
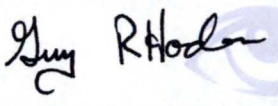
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a) Design Verification by Independent Checking Method	<input checked="" type="checkbox"/>	<input type="checkbox"/>
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c) Calculation Package complete and per CG-EN-PR-203	<input checked="" type="checkbox"/>	<input type="checkbox"/>
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1. INTRODUCTION

1.1. Purpose and Objectives

The following calculation consists of two parts. The first involves the determination of the MCNP Version 6.2 (MCNP6) computer code bias and bias uncertainty. The second part examines the area of applicability (AOA) of the benchmark cases used to determine the bias.

This determination was performed in accordance with ANSI/ANS-8.24-2017, *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations* (Ref. [1]). The methodology used in this determination is taken from NUREG/CR-4604, *Statistical Methods for Nuclear Material Management*, (Ref. [2]) and NUREG/CR-6698, *Guide for Validation of Nuclear Criticality Safety Methodology*, (Ref. [3]) which are both listed in Appendix C of ANSI/ANS-8.24.

1.2. Scope

The MCNP6 computer code is validated as appropriate for use in estimating k_{eff} values. The use of a bias determined in this report requires the reduction of the bias by a Margin of Safety (MOS). The MOS is determined on a case-by-case basis within the applicable evaluation. Typical values of the MOS range from 0.02 to 0.05. Additional margin may be needed for extension of AOA and, like the MOS, is determined in the applicable evaluation. The bias minus the MOS and any additional margin is the Upper Subcritical Limit (USL) for the evaluation.

The bias determinations were performed based on the use of the ENDF/B-VIII.0 based continuous energy data libraries as prepared by the Los Alamos National Laboratory (LANL). The bias determination was performed for low enrichment uranium (LEU) benchmark models based on the range of process parameters (e.g., enrichment, fissile form) used in this report.

1.3. Hardware and Software Description

The software used herein is Version 6.2 of the MCNP code system. MCNP6 was developed at LANL and acquired from the Radiation Safety Information Computational Center (RSICC). The cross-section library used in this calculation report is the ENDF/B-VIII.0 based library that is processed and distributed by LANL [including thermal scattering $S(\alpha, \beta)$ libraries]. The specific material libraries used are listed in Section 6.2.

The MCNP6 code system is installed on the NSTS computational platforms NSTS-LS01 and NSTS-LS2. The installation and verification of MCNP6 performance on each NSTS computer is documented in accordance with the Software Qualification and Validation Plan, ESCD-000038, *MCNP6.2 (NSTS) Software Qualification and Validation Plan* (Ref. [4]).

NSTS-LS01 consists of an AMD® Ryzen Threadripper 3970x 32-core processor configured with 32 GB RAM, and the CentOS 8 Linux 64-bit operating system with GNOME desktop environment. NSTS-LS01 is configured for Remote Desktop Access via a secured, encrypted internet connection with enabled firewall.

NSTS-LS2 consists of an AMD® Ryzen Threadripper 3990x 64-core processor configured with 64 GB RAM, and the Fedora 32 Linux 64-bit operating system with the XFCE window manager. NSTS-LS2 is configured to allow authorized access via X2GO software which uses an encrypted secure shell to connect to X2GO client software with the X2GO server on NSTS-LS2.

2. REQUIREMENTS

2.1. Design Inputs

The following present a brief description for each benchmark used. These descriptions are meant only to give the simplest of indication as to the critical configurations represented by the benchmarks. Complete descriptions of the benchmarks can be found in NEA/NSC/DOC(95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, (Ref. [5]) and should be referred to regarding any detail of the benchmark models discussed herein. A total of 125 benchmark cases are chosen.

2.1.1. LEU-COMP-THERM-002

This benchmark included five configurations that consisted of various arrangements of UO₂ fuel rods. The arrangements are water moderated and reflected.

2.1.2. LEU-COMP-THERM-009

This benchmark included twenty-seven configurations that consisted of various arrangements of UO₂ fuel rods. The fuel rods are arranged in three clusters that are arranged in a single row. Between the clusters are placed plates made of steel, Boral, copper, cadmium, aluminum, or Zircalloy-4. The fuel rods are water moderated and reflected.

2.1.3. LEU-COMP-THERM-013

This benchmark included seven configurations that consisted of three water moderated rectangular cluster of UO₂ fuel rods. The three clusters were separated by plates made of steel, Boral B, Boroflex, cadmium, copper, or copper-cadmium. Two sides of the arrangement of three clusters were reflected by steel walls.

2.1.4. LEU-COMP-THERM-033

This benchmark included fifty-two configurations that consisted rectangular parallelepipeds created from cube blocks of finely divided UF₄ dispersed in paraffin. The configurations were either unreflected or reflected by paraffin or polyethylene.

2.1.5. LEU-COMP-THERM-042

This benchmark included seven configurations that consisted of three water moderated rectangular cluster of UO₂ fuel rods. The three clusters were separated by plates made of steel, Boral B, Boroflex, cadmium, copper, or copper-cadmium. Two sides of the arrangement of three clusters were reflected by steel walls.

2.1.6. LEU-COMP-THERM-049

This benchmark included eighteen configurations that consisted of a stacked array of small boxes filled with UO₂. These were moderated and reflected by polyethylene.

2.1.7. LEU-COMP-THERM-092

This benchmark included six configurations that consisted of an array of stainless-steel-clad cylindrical UO₂ fuel rods. The fuel rods are water moderated and reflected. Control rods consist of Ag-In-Cd. Varying concentrations of soluble boron are in the moderator water.

2.1.8. LEU-SOL-THERM-001

This benchmark included a single configuration that consisted of a cylindrical tank filled with UO₂F₂ solution. The tank was not reflected.

2.1.9. LEU-SOL-THERM-002

This benchmark included three configurations that consisted of spherical geometries of UO₂F₂ solutions with no reflection.

3. REFERENCES

- [1] ANSI/ANS-8.24-2017, *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations*, American Nuclear Society, 2017.
- [2] NUREG/CR-4604, *Statistical Methods for Nuclear Material Management*, Pacific Northwest Laboratory, 1988.
- [3] NUREG/CR-6698, *Guide for Validation of Nuclear Criticality Safety Methodology*, Science Applications International Corporation, 2001.
- [4] ESCD-000038, Rev. 0, *MCNP6.2 (NSTS) Software Qualification and Validation Plan*, Energy Solutions, 2020.
- [5] NEA/NSC/DOC(95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, National Energy Agency, 2019.
- [6] "NIST/SEMATECH e-Handbook of Statistical Methods," October 2013. [Online]. Available: <http://www.itl.nist.gov/div898/handbook/>.

4. ASSUMPTIONS

None.

5. CALCULATION METHODOLOGY

The following sections present the methods for determination of the bias for MCNP6 based on a selection of experimental benchmarks. The benchmarks represent a selection of uranium based critical experiments that were chosen as being representative of the configurations modeled as part of this report. The description of each experiment may be found in NEA/NSC/DOC(95)03 (Ref. [5]).

For each set of benchmark cases the MCNP6 run parameters were 10,000 neutrons/cycle, 100 skipped cycles, and 5,000 active cycles to minimize the code bias in k_{eff} . All results showed convergence of fission-source entropy (within 1 standard deviation of the average) in less than 40 cycles. Each set of cases were run on the NSTS-LS01 and NSTS-LS2 computers and produced identical results.

5.1. Benchmark Data Preparation

The benchmark data consists of results from MCNP6 calculations and experimental data. Not all the benchmarks resulted in an experimental k_{eff} of exactly 1.0. The benchmarks also have experimental uncertainties that need to be accounted for along with MCNP6 calculation uncertainty. As a result, some preparation of the data must be performed before conducting any statistical analyses.

