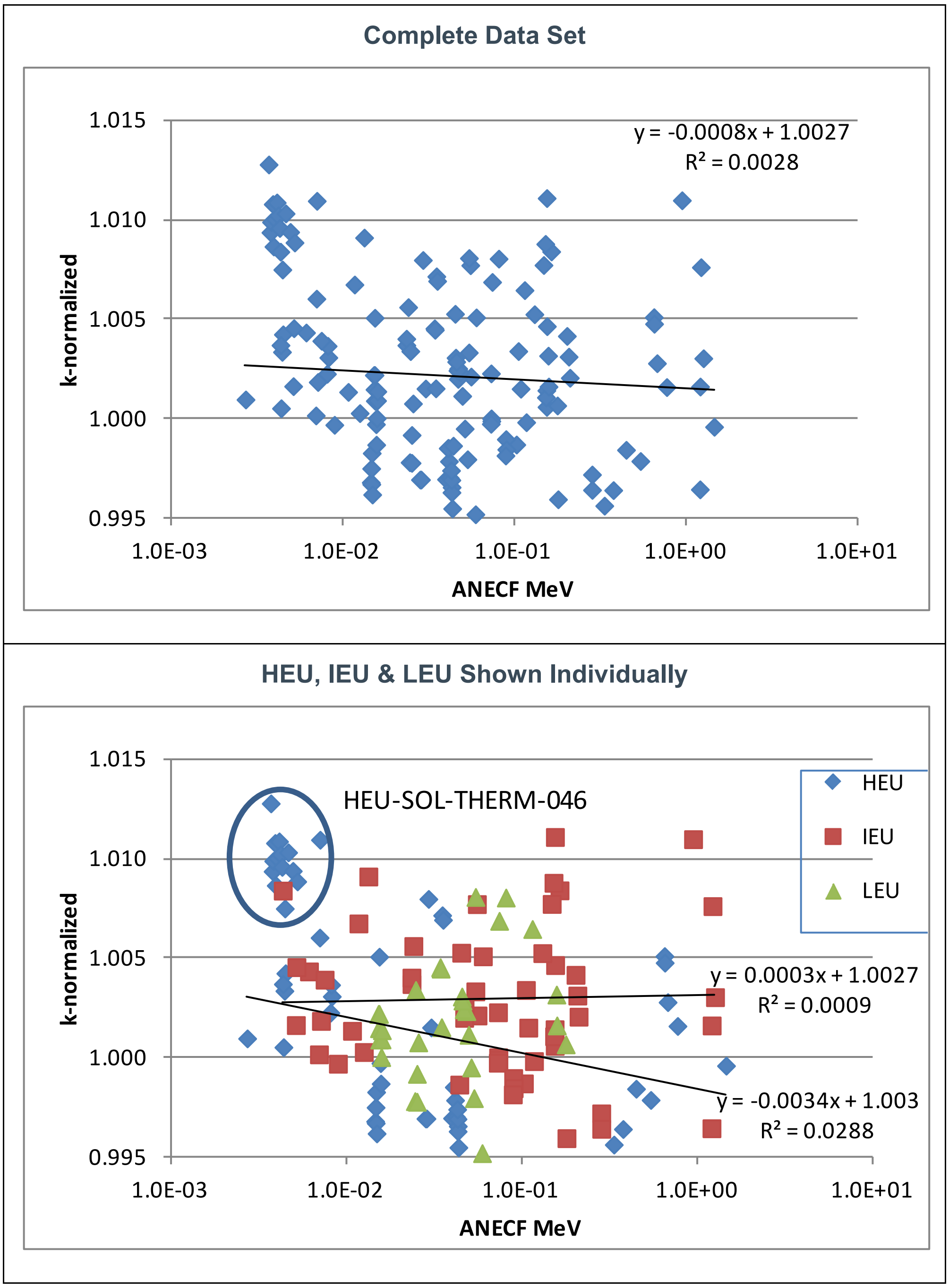

Figure 1 - ANECF Trend

In the complete data set, the very slight negative slope to the data's linear fit is judged to be insignificant as its change in value over the entire data range is on the order of the average total uncertainty (σ-tot) and the R^2 value is much less than the minimally acceptable value of 0.3.

Also included are the individual HEU, IEU and LEU data sets. As shown, the HEU and IEU data sets span the entire ANECF range while the LEU set is concentrated in the center. This is a consequence of the difficulty in creating a LEU critical configuration that is either excessively over or under moderated. The lower trendline displayed is a linear fit for only the HEU data. As indicated, the overestimation of k_{eff} with the HEU-SOL-THERM-046 experiments (as stated in Section 4.3.1) results in the apparent negative slope for this line and the linear fit for the combined data set in the chart above. This overestimation is evaluated below and is judged to be the consequence of a systematic error in the Reference 1 Benchmark description.

The second, upper trendline shown displays a linear fit for only the IEU data, and has no indication of a variable bias with respect to ANECF.

In order to evaluate the overestimation of HEU-SOL-THERM-046, it is compared with other, similar data sets. The HEU-SOL-THERM-007, -012, and -035 sets are very similar and have identical ANECF values, yet do not exhibit this overestimate. Additionally, the IEU-SOL-THERM-002 experiments have similar geometry and identical ANECF values without exhibiting an overestimate. Therefore, it is judged that the overestimate cannot result from a MCNP 6.1 calculation error related to the geometry or cross sections of the shared materials. The materials exclusive to HEU-SOL-THERM-046 are the sulfate solution and the beryllium-graphite reflector.

The following data sets also include beryllium or graphite reflectors without exhibiting an overestimate in their k_{eff} values: HEU-COMP-FAST-002, HEU-COMP-INTER-003, IEU-COMP-THERM-003, IEU-MET-FAST-004 and IEU-SOL-THERM-004. These are shown graphically in Section 5.1.6. Note that only IEU-COMP-THERM-003 and IEU-SOL-THERM-004 have an ANECF values in the thermal range (albeit, slightly more energetic than HEU-SOL-THERM-0046). From this it is judged to be unlikely that an error in the cross sections for the reflector materials is the cause of the overestimate.

The sulfate solution (H_2SO_4-H_2O) is essential to the SHINE applications and this validation; however, it is very rare within the Reference 1 Benchmarks. The IEU-SOL-THERM-004 experiment (included herein) also contains this solution and does not exhibit an overestimate, but this is only one experiment. The sulfur solution was selected for SHINE applications because, among other features, of sulfur's very small neutron absorption cross section (~0.5 barns). This is much lower than most other solution materials usually included in the Benchmark experiments. For example, nitrogen (used in the common nitric acid) has an absorption cross section of about 1.9 barns. Given that the sulfur cross section is so small, it is judged to be very unlikely that an error in the cross section could be the cause of the overestimate.

To further test this notion, the experiments HEU-SOL-THERM-046-01 and IEU-SOL-THERM-004 were recalculated with the sulfur replaced (atom for atom) by sodium. Sodium has a similar atomic mass and virtually identical neutron absorption cross section. The result of this computational experiment was an increase in the k_{eff} values of 0.0012 and 0.0016, respectively.

Additionally, it is noted in Reference 1 that the benchmark calculation results show a 1.5% overestimate when using the APOLLO2-MORET4 code without explanation.

Therefore, it is judged that the overestimate does not result from an error in the MCNP 6.1 calculation or the cross sections. Rather, it is most likely due to a systematic error in the Reference 1 Benchmark description. However, the overestimate is not so large as to make the experiments unusable. These are retained within this validation, with the understanding that they are the cause of the apparent bias with respect to ANECF, $H/^{235}U$ (see Section 5.1.2), moderator (see Section 5.1.5), reflector (see Section 5.1.6), and chemical form (see Section 5.1.7).

5.1.2. H/^{235}U Values

The H/^{235}U value is a physical system parameter used to characterize the system neutron energy. Consistent with the purpose of this validation, the majority of the experiments evaluated are in the thermal neutron range and H/^{235}U values from 20 to 1200 are well represented. However, sufficient higher energy experiments are included with H/^{235}U values as low as 3.1 to demonstrate that there is no trend in the k_{eff} values relative to the H/^{235}U value. Figure 2 presents the MCNP 6.1 data.