The first thing that needs to be done is to normalize the k_{eff} values to 1.0 and to combine the MCNP6 and experimental uncertainties. Normalization of the k_{eff} values is needed in those cases where the benchmark experiments have a k_{eff} other than 1.0. This is done using the following formula:

$$k_{adj} = \frac{k_{calc}}{k_{exp}}$$

Where,

k_{adj} = Adjusted calculated k_{eff} value normalized to 1.0

k_{calc} = The MCNP6 calculated k_{eff} value for a benchmark case

k_{exp} = The experimental k_{eff} value for a benchmark case

The combined uncertainty is determined by:

$$\sigma_{com} = \sqrt{\sigma_{calc}^2 + \sigma_{exp}^2}$$

Where,

σ_{com} = Combined uncertainty

σ_{calc} = The MCNP6 uncertainty for the calculated k_{eff} value for a benchmark case

σ_{exp} = The experimental uncertainty for the k_{eff} value for a benchmark case

5.2. Normality Testing Methodology

5.2.1. Lilliefors Test

The k_{adj} values are examined to determine if they are from a normal distribution. The Lilliefors test as presented in Section 9.6.3.1 of NUREG/CR-4604 (Ref. [2]) was selected given that there are more than 50 values. The first step in this test is to rank the k_{adj} values from smallest to largest and then determine the standardized sample values. As applied to the k_{adj} values, the standardized sample values are determined by the following equation:

$$z_i = \frac{k_i - \bar{k}}{s}$$

Where,

z_i = Standardized sample value for the i^{th} k_{eff} benchmark value

k_i = The k_{adj} value of the i^{th} benchmark case

\bar{k} = The mean of the k_{adj} values

s = Sample standard deviation

The values of z_i are used to determine values of the normal cumulative distribution function (cdf) denoted as $F^*(z)$ based on Table A3 in Reference [2]. It is noted that for negative values of z_i , the value of $F^*(z)$ is one minus the value from Table A3 in Reference [2] based on the absolute value of z_i . Also note that these values may be readily attained using the 'NORMSDIST()' function in Excel. Next, empirical cumulative distribution function values (denoted as $G(z)$) are determined for the ordered k_{adj} values. This is simply the ranked value divided by the total number of cases. The Lilliefors test statistic (T^*) is the largest of all values of $|F^*(z_i) - G(z_i)|$ or $|F^*(z_i) - G(z_{i-1})|$. T^* is compared to $w_{1-\alpha}$ obtained from Table A18 of Reference [2]. For a 95% confidence level and a sample size over 30, $w_{1-\alpha}$ is given by $\frac{0.886}{\sqrt{n}}$ where n is the number of cases. If T^* is less than $w_{1-\alpha}$ the data is probably from a normal distribution.

5.2.2. Normal Probability Plot

The basic description and technique for the normal probability plot are taken from the Section 1.3.3.21 of *NIST/SEMATECH e-Handbook of Statistical Methods* (Ref. [6]). The normal probability plot is formed by:

- Vertical axis: Ordered response values
- Horizontal axis: Normal order statistic medians

The response values are the k_{adj} values ordered from smallest to largest.

The normal order statistic medians are defined by the following function:

$$N_i = G(U_i)$$

Where U_i are the uniform order statistic medians and G is the percent point function of the normal distribution. The percent point function is the inverse of the cumulative distribution function. This provided by the Excel spreadsheet function NORM.S.INV(). The uniform order statistic medians are defined as:

$$U_i = 1 - U_n \text{ for } i=1$$

$$U_i = (i - 0.3175)/(n+0.365) \text{ for } i=2,3,4, \dots, n-1$$

$$U_i = 0.5^{(1/n)} \text{ for } i=n$$

A straight line is fitted to the data. The further the data departs from the straight line, the greater the indication of departures from normality.

5.3. Trend Analysis Methodology

The benchmark data is examined for potential trends in the k_{adj} data versus the Average Energy of Neutron Energy Causing Fission (AENCF) and also versus the enrichment (wt. % ^{235}U). This is used to determine the proper bias determination method for data that has been determined to come from a normal distribution.

The k_{adj} versus AENCF or enrichment data will be fitted to a number of simple functions along with a determination of the coefficient of determination (R^2). Should the value of R^2 be 0.8 or greater, this would indicate correlation between the data and the fitted function. Depending on the exact nature of the correlated fitted function, a trend in the data that may impact the USL determination is possible. An R^2 value less than 0.8 would indicate either a poor or no correlation between the data and the fitted function.

5.4. Bias Determination Methodology

The methods for determining the bias are presented in this section. Depending on the result of the normality testing one of three methods will be used to determine the bias. The following presents the methods used herein.

5.4.1. Bias Determination for Non-Normal Distributions

For data that is demonstrated to likely *not* come from a normal distribution, the bias is determined based on the nonparametric statistical treatment presented in NUREG/CR-6698 (Ref. [3]). 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 is determined with the following equation:

$$\beta = 1 - \sum_{j=0}^{m-1} \frac{n!}{j!(n-j)!} (1-q)^j q^{n-j}$$

Where,

q = the desired population fraction (e.g., 0.95)

n = the number of data in one data sample (e.g., number of benchmark cases)

m = the indexed rank from the smallest to the largest.

This equation can be simplified for a desired population fraction of 0.95 and a rank of 1 (smallest data sample) to:

$$\beta = 1 - q^n = 1 - 0.95^n$$

The bias may then be determined by the following:

$$Bias = k_1 - \sigma_1 - NPM$$

Where,

k_1 = Smallest k_{adj} value from the benchmark cases

σ_1 = Standard deviation for smallest k_{adj} value from the benchmark cases

NPM = Nonparametric margin to account for small sample sizes based on the value of β

5.4.2. Bias Determination for Normal Distributions

For data that is demonstrated to likely come from a normal distribution, the bias is determined based one of two methods as described in NUREG/CR-6698 (Ref. [3]). For data that show no trend in k_{adj} versus the AENCF or enrichment the single-sided tolerance limit method is used to determine the bias. For data that show a trend in k_{adj} versus the AENCF or enrichment the one-sided lower tolerance band method is used. For the benchmark data examined herein, the trend information presented in Attachment F – Trend Analysis Figures demonstrates that no trends were present in the data. Therefore, only the single-sided tolerance limit method is presented here.

The bias determined by the single-sided tolerance limit method is defined by the following set equations:

$$Bias = \bar{k}_{adj} - US_p$$

$$U = \frac{z_p + \sqrt{z_p^2 - ab}}{a}$$

$$a = 1 - \frac{z_{1-\alpha}^2}{2(n-1)}$$

$$b = z_p^2 - \frac{z_{1-\alpha}^2}{n}$$

$$\bar{k}_{adj} = \frac{\sum \frac{1}{\sigma_i^2} k_i}{\sum \frac{1}{\sigma_i^2}}$$

$$S_p = \sqrt{s^2 + \bar{\sigma}^2}$$

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

Where,

\bar{k}_{adj} = Weighted mean k_{adj} value

U = One-sided lower tolerance factor

- $z_{1-\alpha}$ = z value for the cumulative standard normal distribution for a confidence value of $1-\alpha$
- z_p = z value for the cumulative standard normal distribution for a confidence value of p
- n = Number of data points (k_{adj} values) in data set
- k_i = The i^{th} k_{adj} value
- σ_i = Uncertainty of the i^{th} k_{adj} value
- S_p = Square root of the pooled variance
- $\bar{\sigma}^2$ = Average total variance

6. CALCULATIONS

6.1. Bias Determination

Table 4 in Attachment B – Benchmark Data Set contains the results of the 125 cases used to determine the MCNP6 computer code bias for use with low enrichment ^{235}U fissile materials. Table 4 also contains the experimental result and uncertainty as provided in the benchmark experiments handbook (Ref. [5]), the adjusted k_{eff} (k_{adj}), and combined uncertainty (σ_{com}) for each benchmark. The values for k_{adj} and σ_{com} were determined based on the formulas from Section 5.1. The next step was to order the k_{adj} values from smallest to largest. These ordered values are presented in Attachment C – Tables of k_{adj} Values.