The positive slope of the data's linear fit is about 2 times the average total uncertainty (σ-tot) for the collection of experiments. However, it is judged that this does not represent a valid trend because:

- The R^2 value is much less than the minimally acceptable value of 0.3, thus this trendline does not represent an acceptable fit to the data.
- The upward slope of the trendline is largely an artifact of the overestimation of the HEU-SOL-THERM-046 experiments (as stated in Section 4.3.1). This overestimation is evaluated in Section 5.1.1 and is judged to be the consequence of a systematic error in the Reference 1 Benchmark description. While not shown herein, removal of this data set eliminates the apparent upward slope of the trendline.

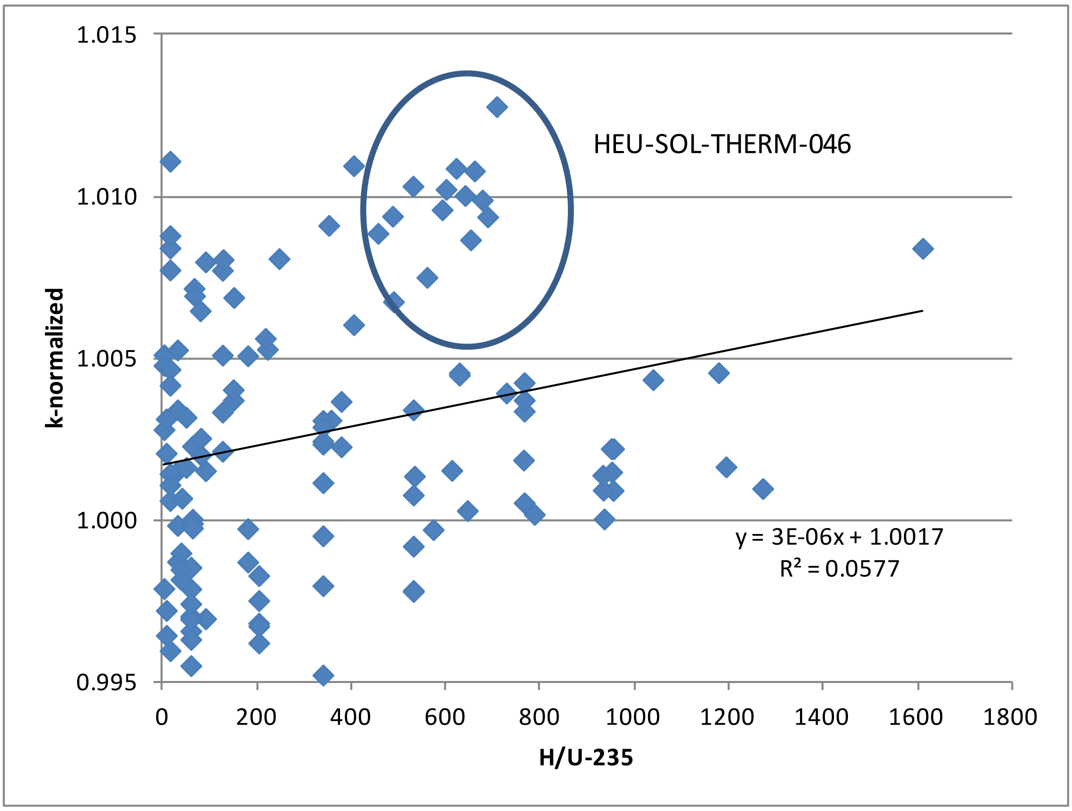

Figure 2 - H/^{235}U Trend

5.1.3. ANECF vs. H/^{235}U

[Proprietary Information]

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Figure 3 - ANECF vs. H/^{235}U Evaluation

Note that there is strong relationship between the two parameters. However, the exact relationship varies as the ^{238}U concentration decreases; i.e., the variation from LEU to IEU to HEU. From this relationship it is judged that the ANECF value accurately characterizes the system neutron energy in the absence of accurate $H/^{235}U$ values and in the presence of other neutron scattering isotopes (e.g., carbon, sulfur).

5.1.4. Enrichment

The system enrichment (wt. % ^{235}U) is a physical system parameter used to characterize the system. Consistent with the purpose of this validation, the majority of the experiments evaluated are intermediate uranium enrichment with wt. % ^{235}U values between 10 and 30%. However, sufficient higher enrichment experiments are included with wt. % ^{235}U values as high as 94% to demonstrate that there is no trend in the k_{eff} values relative to enrichment. Figure 4 presents the MCNP 6.1 data. There is no discernible slope to the data's linear fit over the entire data range and that the R^2 value is much less than the minimally acceptable value of 0.3.

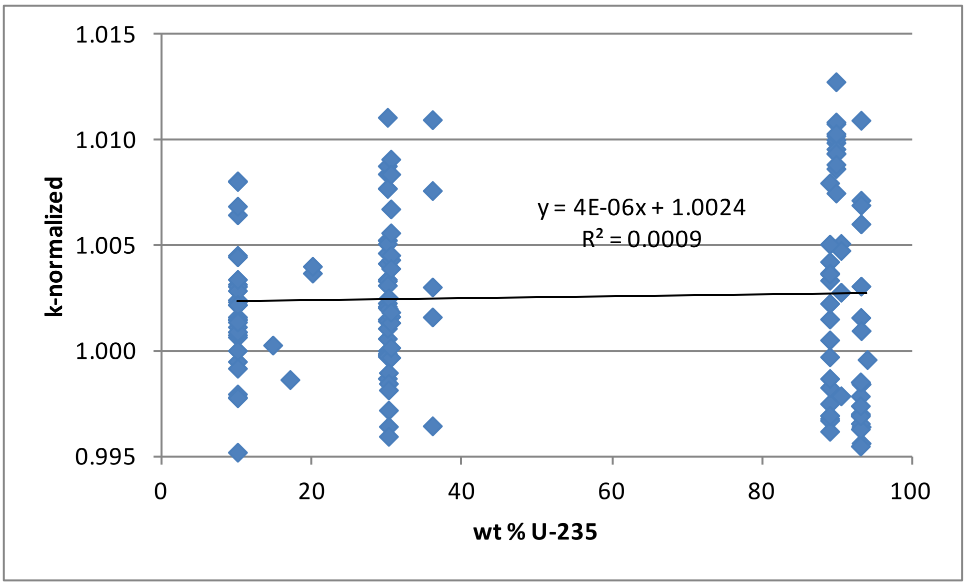

Figure 4 - Enrichment Trend

5.1.5. Moderator

The system neutron moderator material is a physical system parameter used to characterize the system. Figure 5 displays the normalized k_{eff} values for the various moderator materials used herein. Also shown are average bias values for the various moderator materials. Note that the complete data set average k_{eff} and σ-tot values are 1.0026 and 0.0037, respectively. The only significant biases are those related to the sulfate solution (see Section 5.1.1) and graphite. Graphite will not be included as a moderator in the AoA for this evaluation.

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Figure 5 - Moderator Evaluation

5.1.6. Reflector

The system reflector material is a physical system parameter used to characterize the system. Figure 6 displays the normalized k_{eff} values for the various reflector materials used herein. Also shown are average bias values for the various reflector materials. Note that the complete data set average keff and σ-tot values are 1.0026 and 0.0037, respectively. The only significant biases are those related to the beryllium oxide / graphite (see Section 5.1.1) and miscellaneous metals. Only iron (and stainless steel), which are structural materials found in many of the experiments included herein, will be included as a metal reflector in the AoA for this evaluation.

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Figure 6 - Reflector Evaluation

5.1.7. Chemical Form

The chemical form of the system fissile material is a physical system parameter used to characterize the system. Figure 7 displays the normalized k_{eff} values for the various chemical forms of uranium materials used herein. Also shown are average bias values for the various materials. Note that the complete data set average keff and σ-tot values are 1.0026 and 0.0037, respectively. The only significant bias is that related to the sulfate solution (see Section 5.1.1).

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Figure 7 - Chemical Form Evaluation

5.1.8. Homogeneous Vs. Heterogeneous

Eighty-four (84) of the experiments are homogeneous with an average k_{eff} value of 1.0025 and an average σ-tot value of 0.0035. Comparing this with the 56 heterogeneous experiments, with an average k_{eff} value of 1.0026 and an average σ-tot value of 0.0040, indicates that there is no bias between homogeneous and heterogeneous MCNP 6.1 models.

5.2. Normalcy Evaluation

Since 20 wt. % ^{235}U is the target of this evaluation, the IEU data set is evaluated individually. However, the 10 wt. % ^{235}U LEU experiments have been added to the IEU data set to bound the 20% target value. Additionally, the combined LEU, IEU and HEU data set is included for completeness. The summary of the normalcy results is show in Table 4.

Table 4 - Normalcy Results Summary

Intermediate Enriched Uranium	Normal
Low and Intermediate Enriched Uranium	Normal
Combined LEU, IEU and HEU Data Set	Normal

5.2.1. Intermediate Enriched Uranium

The examination of these data includes 54 cases as shown in Appendix 1. [Proprietary Information]

[Proprietary Information]

These calculations are shown in Appendix A and the comparison of the observed distribution vs. the expected distribution of a normal system is shown in Figure 8. The data are judged to be from a normal population because all three normality tests indicate that the data are normal.

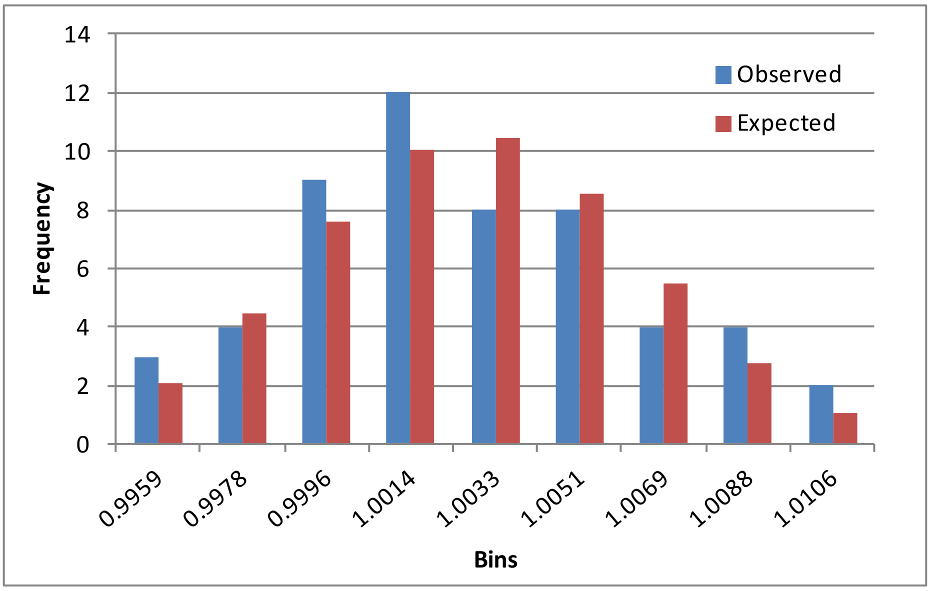

Figure 8 - Intermediate Enriched Distribution

5.2.2. Low and Intermediate Enriched Uranium

The examination of these data includes 84 cases as shown in Appendix 1. [Proprietary Information]

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Proprietary Information

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These calculations are shown in Appendix A and the comparison of the observed distribution vs. the expected distribution of a normal system is shown in Figure 9. The data are judged to be from a normal population because all three normality tests indicate that the data are normal.

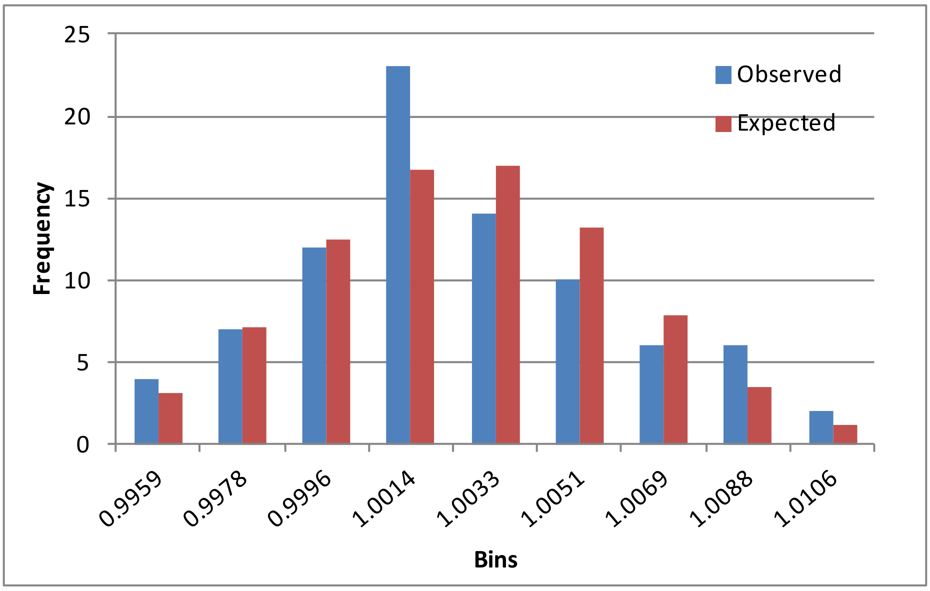

Figure 9 – Low and Intermediate Enriched Distribution

5.2.3. Combined Data Set

As there is no trend associated with combined data set, it can also be evaluated. The examination of these data includes 140 cases as shown in Appendix 1. [Proprietary Information]

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Proprietary Information

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[Proprietary Information]

These calculations are shown in Appendix A and the comparison of the observed distribution vs. the expected distribution of a normal system is shown in Figure 10. The data are judged to be from a normal population because:

- Two of the three normality tests indicate the data are normal, and
- [Proprietary Information]

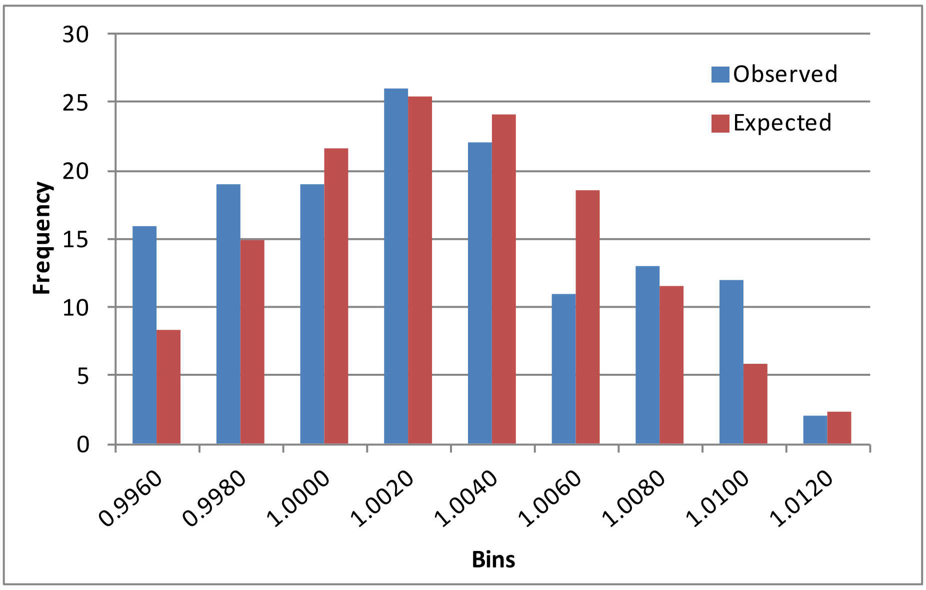

Figure 10 - Combined Group Distribution

5.3. Bias and Bias Uncertainty Evaluation

While the SHINE applications will use nominally 19.75 wt. % ^{235}U materials, three sets of the data are evaluated for bias and bias uncertainty. First, the set including only the 54 IEU experiments with 14.7 to 36 wt. % ^{235}U is considered as this most accurately brackets the SHINE applications. However, as there are only four experiments with less than 30 wt. % ^{235}U in the IEU data set, a second evaluation considers the 84 experiments in the combined LEU and IEU data sets (10 to 36 wt. % ^{235}U). This is judged to better encompass the SHINE application value of approximately 20 wt. % ^{235}U. Lastly, all three LEU, IEU and HEU data sets are combined to evaluate the complete 140 experiment data set.