The data was checked to determine if the data come from a normal distribution based on the Lilliefors test discussed in Section 5.2.1. The results of the test are used to help determine which of the bias determination methods from Section 5.4 is used. The Lilliefors test determinations and the bias results are presented in detail in Attachment D – Lilliefors Testing Tables and summarized in Table 1. The normal probability plots are created based on the discussion in Section 5.2.2 as a visual aid. These are shown in Attachment E – Normal Plot Figures.

Table 1. Summary of Lilliefors Test Results and Initial Bias Determination

Observations	$w_{1-\alpha}$	Max T*	Normal Distribution	Bias ¹
125	0.07925	0.19559	No	0.9798

¹ Bias determination details at the bottom of the Lilliefors test table in Attachment D – Lilliefors Testing Tables

The results of the trend analysis presented in Attachment F – Trend Analysis Figures demonstrate that there is no notable trend within the data that needs to be compensated for in the determination of the bias. The AOA review presented in Section 6.2 should be consulted before using any of the bias results presented in Table 1.

6.2. Area of Applicability Review

The AOA consists of the range or values of various parameters important to the reactivity of the benchmark models. These define the range or values for a system parameter or parameter(s) over which the bias presented above is considered valid without modification. These parameters include such things as fissile material(s), moderators, reflectors, geometry, other significant non-fissile materials (e.g., poisons such as boron or other materials such as steel), and energy characteristics of the experimental system (e.g., fast or thermal). These parameter ranges of the benchmark models are compared to the models of the system being evaluated. If the system parameter ranges fall within the AOA then no additional margin is needed beyond the MOS when determining the USL. If one or more of the system parameters are found to fall outside of the AOA, then an additional margin may be needed on the USL to extend the applicability of the bias determination. The need for an additional margin based on AOA considerations is addressed in the applicable calculation.

Table 2. Basic Properties of the MCNP6 Benchmark Models for LEU

Property	LEU AOA					
Fissile Materials	U (2 – 10 wt. % ²³⁵ U) in the form compound, solution					
Fissile Geometry	Array of fuel rods, rectangular parallelepipeds, UO ₂ in cube in cubic array, cylinder, sphere, slabs					
Moderator Materials	Water, Paraffin, Polyethylene					
Reflector Materials	None, Water, Acrylic, Steel, Plexiglas, Paraffin, Polyethylene, Concrete					
Other Significant absorbers, poisons, or structural materials present	Al alloys, steel, borated steel, Boral, boroflex, Ag-In-Cd, Cu, Cu with Cd, Cd, Zircaloy-4, rubber					
Specific Cross Sections and S(α,β) used (MCNP6 identifiers)	Soluble Boron: 0 – 96 ppm					
	1001.00c	17035.00c	26054.00c	42092.00c	50112.00c	h-h2o.40t h-poly.40t
	5010.00c	17037.00c	26056.00c	42094.00c	50114.00c	
	5011.00c	19039.00c	26057.00c	42095.00c	50115.00c	
	6012.00c	19040.00c	26058.00c	42096.00c	50116.00c	
	6013.00c	19041.00c	27059.00c	42097.00c	50117.00c	
	7014.00c	20040.00c	28058.00c	42098.00c	50118.00c	
	8016.00c	20042.00c	28060.00c	42100.00c	50119.00c	
	8017.00c	20044.00c	28061.00c	47107.00c	50120.00c	
	9019.00c	20046.00c	28062.00c	47109.00c	50122.00c	
	11023.00c	20048.00c	28064.00c	48106.00c	50124.00c	
	12024.00c	22046.00c	29063.00c	48108.00c	92234.00c	
	12025.00c	22047.00c	29065.00c	48110.00c	92235.00c	
	12026.00c	22048.00c	30064.00c	48111.00c	92236.00c	
	13027.00c	22049.00c	30066.00c	48112.00c	92238.00c	
	14028.00c	22050.00c	30067.00c	48113.00c		
	14029.00c	24050.00c	30068.00c	48114.00c		
	14030.00c	24052.00c	30070.00c	48116.00c		
	15031.00c	24053.00c	40090.00c	49113.00c		
	16032.00c	24054.00c	40091.00c	49115.00c		
16033.00c	25055.00c	40092.00c				
16034.00c		40094.00c				
16036.00c		40096.00c				
Average Energy of Neutrons Causing Fission	Range (MeV): 2.43E-02 – 2.88E-01 Average (MeV): 1.40E-01					

7. CONCLUSIONS

This calculation report has determined the bias for the use of the MCNP Version 6.2 code system and ENDF/B-VIII.0 library installed on the NSTS computers for use in performing calculations that estimate k_{eff} values. The bias values determined herein are applicable to problems that involve low enrichment ^{235}U fissile materials with various moderator and reflector materials. The AOA has been detailed in Section 6.2. The determined bias value is summarized in the following table.

Table 3. Summary of Bias Determination

AOA	Bias
LEU	0.9798

Note: The MOS is determined on a case-by-case basis within the evaluation. The use of the bias determined in this report requires the reduction of the bias by a MOS to establish a USL as follows:

$$k_{eff,USL} = Bias - MOS$$

8. ELECTRONIC FILES

8.1. Computer Runs

Filename	File Date	Computer Code	Ver.	Computer	Filename	File Date	Computer Code	Ver.	Computer
LCT002_01.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT002_01.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_01.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT002_01.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_02.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT002_02.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_02.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT002_02.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_03.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT002_03.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_03.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT002_03.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_04.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT002_04.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_04.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT002_04.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_05.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT002_05.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT002_05.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT002_05.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_01.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_01.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_01.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_01.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_02.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_02.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_02.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_02.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_03.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_03.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_03.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_03.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_04.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_04.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_04.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_04.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_05.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_05.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_05.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_05.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_06.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_06.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_06.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_06.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_07.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_07.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_07.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_07.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_08.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_08.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_08.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_08.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_09.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_09.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_09.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_09.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_10.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_10.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_10.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_10.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_11.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_11.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_11.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_11.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_12.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_12.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_12.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_12.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_13.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_13.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_13.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_13.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_14.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_14.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_14.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_14.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_15.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT009_15.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT009_15.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT009_15.ino	11/12/2020	MCNP	6.2	NSTS-LS2

Filename	File Date	Computer Code	Ver.	Computer	Filename	File Date	Computer Code	Ver.	Computer
LCT049_12.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT049_12.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_12.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT049_12.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_13.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT049_13.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_13.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT049_13.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_14.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT049_14.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_14.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT049_14.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_15.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT049_15.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_15.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT049_15.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_16.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT049_16.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_16.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT049_16.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_17.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT049_17.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_17.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT049_17.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_18.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT049_18.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT049_18.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LCT049_18.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LCT092_01.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT092_01.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT092_01.ino	11/19/2020	MCNP	6.2	NSTS-LS01	LCT092_01.ino	11/17/2020	MCNP	6.2	NSTS-LS2
LCT092_02.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT092_02.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT092_02.ino	11/19/2020	MCNP	6.2	NSTS-LS01	LCT092_02.ino	11/17/2020	MCNP	6.2	NSTS-LS2
LCT092_03.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT092_03.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT092_03.ino	11/19/2020	MCNP	6.2	NSTS-LS01	LCT092_03.ino	11/17/2020	MCNP	6.2	NSTS-LS2
LCT092_04.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT092_04.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT092_04.ino	11/19/2020	MCNP	6.2	NSTS-LS01	LCT092_04.ino	11/17/2020	MCNP	6.2	NSTS-LS2
LCT092_05.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT092_05.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT092_05.ino	11/19/2020	MCNP	6.2	NSTS-LS01	LCT092_05.ino	11/17/2020	MCNP	6.2	NSTS-LS2
LCT092_06.in	11/12/2020	MCNP	6.2	NSTS-LS01	LCT092_06.in	11/12/2020	MCNP	6.2	NSTS-LS2
LCT092_06.ino	11/19/2020	MCNP	6.2	NSTS-LS01	LCT092_06.ino	11/17/2020	MCNP	6.2	NSTS-LS2
LST001_01.in	11/12/2020	MCNP	6.2	NSTS-LS01	LST001_01.in	11/12/2020	MCNP	6.2	NSTS-LS2
LST001_01.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LST001_01.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LST002_01.in	11/12/2020	MCNP	6.2	NSTS-LS01	LST002_01.in	11/12/2020	MCNP	6.2	NSTS-LS2
LST002_01.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LST002_01.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LST002_02.in	11/12/2020	MCNP	6.2	NSTS-LS01	LST002_02.in	11/12/2020	MCNP	6.2	NSTS-LS2
LST002_02.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LST002_02.ino	11/12/2020	MCNP	6.2	NSTS-LS2
LST002_03.in	11/12/2020	MCNP	6.2	NSTS-LS01	LST002_03.in	11/12/2020	MCNP	6.2	NSTS-LS2
LST002_03.ino	11/18/2020	MCNP	6.2	NSTS-LS01	LST002_03.ino	11/12/2020	MCNP	6.2	NSTS-LS2

8.2. Other Electronic Files

Filename	File Date	Description
TM12-EN-RPT-0002 Data.xlsm	12/10/2020	Data preparation, normality testing, trend analysis, and bias determination

9. ATTACHMENT A – SAMPLE COMPUTER INPUT/OUTPUT

LCT002_01.in

```
M401 10X11 +5 CLUSTER OF U(4.31)O2 RODS, 2.54 CM PITCH
1 1 .069930523 -1 7 -8 u=1 imp:n=1 $ uo2 fuel
2 0 -2 1 7 -8 u=1 imp:n=1 $ gap
3 3 .059751598 -12 2 u=1 imp:n=1 $ clad
4 4 .11734156 -2 8 u=1 imp:n=1 $ rubber end plug (top)
5 4 .11734156 -2 -7 u=1 imp:n=1 $ rubber end plug (bottom)
6 2 .100059 12 u=1 imp:n=1 $ water
7 0 -4 3 -6 5 imp:n=1 lat=1 u=2 fill=1 $ lattice of fuel rods
8 0 -10 11 -20 21 -9 23 fill=2 imp:n=1 $ rod cluster
9 0 -13 11 -21 19 -9 23 imp:n=1 fill=2 $ partial row of fuel rods
10 2 .100059 13 -10 -21 19 -9 23 imp:n=1 $ water of partial row
11 5 .106563 19 -20 11 -10 -23 29 imp:n=1 $ acrylic support plate
12 2 .100059 (-11:10:20:-19:9:-29) -24 25 -26 27 -28 30 imp:n=1 $ water
13 0 24:-25:26:-27:28:-30 imp:n=0
```

```
1 c/z 1.27 1.27 .6325 $ fuel cylinder
2 c/z 1.27 1.27 .6415 $ clad inner surface
3 px 0.0 $ fuel rod cell boundary
4 px 2.54 $ fuel rod cell boundary
5 py 0.0 $ fuel rod cell boundary
6 py 2.54 $ fuel rod cell boundary
7 pz 0.0 $ bottom of fuel
8 pz 92.075 $ top of fuel
9 pz 94.2975 $ top of clad
10 px 25.399 $ farthest edge of closest cluster ***
11 px .0001 $ closest edge of closest cluster
12 c/z 1.27 1.27 .7075 $ clad outer surface
13 px 12.699 $ edge of partial row ***
19 py 0.0001 $ close edge of cluster + partial row
20 py 30.479 $ sides of clusters ***
21 py 2.541 $ side of partial row and full cluster
23 pz -2.2225 $ bottom of fuel rod
24 px 55.4 $ side of water reflector ***
25 px -30 $ side of water reflector
26 py 60.48 $ side of water reflector ***
27 py -30 $ side of water reflector
28 pz 107.075 $ top of water
29 pz -4.7625 $ bottom of acrylic support plate
30 pz -20.0625 $ bottom of water
```

```
kcode 10000 1 100 5100 50000
sdef x=d1 y=d2 z=d3 cel=d4
sil 0 41
spl 0 1
si2 0 37
sp2 0 1
si3 0 93
sp3 0 1
si4 1 8
sp4 v
print
c
c MATERIALS FOR U(4.31)O2 RODS
c
c m1 is UO2 fuel
m1 92234 5.1835e-6 92235 1.0102e-3
92236 5.1395e-6 92238 2.2157e-2
8016 4.6753e-2
c m2 is water
m2 8016 3.3353e-2 1001 6.6706e-2
mt2 h-h2O.40t
c m3 is 6061 Al (clad)
m3 13027 5.8433e-2
c Cr Total: 6.2310E-05
24050 2.7074E-06
```

	24052	5.2209E-05
	24053	5.9201E-06
	24054	1.4736E-06
c Cu Total:	6.3731E-05	
	29063	4.4083E-05
	29065	1.9648E-05
c Mg Total:	6.6651E-04	
	12024	5.2648E-04
	12025	6.6651E-05
	12026	7.3383E-05
c Ti Total:	2.5375E-05	
	22046	2.0934E-06
	22047	1.8879E-06
	22048	1.8706E-05
	22049	1.3728E-06
	22050	1.3144E-06
	25055	2.2115E-5
c Si Total:	3.4607E-04	
	14028	3.1918E-04
	14029	1.6161E-05
	14030	1.0728E-05
	30064	1.5236E-05
	30066	8.5779E-06
	30067	1.2387E-06
	30068	5.7289E-06
	30070	1.8580E-07
c Fe Total:	1.0152E-04	
	26054	5.9338E-06
	26056	9.3149E-05
	26057	2.1512E-06
	26058	2.8629E-07
c	m4 is rubber (end plugs)	
m4	6012	4.3083E-02
	6013	4.7918E-04
	1001	5.8178E-2
c Ca Total:	2.5660E-03	
	20040	2.4875E-03
	20042	1.6602E-05
	20043	3.4641E-06
	20044	5.3527E-05
	20046	1.0264E-07
	20048	4.7984E-06
	16032	4.7820E-4
c Si Total:	9.6360E-05	
	14028	8.8873E-05
	14029	4.5000E-06
	14030	2.9872E-06
	8016	1.2461E-2
mt4	h-poly.40t	
c	m5 is acrylic (support plate)	
m5	1001	5.6642E-2
	6012	3.5256E-02
	6013	3.9213E-04
	8016	1.4273E-2
mt5	h-poly.40t	

10. ATTACHMENT B – BENCHMARK DATA SET

The following table provides all the results for all the benchmark cases run. The results are identical for all cases run on NSTS-LS01 and NSTS-LS2.