A summary of the weighted bias and USL calculations is shown in Table 5. Per Reference 10, positive bias values are not used and the bias is set to zero for the USL calculation. The SHINE specific MoS value of 0.05 is included in the USL. The USL value of 0.9391 is recommended for use with the SHINE 20 wt. % ^{235}U materials, which was selected from Table 5 as the most conservative value.

Table 5 - USL Results Summary

	Bias	Bias Uncertainty	USL
Intermediate Enriched Uranium	0.0025	0.0109	**0.9391**
Low and Intermediate Enriched Uranium	0.0020	0.0078	0.9422
Combined Enrichments	0.0011	0.0091	0.9409

5.3.1. Intermediate Enriched Uranium

As the data are judged to be from a normal distribution the bias and bias uncertainty is represented with a Lower Tolerance Limit (LTL). The USL calculation for MCNP 6.1 (0.9391) is developed in Table 6. Note that the positive bias of 0.0025 is set to zero.

Table 6 – Intermediate Enriched USL

File Name	k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
IEU-COMP-THERM-001-01	1.00207	0.00406	60744.4844	6.0870E+04	0.0120
IEU-COMP-THERM-001-02	1.00466	0.00406	60744.4844	6.1028E+04	0.2796
IEU-COMP-THERM-001-03	0.99872	0.00406	60744.4844	6.0667E+04	0.8747
IEU-COMP-THERM-001-04	1.00003	0.00407	60485.4563	6.0487E+04	0.3734
IEU-COMP-THERM-001-05	1.00528	0.00405	61079.5194	6.1402E+04	0.4671
IEU-COMP-THERM-001-06	1.00341	0.00406	60693.9749	6.0901E+04	0.0486
IEU-COMP-THERM-001-07	1.00152	0.00407	60485.4563	6.0577E+04	0.0598
IEU-COMP-THERM-001-08	0.99984	0.00406	60794.3388	6.0785E+04	0.4349
IEU-COMP-THERM-001-09	1.00841	0.00406	60693.9749	6.1204E+04	2.1094
IEU-COMP-THERM-001-10	1.00144	0.00406	60591.0047	6.0678E+04	0.0700
IEU-COMP-THERM-001-11	1.00061	0.00406	60744.4844	6.0782E+04	0.2204
IEU-COMP-THERM-001-12	1.00109	0.00405	61033.6662	6.1100E+04	0.1239
IEU-COMP-THERM-001-13	0.99990	0.00406	60744.4844	6.0738E+04	0.4153
IEU-COMP-THERM-001-14	0.99976	0.00406	60693.9749	6.0679E+04	0.4606

File Name	k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
IEU-COMP-THERM-001-15	1.00229	0.00406	60744.4844	6.0884E+04	0.0031
IEU-COMP-THERM-001-16	1.00334	0.00406	60794.3388	6.0997E+04	0.0414
IEU-COMP-THERM-001-17	1.00417	0.00407	60322.3627	6.0574E+04	0.1653
IEU-COMP-THERM-001-18	1.00526	0.00407	60322.3627	6.0640E+04	0.4546
IEU-COMP-THERM-001-19	1.00510	0.00406	60538.5509	6.0847E+04	0.4046
IEU-COMP-THERM-001-20	1.00879	0.00406	60794.3388	6.1329E+04	2.3940
IEU-COMP-THERM-001-21	1.00313	0.00405	60843.5348	6.1034E+04	0.0230
IEU-COMP-THERM-001-26	1.00772	0.00405	60939.9376	6.1410E+04	1.6512
IEU-COMP-THERM-001-27	1.00213	0.00406	60744.4844	6.0874E+04	0.0090
IEU-COMP-THERM-001-28	1.01109	0.00405	60843.5348	6.1518E+04	4.4742
IEU-COMP-THERM-001-29	1.00773	0.00406	60744.4844	6.1214E+04	1.6522
IEU-COMP-THERM-002-01	0.99866	0.00393	64882.4006	6.4796E+04	0.9631
IEU-COMP-THERM-003-01	1.00371	0.00561	31808.2345	3.1926E+04	0.0453
IEU-COMP-THERM-003-02	1.00403	0.00561	31802.4685	3.1931E+04	0.0732
IEU-COMP-THERM-015-04	0.99721	0.00320	97519.1137	9.7248E+04	2.7390
IEU-COMP-THERM-015-05	0.99644	0.00310	103927.4171	1.0356E+05	3.8306
IEU-COMP-THERM-015-07	0.99597	0.00360	77060.0066	7.6750E+04	3.2984
IEU-COMP-THERM-015-08	0.99899	0.00440	51607.8423	5.1556E+04	0.6415
IEU-COMP-THERM-015-09	0.99848	0.00470	45234.7457	4.5166E+04	0.7369
IEU-COMP-THERM-015-10	0.99817	0.00450	49334.9647	4.9245E+04	0.9317
IEU-COMP-THERM-015-11	1.00201	0.00500	39968.6646	4.0049E+04	0.0101
IEU-COMP-THERM-015-12	1.00253	0.00510	38417.8013	3.8515E+04	0.0000
IEU-MET-FAST-003-01	1.00305	0.00192	271525.1568	2.7235E+05	0.0778
IEU-MET-FAST-004-01	1.00762	0.00321	96965.9359	9.7705E+04	2.5273
IEU-MET-FAST-005-01	1.00163	0.00232	186466.2776	1.8677E+05	0.1459
IEU-MET-FAST-006-01	0.99647	0.00252	158017.8244	1.5746E+05	5.7737
IEU-MET-FAST-009-01	1.01098	0.00531	35507.7069	3.5898E+04	2.5445
IEU-SOL-THERM-002-01	1.00911	0.00260	147501.3275	1.4884E+05	6.4089
IEU-SOL-THERM-002-02	0.99971	0.00320	97495.3446	9.7467E+04	0.7669
IEU-SOL-THERM-002-03	1.00018	0.00380	69204.1522	6.9217E+04	0.3772
IEU-SOL-THERM-002-04	1.00165	0.00460	47240.8955	4.7319E+04	0.0354
IEU-SOL-THERM-002-05	1.00562	0.00420	56607.1914	5.6925E+04	0.5445
IEU-SOL-THERM-002-07	1.00136	0.00320	97469.6869	9.7602E+04	0.1297
IEU-SOL-THERM-002-08	1.00434	0.00420	56657.2238	5.6903E+04	0.1891
IEU-SOL-THERM-002-09	1.00840	0.00540	34286.0278	3.4574E+04	1.1872
IEU-SOL-THERM-002-10	1.00186	0.00380	69194.0964	6.9323E+04	0.0297
IEU-SOL-THERM-002-11	1.00456	0.00480	43387.5244	4.3585E+04	0.1812

File Name		k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
IEU-SOL-THERM-002-12		1.00393	0.00420	56650.4835	5.6873E+04	0.1132
IEU-SOL-THERM-002-13		1.00675	0.00420	56626.4242	5.7009E+04	1.0161
IEU-SOL-THERM-004-01		1.00030	0.00410	59408.8816	5.9427E+04	0.2921
	k_{mean}	1.0025		$\Sigma\ 1/(\sigma_\iota)^2$	$\Sigma\ 1/(\sigma_\iota)^2 * k_{eff}$	
		1.0000		3.7897E+06	3.7992E+06	
	$(\sigma_{mean})^2$	S^2		S_t	K*	USL
	1.4249E-05	1.3765E-05		5.2929E-03	2.065	**0.9391**

5.3.2. Low and Intermediate Enriched Uranium

As the data are judged to be from a normal distribution the bias and bias uncertainty is represented with a Lower Tolerance Limit (LTL). The USL calculation for MCNP 6.1 (0.9422) is developed in Table 7. Note that the positive bias of 0.0020 is set to zero.