Table 4: Benchmark Results for MCNP6

Benchmark ID from Ref. [5]	Case #	k_{exp}	σ_{exp}	k_{calc}	σ_{calc}	k_{adj}	σ_{com}
LEU-COMP-THERM-002	1	0.9997	0.0020	0.99854	0.00010	0.9988	0.0020
LEU-COMP-THERM-002	2	0.9997	0.0020	0.99964	0.00010	0.9999	0.0020
LEU-COMP-THERM-002	3	0.9997	0.0020	0.99937	0.00010	0.9997	0.0020
LEU-COMP-THERM-002	4	0.9997	0.0018	0.99884	0.00010	0.9991	0.0018
LEU-COMP-THERM-002	5	0.9997	0.0019	0.99777	0.00010	0.9981	0.0019
LEU-COMP-THERM-009	1	1.0000	0.0021	0.99928	0.00010	0.9993	0.0021
LEU-COMP-THERM-009	2	1.0000	0.0021	0.99890	0.00010	0.9989	0.0021
LEU-COMP-THERM-009	3	1.0000	0.0021	0.99854	0.00010	0.9985	0.0021
LEU-COMP-THERM-009	4	1.0000	0.0021	0.99928	0.00010	0.9993	0.0021
LEU-COMP-THERM-009	5	1.0000	0.0021	0.99962	0.00010	0.9996	0.0021
LEU-COMP-THERM-009	6	1.0000	0.0021	0.99904	0.00010	0.9990	0.0021
LEU-COMP-THERM-009	7	1.0000	0.0021	0.99971	0.00010	0.9997	0.0021
LEU-COMP-THERM-009	8	1.0000	0.0021	0.99884	0.00011	0.9988	0.0021
LEU-COMP-THERM-009	9	1.0000	0.0021	0.99929	0.00011	0.9993	0.0021
LEU-COMP-THERM-009	10	1.0000	0.0021	0.99910	0.00010	0.9991	0.0021
LEU-COMP-THERM-009	11	1.0000	0.0021	0.99916	0.00010	0.9992	0.0021
LEU-COMP-THERM-009	12	1.0000	0.0021	0.99965	0.00010	0.9997	0.0021
LEU-COMP-THERM-009	13	1.0000	0.0021	0.99971	0.00010	0.9997	0.0021
LEU-COMP-THERM-009	14	1.0000	0.0021	0.99786	0.00010	0.9979	0.0021
LEU-COMP-THERM-009	15	1.0000	0.0021	0.99967	0.00010	0.9997	0.0021
LEU-COMP-THERM-009	16	1.0000	0.0021	0.99877	0.00011	0.9988	0.0021
LEU-COMP-THERM-009	17	1.0000	0.0021	0.99971	0.00010	0.9997	0.0021
LEU-COMP-THERM-009	18	1.0000	0.0021	0.99857	0.00010	0.9986	0.0021
LEU-COMP-THERM-009	19	1.0000	0.0021	0.99957	0.00011	0.9996	0.0021
LEU-COMP-THERM-009	20	1.0000	0.0021	0.99886	0.00011	0.9989	0.0021
LEU-COMP-THERM-009	21	1.0000	0.0021	0.99951	0.00010	0.9995	0.0021
LEU-COMP-THERM-009	22	1.0000	0.0021	0.99903	0.00011	0.9990	0.0021
LEU-COMP-THERM-009	23	1.0000	0.0021	0.99971	0.00010	0.9997	0.0021
LEU-COMP-THERM-009	24	1.0000	0.0021	0.99893	0.00010	0.9989	0.0021
LEU-COMP-THERM-009	25	1.0000	0.0021	0.99913	0.00010	0.9991	0.0021
LEU-COMP-THERM-009	26	1.0000	0.0021	0.99938	0.00010	0.9994	0.0021
LEU-COMP-THERM-013	1	1.0000	0.0018	1.00047	0.00011	1.0005	0.0018
LEU-COMP-THERM-013	2	1.0000	0.0018	1.00009	0.00011	1.0001	0.0018
LEU-COMP-THERM-013	3	1.0000	0.0018	0.99992	0.00011	0.9999	0.0018
LEU-COMP-THERM-013	4	1.0000	0.0018	1.00047	0.00011	1.0005	0.0018
LEU-COMP-THERM-013	5	1.0000	0.0032	0.98707	0.00011	0.9871	0.0032
LEU-COMP-THERM-013	6	1.0000	0.0018	0.99967	0.00011	0.9997	0.0018
LEU-COMP-THERM-013	7	1.0000	0.0018	0.99944	0.00011	0.9994	0.0018
LEU-COMP-THERM-033	1	1.0000	0.0038	1.00297	0.00010	1.0030	0.0038
LEU-COMP-THERM-033	2	1.0000	0.0038	1.00360	0.00010	1.0036	0.0038
LEU-COMP-THERM-033	3	1.0000	0.0038	1.00455	0.00010	1.0046	0.0038
LEU-COMP-THERM-033	4	1.0000	0.0038	1.00360	0.00010	1.0036	0.0038

Benchmark ID from Ref. [5]	Case #	k_{exp}	σ_{exp}	k_{calc}	σ_{calc}	k_{adj}	σ_{com}
LEU-COMP-THERM-033	5	1.0000	0.0039	1.00603	0.00010	1.0060	0.0039
LEU-COMP-THERM-033	6	1.0000	0.0039	0.99752	0.00010	0.9975	0.0039
LEU-COMP-THERM-033	7	1.0000	0.0039	0.99756	0.00010	0.9976	0.0039
LEU-COMP-THERM-033	8	1.0000	0.0040	0.99893	0.00010	0.9989	0.0040
LEU-COMP-THERM-033	9	1.0000	0.0040	0.99943	0.00010	0.9994	0.0040
LEU-COMP-THERM-033	10	1.0000	0.0039	0.99141	0.00010	0.9914	0.0039
LEU-COMP-THERM-033	11	1.0000	0.0039	0.99306	0.00009	0.9931	0.0039
LEU-COMP-THERM-033	12	1.0000	0.0039	0.99439	0.00009	0.9944	0.0039
LEU-COMP-THERM-033	13	1.0000	0.0041	1.00164	0.00009	1.0016	0.0041
LEU-COMP-THERM-033	14	1.0000	0.0051	0.99448	0.00007	0.9945	0.0051
LEU-COMP-THERM-033	15	1.0000	0.0051	0.99472	0.00007	0.9947	0.0051
LEU-COMP-THERM-033	16	1.0000	0.0051	0.99499	0.00007	0.9950	0.0051
LEU-COMP-THERM-033	17	1.0000	0.0038	0.99374	0.00011	0.9937	0.0038
LEU-COMP-THERM-033	18	1.0000	0.0038	0.99537	0.00011	0.9954	0.0038
LEU-COMP-THERM-033	19	1.0000	0.0038	0.99765	0.00011	0.9977	0.0038
LEU-COMP-THERM-033	20	1.0000	0.0038	0.99885	0.00011	0.9989	0.0038
LEU-COMP-THERM-033	21	1.0000	0.0038	0.99947	0.00011	0.9995	0.0038
LEU-COMP-THERM-033	22	1.0000	0.0039	1.01380	0.00011	1.0138	0.0039
LEU-COMP-THERM-033	23	1.0000	0.0040	1.00458	0.00011	1.0046	0.0040
LEU-COMP-THERM-033	24	1.0000	0.0040	1.00418	0.00010	1.0042	0.0040
LEU-COMP-THERM-033	25	1.0000	0.0040	1.00342	0.00011	1.0034	0.0040
LEU-COMP-THERM-033	26	1.0000	0.0039	1.00688	0.00010	1.0069	0.0039
LEU-COMP-THERM-033	27	1.0000	0.0039	1.00720	0.00010	1.0072	0.0039
LEU-COMP-THERM-033	28	1.0000	0.0039	1.00735	0.00010	1.0074	0.0039
LEU-COMP-THERM-033	29	1.0000	0.0039	1.00677	0.00011	1.0068	0.0039
LEU-COMP-THERM-033	30	1.0000	0.0039	1.00481	0.00010	1.0048	0.0039
LEU-COMP-THERM-033	31	1.0000	0.0039	1.00436	0.00010	1.0044	0.0039
LEU-COMP-THERM-033	32	1.0000	0.0039	1.00455	0.00010	1.0046	0.0039
LEU-COMP-THERM-033	33	1.0000	0.0039	1.00435	0.00010	1.0044	0.0039
LEU-COMP-THERM-033	34	1.0000	0.0039	1.00446	0.00010	1.0045	0.0039
LEU-COMP-THERM-033	35	1.0000	0.0040	1.00307	0.00010	1.0031	0.0040
LEU-COMP-THERM-033	36	1.0000	0.0040	1.00316	0.00010	1.0032	0.0040
LEU-COMP-THERM-033	37	1.0000	0.0040	1.00254	0.00010	1.0025	0.0040
LEU-COMP-THERM-033	38	1.0000	0.0040	1.00261	0.00010	1.0026	0.0040
LEU-COMP-THERM-033	39	1.0000	0.0040	1.00268	0.00010	1.0027	0.0040
LEU-COMP-THERM-033	40	1.0000	0.0040	1.00219	0.00010	1.0022	0.0040
LEU-COMP-THERM-033	41	1.0000	0.0041	1.00293	0.00009	1.0029	0.0041
LEU-COMP-THERM-033	42	1.0000	0.0041	1.00169	0.00009	1.0017	0.0041
LEU-COMP-THERM-033	43	1.0000	0.0050	1.00079	0.00009	1.0008	0.0050
LEU-COMP-THERM-033	44	1.0000	0.0050	0.99503	0.00007	0.9950	0.0050
LEU-COMP-THERM-033	45	1.0000	0.0050	0.99467	0.00008	0.9947	0.0050
LEU-COMP-THERM-033	46	1.0000	0.0050	0.99409	0.00008	0.9941	0.0050
LEU-COMP-THERM-033	47	1.0000	0.0042	1.01824	0.00012	1.0182	0.0042
LEU-COMP-THERM-033	48	1.0000	0.0042	1.01685	0.00012	1.0169	0.0042
LEU-COMP-THERM-033	49	1.0000	0.0042	1.01700	0.00011	1.0170	0.0042
LEU-COMP-THERM-033	50	1.0000	0.0041	1.01851	0.00012	1.0185	0.0041
LEU-COMP-THERM-033	51	1.0000	0.0041	1.01966	0.00012	1.0197	0.0041
LEU-COMP-THERM-033	52	1.0000	0.0041	1.01572	0.00011	1.0157	0.0041

Benchmark ID from Ref. [5]	Case #	k_{exp}	σ_{exp}	k_{calc}	σ_{calc}	k_{adj}	σ_{com}
LEU-COMP-THERM-042	1	1.0000	0.0016	0.99770	0.00010	0.9977	0.0016
LEU-COMP-THERM-042	2	1.0000	0.0016	0.99756	0.00010	0.9976	0.0016
LEU-COMP-THERM-042	3	1.0000	0.0016	0.99831	0.00010	0.9983	0.0016
LEU-COMP-THERM-042	4	1.0000	0.0017	0.99876	0.00010	0.9988	0.0017
LEU-COMP-THERM-042	5	1.0000	0.0033	0.99871	0.00010	0.9987	0.0033
LEU-COMP-THERM-042	6	1.0000	0.0016	0.99886	0.00010	0.9989	0.0016
LEU-COMP-THERM-042	7	1.0000	0.0018	0.99722	0.00010	0.9972	0.0018
LEU-COMP-THERM-049	1	1.0000	0.0034	0.99564	0.00011	0.9956	0.0034
LEU-COMP-THERM-049	2	1.0000	0.0034	0.99618	0.00011	0.9962	0.0034
LEU-COMP-THERM-049	3	1.0000	0.0034	0.99617	0.00011	0.9962	0.0034
LEU-COMP-THERM-049	4	1.0000	0.0034	0.99655	0.00011	0.9966	0.0034
LEU-COMP-THERM-049	5	1.0000	0.0042	0.99580	0.00011	0.9958	0.0042
LEU-COMP-THERM-049	6	1.0000	0.0042	0.99738	0.00011	0.9974	0.0042
LEU-COMP-THERM-049	7	1.0000	0.0042	0.99650	0.00011	0.9965	0.0042
LEU-COMP-THERM-049	8	1.0000	0.0042	0.99591	0.00011	0.9959	0.0042
LEU-COMP-THERM-049	9	1.0000	0.0037	0.99564	0.00011	0.9956	0.0037
LEU-COMP-THERM-049	10	1.0000	0.0037	0.99784	0.00011	0.9978	0.0037
LEU-COMP-THERM-049	11	1.0000	0.0037	0.99615	0.00011	0.9962	0.0037
LEU-COMP-THERM-049	12	1.0000	0.0037	0.99610	0.00011	0.9961	0.0037
LEU-COMP-THERM-049	13	1.0000	0.0036	0.99562	0.00011	0.9956	0.0036
LEU-COMP-THERM-049	14	1.0000	0.0036	0.99608	0.00011	0.9961	0.0036
LEU-COMP-THERM-049	15	1.0000	0.0036	0.99736	0.00011	0.9974	0.0036
LEU-COMP-THERM-049	16	1.0000	0.0036	0.99667	0.00011	0.9967	0.0036
LEU-COMP-THERM-049	17	1.0000	0.0036	0.99671	0.00011	0.9967	0.0036
LEU-COMP-THERM-049	18	1.0000	0.0030	0.99951	0.00011	0.9995	0.0030
LEU-COMP-THERM-092	1	1.00033	0.00044	1.00089	0.00010	1.0006	0.0005
LEU-COMP-THERM-092	2	1.00033	0.00044	0.99967	0.00010	0.9993	0.0005
LEU-COMP-THERM-092	3	1.00032	0.00044	0.99860	0.00010	0.9983	0.0005
LEU-COMP-THERM-092	4	1.00033	0.00044	0.99632	0.00010	0.9960	0.0005
LEU-COMP-THERM-092	5	1.00033	0.00046	0.99168	0.00010	0.9914	0.0005
LEU-COMP-THERM-092	6	1.00033	0.00055	0.98076	0.00010	0.9804	0.0006
LEU-SOL-THERM-001	1	0.9991	0.0029	1.01215	0.00011	1.0131	0.0029
LEU-SOL-THERM-002	1	1.0038	0.0040	1.00016	0.00008	0.9964	0.0040
LEU-SOL-THERM-002	2	1.0024	0.0037	0.99591	0.00009	0.9935	0.0037
LEU-SOL-THERM-002	3	1.0024	0.0044	1.00101	0.00008	0.9986	0.0044

11. ATTACHMENT C – TABLES OF K_{ADJ} VALUES

The following table contains the ordered k_{adj} values. The MCNP6 output filename is also provided to aid in traceability.