Table 7 - Low and Intermediate Enriched USL

File Name	k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
IEU-COMP-THERM-001-01	1.00207	0.00406	60744.4844	6.0870E+04	0.0003
IEU-COMP-THERM-001-02	1.00466	0.00406	60744.4844	6.1028E+04	0.4293
IEU-COMP-THERM-001-03	0.99872	0.00406	60744.4844	6.0667E+04	0.6541
IEU-COMP-THERM-001-04	1.00003	0.00407	60485.4563	6.0487E+04	0.2351
IEU-COMP-THERM-001-05	1.00528	0.00405	61079.5194	6.1402E+04	0.6565
IEU-COMP-THERM-001-06	1.00341	0.00406	60693.9749	6.0901E+04	0.1204
IEU-COMP-THERM-001-07	1.00152	0.00407	60485.4563	6.0577E+04	0.0140
IEU-COMP-THERM-001-08	0.99984	0.00406	60794.3388	6.0785E+04	0.2840
IEU-COMP-THERM-001-09	1.00841	0.00406	60693.9749	6.1204E+04	2.4926
IEU-COMP-THERM-001-10	1.00144	0.00406	60591.0047	6.0678E+04	0.0191
IEU-COMP-THERM-001-11	1.00061	0.00406	60744.4844	6.0782E+04	0.1176
IEU-COMP-THERM-001-12	1.00109	0.00405	61033.6662	6.1100E+04	0.0507
IEU-COMP-THERM-001-13	0.99990	0.00406	60744.4844	6.0738E+04	0.2683
IEU-COMP-THERM-001-14	0.99976	0.00406	60693.9749	6.0679E+04	0.3050
IEU-COMP-THERM-001-15	1.00229	0.00406	60744.4844	6.0884E+04	0.0051
IEU-COMP-THERM-001-16	1.00334	0.00406	60794.3388	6.0997E+04	0.1089
IEU-COMP-THERM-001-17	1.00417	0.00407	60322.3627	6.0574E+04	0.2837
IEU-COMP-THERM-001-18	1.00526	0.00407	60322.3627	6.0640E+04	0.6405

File Name	k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
IEU-COMP-THERM-001-19	1.00510	0.00406	60538.5509	6.0847E+04	0.5812
IEU-COMP-THERM-001-20	1.00879	0.00406	60794.3388	6.1329E+04	2.8016
IEU-COMP-THERM-001-21	1.00313	0.00405	60843.5348	6.1034E+04	0.0775
IEU-COMP-THERM-001-26	1.00772	0.00405	60939.9376	6.1410E+04	1.9928
IEU-COMP-THERM-001-27	1.00213	0.00406	60744.4844	6.0874E+04	0.0010
IEU-COMP-THERM-001-28	1.01109	0.00405	60843.5348	6.1518E+04	5.0257
IEU-COMP-THERM-001-29	1.00773	0.00406	60744.4844	6.1214E+04	1.9934
IEU-COMP-THERM-002-01	0.99866	0.00393	64882.4006	6.4796E+04	0.7236
IEU-COMP-THERM-003-01	1.00371	0.00561	31808.2345	3.1926E+04	0.0926
IEU-COMP-THERM-003-02	1.00403	0.00561	31802.4685	3.1931E+04	0.1310
IEU-COMP-THERM-15-04	0.99721	0.00320	97519.1137	9.7248E+04	2.2342
IEU-COMP-THERM-15-05	0.99644	0.00310	103927.4171	1.0356E+05	3.2104
IEU-COMP-THERM-15-07	0.99597	0.00360	77060.0066	7.6750E+04	2.8012
IEU-COMP-THERM-15-08	0.99899	0.00440	51607.8423	5.1556E+04	0.4684
IEU-COMP-THERM-15-09	0.99848	0.00470	45234.7457	4.5166E+04	0.5614
IEU-COMP-THERM-15-10	0.99817	0.00450	49334.9647	4.9245E+04	0.7246
IEU-COMP-THERM-15-11	1.00201	0.00500	39968.6646	4.0049E+04	0.0000
IEU-COMP-THERM-15-12	1.00253	0.00510	38417.8013	3.8515E+04	0.0109
IEU-MET-FAST-003-01	1.00305	0.00192	271525.1568	2.7235E+05	0.2985
IEU-MET-FAST-004-01	1.00762	0.00321	96965.9359	9.7705E+04	3.0610
IEU-MET-FAST-005-01	1.00163	0.00232	186466.2776	1.8677E+05	0.0257
IEU-MET-FAST-006-01	0.99647	0.00252	158017.8244	1.5746E+05	4.8350
IEU-MET-FAST-009-01	1.01098	0.00531	35507.7069	3.5898E+04	2.8624
IEU-SOL-THERM-002-01	1.00911	0.00260	147501.3275	1.4884E+05	7.4457
IEU-SOL-THERM-002-02	0.99971	0.00320	97495.3446	9.7467E+04	0.5119
IEU-SOL-THERM-002-03	1.00018	0.00380	69204.1522	6.9217E+04	0.2296
IEU-SOL-THERM-002-04	1.00165	0.00460	47240.8955	4.7319E+04	0.0059
IEU-SOL-THERM-002-05	1.00562	0.00420	56607.1914	5.6925E+04	0.7396
IEU-SOL-THERM-002-07	1.00136	0.00320	97469.6869	9.7602E+04	0.0400
IEU-SOL-THERM-002-08	1.00434	0.00420	56657.2238	5.6903E+04	0.3103
IEU-SOL-THERM-002-09	1.00840	0.00540	34286.0278	3.4574E+04	1.4033
IEU-SOL-THERM-002-10	1.00186	0.00380	69194.0964	6.9323E+04	0.0014
IEU-SOL-THERM-002-11	1.00456	0.00480	43387.5244	4.3585E+04	0.2836
IEU-SOL-THERM-002-12	1.00393	0.00420	56650.4835	5.6873E+04	0.2103
IEU-SOL-THERM-002-13	1.00675	0.00420	56626.4242	5.7009E+04	1.2772
IEU-SOL-THERM-004-01	1.00030	0.00410	59408.8816	5.9427E+04	0.1725
LEU-COMP-THERM-022-01	1.00318	0.00461	47058.8235	4.7208E+04	0.0654