Table 5: Ordered k_{adj} Values for LEU

Filename	Observation	k_{adj}	σ_{com}
LCT092_06.ino	1	0.9804	0.0006
LCT013_05.ino	2	0.9871	0.0032
LCT092_05.ino	3	0.9914	0.0005
LCT033_10.ino	4	0.9914	0.0039
LCT033_11.ino	5	0.9931	0.0039
LST002_02.ino	6	0.9935	0.0037
LCT033_17.ino	7	0.9937	0.0038
LCT033_46.ino	8	0.9941	0.0050
LCT033_12.ino	9	0.9944	0.0039
LCT033_14.ino	10	0.9945	0.0051
LCT033_45.ino	11	0.9947	0.0050
LCT033_15.ino	12	0.9947	0.0051
LCT033_16.ino	13	0.9950	0.0051
LCT033_44.ino	14	0.9950	0.0050
LCT033_18.ino	15	0.9954	0.0038
LCT049_13.ino	16	0.9956	0.0036
LCT049_01.ino	17	0.9956	0.0034
LCT049_09.ino	18	0.9956	0.0037
LCT049_05.ino	19	0.9958	0.0042
LCT049_08.ino	20	0.9959	0.0042
LCT092_04.ino	21	0.9960	0.0005
LCT049_14.ino	22	0.9961	0.0036
LCT049_12.ino	23	0.9961	0.0037
LCT049_11.ino	24	0.9962	0.0037
LCT049_03.ino	25	0.9962	0.0034
LCT049_02.ino	26	0.9962	0.0034
LST002_01.ino	27	0.9964	0.0040
LCT049_07.ino	28	0.9965	0.0042
LCT049_04.ino	29	0.9966	0.0034
LCT049_16.ino	30	0.9967	0.0036
LCT049_17.ino	31	0.9967	0.0036
LCT042_07.ino	32	0.9972	0.0018
LCT049_15.ino	33	0.9974	0.0036
LCT049_06.ino	34	0.9974	0.0042
LCT033_06.ino	35	0.9975	0.0039
LCT033_07.ino	36	0.9976	0.0039
LCT042_02.ino	37	0.9976	0.0016
LCT033_19.ino	38	0.9977	0.0038
LCT042_01.ino	39	0.9977	0.0016
LCT049_10.ino	40	0.9978	0.0037
LCT009_14.ino	41	0.9979	0.0021
LCT002_05.ino	42	0.9981	0.0019
LCT092_03.ino	43	0.9983	0.0005
LCT042_03.ino	44	0.9983	0.0016
LCT009_03.ino	45	0.9985	0.0021

Filename	Observation	K _{adj}	σ _{com}
LCT009_18.ino	46	0.9986	0.0021
LST002_03.ino	47	0.9986	0.0044
LCT042_05.ino	48	0.9987	0.0033
LCT042_04.ino	49	0.9988	0.0017
LCT009_16.ino	50	0.9988	0.0021
LCT002_01.ino	51	0.9988	0.0020
LCT009_08.ino	52	0.9988	0.0021
LCT033_20.ino	53	0.9989	0.0038
LCT009_20.ino	54	0.9989	0.0021
LCT042_06.ino	55	0.9989	0.0016
LCT009_02.ino	56	0.9989	0.0021
LCT009_24.ino	57	0.9989	0.0021
LCT033_08.ino	58	0.9989	0.0040
LCT009_22.ino	59	0.9990	0.0021
LCT009_06.ino	60	0.9990	0.0021
LCT009_10.ino	61	0.9991	0.0021
LCT009_25.ino	62	0.9991	0.0021
LCT002_04.ino	63	0.9991	0.0018
LCT009_11.ino	64	0.9992	0.0021
LCT009_01.ino	65	0.9993	0.0021
LCT009_04.ino	66	0.9993	0.0021
LCT009_09.ino	67	0.9993	0.0021
LCT092_02.ino	68	0.9993	0.0005
LCT009_26.ino	69	0.9994	0.0021
LCT033_09.ino	70	0.9994	0.0040
LCT013_07.ino	71	0.9994	0.0018
LCT033_21.ino	72	0.9995	0.0038
LCT009_21.ino	73	0.9995	0.0021
LCT049_18.ino	74	0.9995	0.0030
LCT009_19.ino	75	0.9996	0.0021
LCT009_05.ino	76	0.9996	0.0021
LCT009_12.ino	77	0.9997	0.0021
LCT002_03.ino	78	0.9997	0.0020
LCT009_15.ino	79	0.9997	0.0021
LCT013_06.ino	80	0.9997	0.0018
LCT009_07.ino	81	0.9997	0.0021
LCT009_13.ino	82	0.9997	0.0021
LCT009_17.ino	83	0.9997	0.0021
LCT009_23.ino	84	0.9997	0.0021
LCT013_03.ino	85	0.9999	0.0018
LCT002_02.ino	86	0.9999	0.0020
LCT013_02.ino	87	1.0001	0.0018
LCT013_01.ino	88	1.0005	0.0018
LCT013_04.ino	89	1.0005	0.0018
LCT092_01.ino	90	1.0006	0.0005
LCT033_43.ino	91	1.0008	0.0050
LCT033_13.ino	92	1.0016	0.0041
LCT033_42.ino	93	1.0017	0.0041
LCT033_40.ino	94	1.0022	0.0040
LCT033_37.ino	95	1.0025	0.0040
LCT033_38.ino	96	1.0026	0.0040
LCT033_39.ino	97	1.0027	0.0040

Filename	Observation	k_{adj}	σ_{com}
LCT033_41.ino	98	1.0029	0.0041
LCT033_01.ino	99	1.0030	0.0038
LCT033_35.ino	100	1.0031	0.0040
LCT033_36.ino	101	1.0032	0.0040
LCT033_25.ino	102	1.0034	0.0040
LCT033_02.ino	103	1.0036	0.0038
LCT033_04.ino	104	1.0036	0.0038
LCT033_24.ino	105	1.0042	0.0040
LCT033_33.ino	106	1.0044	0.0039
LCT033_31.ino	107	1.0044	0.0039
LCT033_34.ino	108	1.0045	0.0039
LCT033_03.ino	109	1.0046	0.0038
LCT033_32.ino	110	1.0046	0.0039
LCT033_23.ino	111	1.0046	0.0040
LCT033_30.ino	112	1.0048	0.0039
LCT033_05.ino	113	1.0060	0.0039
LCT033_29.ino	114	1.0068	0.0039
LCT033_26.ino	115	1.0069	0.0039
LCT033_27.ino	116	1.0072	0.0039
LCT033_28.ino	117	1.0074	0.0039
LST001_01.ino	118	1.0131	0.0029
LCT033_22.ino	119	1.0138	0.0039
LCT033_52.ino	120	1.0157	0.0041
LCT033_48.ino	121	1.0169	0.0042
LCT033_49.ino	122	1.0170	0.0042
LCT033_47.ino	123	1.0182	0.0042
LCT033_50.ino	124	1.0185	0.0041
LCT033_51.ino	125	1.0197	0.0041

12. ATTACHMENT D – LILLIEFORS TESTING TABLES

Table 6: Lilliefors Normality Test Determination for MCNP6 Benchmark Results for LEU