File Name		k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
LEU-COMP-THERM-022-02		1.00647	0.00461	47058.8235	4.7363E+04	0.9396
LEU-COMP-THERM-022-03		1.00688	0.00361	76663.0124	7.7190E+04	1.8245
LEU-COMP-THERM-022-04		1.00808	0.00371	72536.8306	7.3123E+04	2.6801
LEU-COMP-THERM-022-05		1.00308	0.00381	68851.0820	6.9063E+04	0.0801
LEU-COMP-THERM-022-06		1.00154	0.00461	47130.6840	4.7203E+04	0.0100
LEU-COMP-THERM-022-07		1.00455	0.00461	47108.4814	4.7323E+04	0.3060
LEU-COMP-THERM-023-01		0.99522	0.00441	51444.5633	5.1199E+04	2.3659
LEU-COMP-THERM-023-02		0.99798	0.00441	51429.4825	5.1326E+04	0.8317
LEU-COMP-THERM-023-03		0.99952	0.00441	51444.5633	5.1420E+04	0.3168
LEU-COMP-THERM-023-04		1.00116	0.00441	51444.5633	5.1504E+04	0.0364
LEU-COMP-THERM-023-05		1.00235	0.00441	51429.4825	5.1550E+04	0.0062
LEU-COMP-THERM-023-06		1.00244	0.00441	51486.6778	5.1612E+04	0.0099
LEU-COMP-THERM-024-01		1.00068	0.00541	34194.9316	3.4218E+04	0.0597
LEU-COMP-THERM-024-02		1.00805	0.00401	62195.2433	6.2696E+04	2.2754
LEU-COMP-THERM-032-01		1.00163	0.00451	49149.4684	4.9230E+04	0.0068
LEU-COMP-THERM-032-04		1.00288	0.00371	72659.1053	7.2868E+04	0.0561
LEU-COMP-THERM-032-07		1.00448	0.00451	49242.6481	4.9463E+04	0.3025
LEU-SOL-THERM-06-01		0.99783	0.00371	72536.8306	7.2379E+04	1.2623
LEU-SOL-THERM-06-02		1.00341	0.00381	68823.1246	6.9058E+04	0.1365
LEU-SOL-THERM-06-03		0.99780	0.00411	59150.2475	5.9020E+04	1.0442
LEU-SOL-THERM-06-04		0.99920	0.00411	59192.2624	5.9145E+04	0.4646
LEU-SOL-THERM-06-05		1.00078	0.00471	45097.6590	4.5133E+04	0.0673
LEU-SOL-THERM-08-72		1.00221	0.00142	498977.0970	5.0008E+05	0.0217
LEU-SOL-THERM-08-74		1.00092	0.00151	436681.2227	4.3708E+05	0.5110
LEU-SOL-THERM-08-76		1.00149	0.00142	498977.0970	4.9972E+05	0.1305
LEU-SOL-THERM-08-78		1.00221	0.00142	498977.0970	5.0008E+05	0.0217
LEU-SOL-THERM-09-92		1.00004	0.00142	497908.7831	4.9793E+05	1.9157
LEU-SOL-THERM-09-93		1.00093	0.00142	498977.0970	4.9944E+05	0.5728
LEU-SOL-THERM-09-94		1.00139	0.00142	498977.0970	4.9967E+05	0.1865
	k_{mean}	1.0020		$\Sigma\ 1/(\sigma_\iota)^2$	$\Sigma\ 1/(\sigma_\iota)^2 * k_{eff}$	
		1.0000		8.5065E+06	8.5235E+06	
	$(\sigma_{mean})^2$	S^2		S_t	K*	USL
	9.8748E-06	6.1730E-06		4.0060E-03	1.952	**0.9422**

5.3.3. Combined LEU, IEU and HEU Enrichments

As the data are judged to be from a normal distribution the bias and bias uncertainty is represented with a Lower Tolerance Limit (LTL). The USL calculation for MCNP 6.1 (0.9409) is developed in Table 8. Note that the positive bias of 0.0011 is set to zero.

Table 8 - Combined USL

File Name	k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
HEU-COMP-FAST-02	1.0016	0.0007	2102607.2330	2.1060E+06	0.4936
HEU-COMP-INTER-03-02	1.0051	0.0061	26817.9917	2.6955E+04	0.4274
HEU-COMP-INTER-03-03	1.0048	0.0056	31802.4685	3.1954E+04	0.4265
HEU-COMP-INTER-03-04	1.0028	0.0055	32972.3955	3.3065E+04	0.0933
HEU-COMP-INTER-03-05	0.9979	0.0047	45085.6628	4.4991E+04	0.4698
HEU-MET-FAST-001	0.9996	0.0010	949757.8118	9.4939E+05	2.1595
HEU-MET-INTER-006-01	0.9956	0.0009	1358511.0719	1.3526E+06	40.6166
HEU-MET-INTER-006-02	0.9964	0.0009	1346982.7586	1.3422E+06	29.5972
HEU-MET-INTER-006-03	0.9985	0.0010	1072386.0590	1.0707E+06	7.6196
HEU-SOL-THERM-007-01	1.0110	0.0035	79935.4122	8.0811E+04	7.7274
HEU-SOL-THERM-007-03	1.0060	0.0035	79935.4122	8.0418E+04	1.9366
HEU-SOL-THERM-007-07	1.0031	0.0035	79935.4122	8.0182E+04	0.3109
HEU-SOL-THERM-007-11	1.0072	0.0035	79595.0205	8.0165E+04	2.9058
HEU-SOL-THERM-007-14	1.0069	0.0035	79595.0205	8.0147E+04	2.6888
HEU-SOL-THERM-012-01	1.0010	0.0058	29606.0325	2.9635E+04	0.0006
HEU-SOL-THERM-27-01	0.9968	0.0046	46849.5987	4.6701E+04	0.8654
HEU-SOL-THERM-27-02	0.9967	0.0043	53572.1939	5.3397E+04	1.0315
HEU-SOL-THERM-27-03	0.9975	0.0037	72116.7715	7.1938E+04	0.9335
HEU-SOL-THERM-27-04	0.9983	0.0037	72202.1661	7.2079E+04	0.5774
HEU-SOL-THERM-27-05	0.9962	0.0044	51208.2589	5.1014E+04	1.2335
HEU-SOL-THERM-31-01	0.9970	0.0046	46938.6606	4.6796E+04	0.8115
HEU-SOL-THERM-31-02	1.0080	0.0058	29592.7155	2.9829E+04	1.3935
HEU-SOL-THERM-31-03	0.9970	0.0058	29592.7155	2.9503E+04	0.5116
HEU-SOL-THERM-31-04	1.0015	0.0068	21551.7241	2.1585E+04	0.0037
HEU-SOL-THERM-35-01	1.0005	0.0031	102596.7231	1.0265E+05	0.0343
HEU-SOL-THERM-35-02	1.0034	0.0032	96435.7352	9.6761E+04	0.4891
HEU-SOL-THERM-35-03	1.0043	0.0030	109619.0737	1.1008E+05	1.0754
HEU-SOL-THERM-35-04	1.0037	0.0030	109533.8240	1.0994E+05	0.7360
HEU-SOL-THERM-35-05	1.0023	0.0033	90223.3931	9.0428E+04	0.1198
HEU-SOL-THERM-35-06	1.0037	0.0029	116230.4152	1.1666E+05	0.7570
HEU-SOL-THERM-35-07	1.0051	0.0035	80186.6746	8.0594E+04	1.2588
HEU-SOL-THERM-35-08	0.9987	0.0038	68208.6366	6.8121E+04	0.3955

File Name	k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
HEU-SOL-THERM-35-09	0.9997	0.0041	58716.8030	5.8702E+04	0.1115
HEU-SOL-THERM-38-01	0.9955	0.0025	159081.1473	1.5837E+05	5.0029
HEU-SOL-THERM-38-02	0.9970	0.0025	159081.1473	1.5860E+05	2.7238
HEU-SOL-THERM-38-07	0.9979	0.0032	97276.2646	9.7070E+04	1.0198
HEU-SOL-THERM-38-08	0.9986	0.0026	147058.8235	1.4685E+05	0.9697
HEU-SOL-THERM-38-09	0.9985	0.0033	91491.3083	9.1358E+04	0.6080
HEU-SOL-THERM-38-10	0.9970	0.0026	147058.8235	1.4662E+05	2.4455
HEU-SOL-THERM-38-11	0.9966	0.0025	158982.5119	1.5844E+05	3.2738
HEU-SOL-THERM-38-12	0.9963	0.0025	158982.5119	1.5840E+05	3.6597
HEU-SOL-THERM-38-17	0.9969	0.0026	147058.8235	1.4661E+05	2.5669
HEU-SOL-THERM-38-18	0.9974	0.0032	97276.2646	9.7025E+04	1.3302
HEU-SOL-THERM-46-01	1.0128	0.0029	117807.8319	1.1931E+05	16.0113
HEU-SOL-THERM-46-02	1.0094	0.0029	117884.2141	1.1899E+05	8.0270
HEU-SOL-THERM-46-03	1.0099	0.0029	117728.7764	1.1889E+05	9.0574
HEU-SOL-THERM-46-04	1.0108	0.0029	117807.8319	1.1908E+05	11.0166
HEU-SOL-THERM-46-05	1.0087	0.0030	110082.4518	1.1104E+05	6.2627
HEU-SOL-THERM-46-06	1.0100	0.0029	117647.0588	1.1883E+05	9.3420
HEU-SOL-THERM-46-07	1.0109	0.0031	103216.2173	1.0434E+05	9.8123
HEU-SOL-THERM-46-08	1.0102	0.0032	96748.2900	9.7737E+04	8.0133
HEU-SOL-THERM-46-09	1.0096	0.0037	72568.9405	7.3265E+04	5.2081
HEU-SOL-THERM-46-10	1.0075	0.0029	117562.6903	1.1844E+05	4.7911
HEU-SOL-THERM-46-11	1.0103	0.0028	125906.5270	1.2720E+05	10.5431
HEU-SOL-THERM-46-12	1.0094	0.0029	117562.6903	1.1867E+05	8.0439
HEU-SOL-THERM-46-13	1.0089	0.0030	109861.1355	1.1083E+05	6.5855
IEU-COMP-THERM-001-01	1.0021	0.0041	60744.4844	6.0870E+04	0.0551
IEU-COMP-THERM-001-02	1.0047	0.0041	60744.4844	6.1028E+04	0.7621
IEU-COMP-THERM-001-03	0.9987	0.0041	60744.4844	6.0667E+04	0.3493
IEU-COMP-THERM-001-04	1.0000	0.0041	60485.4563	6.0487E+04	0.0716
IEU-COMP-THERM-001-05	1.0053	0.0040	61079.5194	6.1402E+04	1.0581
IEU-COMP-THERM-001-06	1.0034	0.0041	60693.9749	6.0901E+04	0.3189
IEU-COMP-THERM-001-07	1.0015	0.0041	60485.4563	6.0577E+04	0.0098
IEU-COMP-THERM-001-08	0.9998	0.0041	60794.3388	6.0785E+04	0.0993
IEU-COMP-THERM-001-09	1.0084	0.0041	60693.9749	6.1204E+04	3.2274
IEU-COMP-THERM-001-10	1.0014	0.0041	60591.0047	6.0678E+04	0.0063
IEU-COMP-THERM-001-11	1.0006	0.0041	60744.4844	6.0782E+04	0.0157
IEU-COMP-THERM-001-12	1.0011	0.0040	61033.6662	6.1100E+04	0.0000
IEU-COMP-THERM-001-13	0.9999	0.0041	60744.4844	6.0738E+04	0.0901

File Name	k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
IEU-COMP-THERM-001-14	0.9998	0.0041	60693.9749	6.0679E+04	0.1119
IEU-COMP-THERM-001-15	1.0023	0.0041	60744.4844	6.0884E+04	0.0835
IEU-COMP-THERM-001-16	1.0033	0.0041	60794.3388	6.0997E+04	0.3002
IEU-COMP-THERM-001-17	1.0042	0.0041	60322.3627	6.0574E+04	0.5619
IEU-COMP-THERM-001-18	1.0053	0.0041	60322.3627	6.0640E+04	1.0350
IEU-COMP-THERM-001-19	1.0051	0.0041	60538.5509	6.0847E+04	0.9600
IEU-COMP-THERM-001-20	1.0088	0.0041	60794.3388	6.1329E+04	3.5784
IEU-COMP-THERM-001-21	1.0031	0.0041	60843.5348	6.1034E+04	0.2463
IEU-COMP-THERM-001-26	1.0077	0.0041	60939.9376	6.1410E+04	2.6562
IEU-COMP-THERM-001-27	1.0021	0.0041	60744.4844	6.0874E+04	0.0622
IEU-COMP-THERM-001-28	1.0111	0.0041	60843.5348	6.1518E+04	6.0505
IEU-COMP-THERM-001-29	1.0077	0.0041	60744.4844	6.1214E+04	2.6557
IEU-COMP-THERM-002-01	0.9987	0.0039	64882.4006	6.4796E+04	0.3914
IEU-COMP-THERM-003-01	1.0037	0.0056	31808.2345	3.1926E+04	0.2134
IEU-COMP-THERM-003-02	1.0040	0.0056	31802.4685	3.1931E+04	0.2700
IEU-COMP-THERM-15-04	0.9972	0.0032	97519.1137	9.7248E+04	1.4855
IEU-COMP-THERM-15-05	0.9964	0.0031	103927.4171	1.0356E+05	2.2707
IEU-COMP-THERM-15-07	0.9960	0.0036	77060.0066	7.6750E+04	2.0403
IEU-COMP-THERM-15-08	0.9990	0.0044	51607.8423	5.1556E+04	0.2339
IEU-COMP-THERM-15-09	0.9985	0.0047	45234.7457	4.5166E+04	0.3151
IEU-COMP-THERM-15-10	0.9982	0.0045	49334.9647	4.9245E+04	0.4290
IEU-COMP-THERM-15-11	1.0020	0.0050	39968.6646	4.0049E+04	0.0320
IEU-COMP-THERM-15-12	1.0025	0.0051	38417.8013	3.8515E+04	0.0770
IEU-MET-FAST-003-01	1.0031	0.0019	271525.1568	2.7235E+05	1.0136
IEU-MET-FAST-004-01	1.0076	0.0032	96965.9359	9.7705E+04	4.0995
IEU-MET-FAST-005-01	1.0016	0.0023	186466.2776	1.8677E+05	0.0489
IEU-MET-FAST-006-01	0.9965	0.0025	158017.8244	1.5746E+05	3.4136
IEU-MET-FAST-009-01	1.0110	0.0053	35507.7069	3.5898E+04	3.4535
IEU-SOL-THERM-002-01	1.0091	0.0026	147501.3275	1.4884E+05	9.4129
IEU-SOL-THERM-002-02	0.9997	0.0032	97495.3446	9.7467E+04	0.1932
IEU-SOL-THERM-002-03	1.0002	0.0038	69204.1522	6.9217E+04	0.0609
IEU-SOL-THERM-002-04	1.0016	0.0046	47240.8955	4.7319E+04	0.0134
IEU-SOL-THERM-002-05	1.0056	0.0042	56607.1914	5.6925E+04	1.1454
IEU-SOL-THERM-002-07	1.0014	0.0032	97469.6869	9.7602E+04	0.0058
IEU-SOL-THERM-002-08	1.0043	0.0042	56657.2238	5.6903E+04	0.5888
IEU-SOL-THERM-002-09	1.0084	0.0054	34286.0278	3.4574E+04	1.8177
IEU-SOL-THERM-002-10	1.0019	0.0038	69194.0964	6.9323E+04	0.0380

File Name		k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
IEU-SOL-THERM-002-11		1.0046	0.0048	43387.5244	4.3585E+04	0.5135
IEU-SOL-THERM-002-12		1.0039	0.0042	56650.4835	5.6873E+04	0.4475
IEU-SOL-THERM-002-13		1.0068	0.0042	56626.4242	5.7009E+04	1.7967
IEU-SOL-THERM-004-01		1.0003	0.0041	59408.8816	5.9427E+04	0.0400
LEU-COMP-THERM-022-01		1.0032	0.0046	47058.8235	4.7208E+04	0.2001
LEU-COMP-THERM-022-02		1.0065	0.0046	47058.8235	4.7363E+04	1.3480
LEU-COMP-THERM-022-03		1.0069	0.0036	76663.0124	7.7190E+04	2.5454
LEU-COMP-THERM-022-04		1.0081	0.0037	72536.8306	7.3123E+04	3.5159
LEU-COMP-THERM-022-05		1.0031	0.0038	68851.0820	6.9063E+04	0.2651
LEU-COMP-THERM-022-06		1.0015	0.0046	47130.6840	4.7203E+04	0.0084
LEU-COMP-THERM-022-07		1.0046	0.0046	47108.4814	4.7323E+04	0.5549
LEU-COMP-THERM-023-01		0.9952	0.0044	51444.5633	5.1199E+04	1.7895
LEU-COMP-THERM-023-02		0.9980	0.0044	51429.4825	5.1326E+04	0.5064
LEU-COMP-THERM-023-03		0.9995	0.0044	51444.5633	5.1420E+04	0.1314
LEU-COMP-THERM-023-04		1.0012	0.0044	51444.5633	5.1504E+04	0.0001
LEU-COMP-THERM-023-05		1.0024	0.0044	51429.4825	5.1550E+04	0.0781
LEU-COMP-THERM-023-06		1.0024	0.0044	51486.6778	5.1612E+04	0.0900
LEU-COMP-THERM-024-01		1.0007	0.0054	34194.9316	3.4218E+04	0.0066
LEU-COMP-THERM-024-02		1.0081	0.0040	62195.2433	6.2696E+04	2.9887
LEU-COMP-THERM-032-01		1.0016	0.0045	49149.4684	4.9230E+04	0.0129
LEU-COMP-THERM-032-04		1.0029	0.0037	72659.1053	7.2868E+04	0.2256
LEU-COMP-THERM-032-07		1.0045	0.0045	49242.6481	4.9463E+04	0.5566
LEU-SOL-THERM-06-01		0.9978	0.0037	72536.8306	7.2379E+04	0.7841
LEU-SOL-THERM-06-02		1.0034	0.0038	68823.1246	6.9058E+04	0.3616
LEU-SOL-THERM-06-03		0.9978	0.0041	59150.2475	5.9020E+04	0.6511
LEU-SOL-THERM-06-04		0.9992	0.0041	59192.2624	5.9145E+04	0.2177
LEU-SOL-THERM-06-05		1.0008	0.0047	45097.6590	4.5133E+04	0.0051
LEU-SOL-THERM-08-72		1.0022	0.0014	498977.0970	5.0008E+05	0.5954
LEU-SOL-THERM-08-74		1.0009	0.0015	436681.2227	4.3708E+05	0.0171
LEU-SOL-THERM-08-76		1.0015	0.0014	498977.0970	4.9972E+05	0.0691
LEU-SOL-THERM-08-78		1.0022	0.0014	498977.0970	5.0008E+05	0.5954
LEU-SOL-THERM-09-92		1.0000	0.0014	497908.7831	4.9793E+05	0.5785
LEU-SOL-THERM-09-93		1.0009	0.0014	498977.0970	4.9944E+05	0.0176
LEU-SOL-THERM-09-94		1.0014	0.0014	498977.0970	4.9967E+05	0.0370
	k_{mean}	1.0011		$\Sigma\ 1/(\sigma_\iota)^2$	$\Sigma\ 1/(\sigma_\iota)^2 * k_{eff}$	
		1.0000		1.9963E+07	1.9985E+07	

File Name		k_{eff}	σ_ι	$1/(\sigma_\iota)^2$	Weighted k_{eff}	Weighted Variance
	$(\sigma_{mean})^2$	S^2		S_t	K*	USL
	7.0129E-06	1.6403E-05		4.8390E-03	1.8765	**0.9409**

6. Area of Applicability

With the use of the minimum USL for the IEU data set and with the observation that no trends exist in the combined LEU, IEU and HEU data set, it is judged that this validation may be conservatively used with the AoA of the combined data set. An exception is made in that the uranium enrichment is constrained to the values bracketed by the LEU-IEU data set.

This validation is appropriate for homogeneous and heterogeneous intermediate enriched uranium systems. A summary of the area of applicability for these experiments is provided in Table 9. For systems outside the validation area of applicability, an increased MoS value may be warranted, depending on the specific problem being analyzed. The analyst must document any extrapolation beyond the validation area of applicability and justification must be made for any adjustments to the MoS when extrapolating.

Table 9 - Area of Applicability Summary

Parameter	Area of Applicability
Fissile Material*	UO_2, UH_3, Metal, $UO_2(NO_3)_2$, UF_4, U-ZrH, UO_2F2, U_xO_y, UO_2SO_4
Fissile Material Form	Solid and Solution
H/^{235}U ratio*	$0 \leq H/^{235}U \leq 1400$
Average Neutron Energy Causing Fission (MeV)	0.0027 < ANECF < 1.46
Enrichment*	10 to 36 wt.% ^{235}U
Moderating Materials*	None, Water, nitric acid, sulfuric acid, Hydrocarbon, CF_2
Reflecting Materials	None, Water, Concrete, BeO, Hydrocarbon Material, Iron, Graphite
Absorber Materials*	Boron, Cadmium, Aluminium, Steel, Stainless Steel, Hydrocarbon Material
Geometry	Homogeneous and Heterogeneous Spheres, Hemispheres, Cylinders, Cuboids Single Units and Arrays

***See following text.**

6.1. AoA Sensitivity - $H/^{235}U$ Ratio

The $H/^{235}U$ ratio of the experiments has values ranging from 0 to 1611 and Figure 2 of Section 5.1.2 demonstrates that ratios up to an $H/^{235}U$ ratio of 1200 are well covered. However, above 1272 there is only one value. However, as described in Reference 5, a ± 20% interpolation is considered acceptable for the ratio of moderator to fissile material in an AoA. Adding 20% to the 1200 value yields 1440. Therefore, given that Section 5.1.2 demonstrates that there is no trend between $H/^{235}U$ values and bias, it is judged herein that this validation can be conservatively used for the $H/^{235}U$ value range listed in Table 9.

6.2. AoA Sensitivity - ^{235}U Enrichment

The enrichment range for the data set experiments ranges from 10 to 94 wt.% ^{235}U, while the enrichment of greatest interest in SHINE criticality applications is approximately 20 wt.% ^{235}U. Figure 4 of Section 5.1.4 shows the distribution of the bias as a function of enrichment and indicates that there is no trend and that values around 20% enrichment are well covered. Therefore, this validation is conservatively adjusted to use only the enrichment range listed in Table 9.

6.3. AoA Sensitivity - U:O Ratio

While the chemical form U_3O_8 is not utilized in any of the experiments herein, UO_2 and other chemical forms containing a variety of U:O ratios are included. Additionally, Section 5.1.7 found no bias variability with chemical form. Therefore, this validation can be conservatively used for applications utilizing U_3O_8 or any other U:O ratio material.

6.4. AoA Sensitivity – Sulfate Solution

SHINE applications contain uranium in the chemical form of UO_2SO_4 and sulfate solution moderator (H_2SO_4-H_2O). However, these are contained in only one IEU experiment, IEU-SOL-TERM-004.

Additional sulfate solution experiments are included with the HEU-SOL-THERM-046 data set. Since no trends in the parameters of interest were observed (see Section 5.1) it is judged that this validation (with the IEU USL) can be conservatively used with IEU and sulfate solutions.

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6.5. AoA Sensitivity – Boron

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Table 10 - Boron Sensitivity

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7. References

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Appendix A. Combined Data Normalcy Test Calculations

Tables A1 through Table A3 present the calculations for the IEU data set normality tests for MCNP data from Section 5.2.1. Tables A4 through Table A6 present the calculations for the LEU-IEU data set normality tests for MCNP data from Section 5.2.2. Tables A7 through Table A9 present the calculations for the combined data set normality tests for MCNP data from Section 5.2.3.

Table A1 – IEU Data Set Modified Chi Square Normality Test

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Table A2 – IEU Data Set [Proprietary Information]

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Table A3 – IEU Data Set [Proprietary Information]

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Table A4 – LEU-IEU Data Set Modified Chi Square Normality Test

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Table A5 – LEU-IEU Data Set [Proprietary Information]

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Table A6 – LEU – IEU Data Set [Proprietary Information]

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Table A7 – Combined Data Set Modified Chi Square Normality Test

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Table A8 – Combined Data Set [Proprietary Information]

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Table A9 – Combined Data Set [Proprietary Information]

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Appendix B. Electronic Copy of Input / Output Files

A CD with all Input and output files is included with the original copy