Case #	k_{adj}	σ_{com}	z_i	F(z)	G(z)	$ F^*(z_i)-G(z_i) $	$ F^*(z_i)-G(z_{i-1}) $
1	0.9804	0.0006	-3.40840	0.00033	0.00800	0.00767	0.00033
2	0.9871	0.0032	-2.25560	0.01205	0.01600	0.00395	0.00405
3	0.9914	0.0005	-1.51131	0.06535	0.02400	0.04135	0.04935
4	0.9914	0.0039	-1.50138	0.06663	0.03200	0.03463	0.04263
5	0.9931	0.0039	-1.21464	0.11225	0.04000	0.07225	0.08025
6	0.9935	0.0037	-1.13374	0.12845	0.04800	0.08045	0.08845
7	0.9937	0.0038	-1.09647	0.13644	0.05600	0.08044	0.08844
8	0.9941	0.0050	-1.03564	0.15018	0.06400	0.08618	0.09418
9	0.9944	0.0039	-0.98351	0.16268	0.07200	0.09068	0.09868
10	0.9945	0.0051	-0.96787	0.16656	0.08000	0.08656	0.09456
11	0.9947	0.0050	-0.93485	0.17493	0.08800	0.08693	0.09493
12	0.9947	0.0051	-0.92616	0.17718	0.09600	0.08118	0.08918
13	0.9950	0.0051	-0.87924	0.18964	0.10400	0.08564	0.09364
14	0.9950	0.0050	-0.87229	0.19153	0.11200	0.07953	0.08753
15	0.9954	0.0038	-0.81320	0.20805	0.12000	0.08805	0.09605
16	0.9956	0.0036	-0.76975	0.22072	0.12800	0.09272	0.10072
17	0.9956	0.0034	-0.76628	0.22176	0.13600	0.08576	0.09376
18	0.9956	0.0037	-0.76628	0.22176	0.14400	0.07776	0.08576
19	0.9958	0.0042	-0.73847	0.23011	0.15200	0.07811	0.08611
20	0.9959	0.0042	-0.71936	0.23596	0.16000	0.07596	0.08396
21	0.9960	0.0005	-0.70522	0.24034	0.16800	0.07234	0.08034
22	0.9961	0.0036	-0.68981	0.24516	0.17600	0.06916	0.07716
23	0.9961	0.0037	-0.68634	0.24625	0.18400	0.06225	0.07025
24	0.9962	0.0037	-0.67765	0.24900	0.19200	0.05700	0.06500
25	0.9962	0.0034	-0.67417	0.25010	0.20000	0.05010	0.05810
26	0.9962	0.0034	-0.67244	0.25065	0.20800	0.04265	0.05065
27	0.9964	0.0040	-0.63876	0.26149	0.21600	0.04549	0.05349
28	0.9965	0.0042	-0.61682	0.26868	0.22400	0.04468	0.05268
29	0.9966	0.0034	-0.60814	0.27155	0.23200	0.03955	0.04755
30	0.9967	0.0036	-0.58728	0.27851	0.24000	0.03851	0.04651
31	0.9967	0.0036	-0.58033	0.28085	0.24800	0.03285	0.04085
32	0.9972	0.0018	-0.49170	0.31147	0.25600	0.05547	0.06347
33	0.9974	0.0036	-0.46737	0.32012	0.26400	0.05612	0.06412
34	0.9974	0.0042	-0.46390	0.32136	0.27200	0.04936	0.05736
35	0.9975	0.0039	-0.43957	0.33013	0.28000	0.05013	0.05813
36	0.9976	0.0039	-0.43261	0.33265	0.28800	0.04465	0.05265
37	0.9976	0.0016	-0.43261	0.33265	0.29600	0.03665	0.04465
38	0.9977	0.0038	-0.41697	0.33835	0.30400	0.03435	0.04235
39	0.9977	0.0016	-0.40829	0.34153	0.31200	0.02953	0.03753
40	0.9978	0.0037	-0.38396	0.35051	0.32000	0.03051	0.03851
41	0.9979	0.0021	-0.38048	0.35179	0.32800	0.02379	0.03179
42	0.9981	0.0019	-0.34409	0.36539	0.33600	0.02939	0.03739
43	0.9983	0.0005	-0.30740	0.37927	0.34400	0.03527	0.04327
44	0.9983	0.0016	-0.30228	0.38122	0.35200	0.02922	0.03722
45	0.9985	0.0021	-0.26231	0.39654	0.36000	0.03654	0.04454
46	0.9986	0.0021	-0.25709	0.39855	0.36800	0.03055	0.03855
47	0.9986	0.0044	-0.24956	0.40146	0.37600	0.02546	0.03346
48	0.9987	0.0033	-0.23276	0.40797	0.38400	0.02397	0.03197

Case #	Kadj	σ_{com}	Z_i	F(z)	G(z)	$ F^*(z_i)-G(z_i) $	$ F^*(z_i)-G(z_{i-1}) $
49	0.9988	0.0017	-0.22407	0.41135	0.39200	0.01935	0.02735
50	0.9988	0.0021	-0.22234	0.41203	0.40000	0.01203	0.02003
51	0.9988	0.0020	-0.21023	0.41674	0.40800	0.00874	0.01674
52	0.9988	0.0021	-0.21017	0.41677	0.41600	0.00077	0.00877
53	0.9989	0.0038	-0.20843	0.41744	0.42400	0.00656	0.00144
54	0.9989	0.0021	-0.20670	0.41812	0.43200	0.01388	0.00588
55	0.9989	0.0016	-0.20670	0.41812	0.44000	0.02188	0.01388
56	0.9989	0.0021	-0.19975	0.42084	0.44800	0.02716	0.01916
57	0.9989	0.0021	-0.19453	0.42288	0.45600	0.03312	0.02512
58	0.9989	0.0040	-0.19453	0.42288	0.46400	0.04112	0.03312
59	0.9990	0.0021	-0.17715	0.42969	0.47200	0.04231	0.03431
60	0.9990	0.0021	-0.17542	0.43038	0.48000	0.04962	0.04162
61	0.9991	0.0021	-0.16499	0.43448	0.48800	0.05352	0.04552
62	0.9991	0.0021	-0.15978	0.43653	0.49600	0.05947	0.05147
63	0.9991	0.0018	-0.15808	0.43720	0.50400	0.06680	0.05880
64	0.9992	0.0021	-0.15456	0.43858	0.51200	0.07342	0.06542
65	0.9993	0.0021	-0.13371	0.44682	0.52000	0.07318	0.06518
66	0.9993	0.0021	-0.13371	0.44682	0.52800	0.08118	0.07318
67	0.9993	0.0021	-0.13197	0.44750	0.53600	0.08850	0.08050
68	0.9993	0.0005	-0.12324	0.45096	0.54400	0.09304	0.08504
69	0.9994	0.0021	-0.11633	0.45370	0.55200	0.09830	0.09030
70	0.9994	0.0040	-0.10764	0.45714	0.56000	0.10286	0.09486
71	0.9994	0.0018	-0.10590	0.45783	0.56800	0.11017	0.10217
72	0.9995	0.0038	-0.10069	0.45990	0.57600	0.11610	0.10810
73	0.9995	0.0021	-0.09374	0.46266	0.58400	0.12134	0.11334
74	0.9995	0.0030	-0.09374	0.46266	0.59200	0.12934	0.12134
75	0.9996	0.0021	-0.08331	0.46680	0.60000	0.13320	0.12520
76	0.9996	0.0021	-0.07462	0.47026	0.60800	0.13774	0.12974
77	0.9997	0.0021	-0.06941	0.47233	0.61600	0.14367	0.13567
78	0.9997	0.0020	-0.06595	0.47371	0.62400	0.15029	0.14229
79	0.9997	0.0021	-0.06593	0.47372	0.63200	0.15828	0.15028
80	0.9997	0.0018	-0.06593	0.47372	0.64000	0.16628	0.15828
81	0.9997	0.0021	-0.05898	0.47648	0.64800	0.17152	0.16352
82	0.9997	0.0021	-0.05898	0.47648	0.65600	0.17952	0.17152
83	0.9997	0.0021	-0.05898	0.47648	0.66400	0.18752	0.17952
84	0.9997	0.0021	-0.05898	0.47648	0.67200	0.19552	0.18752
85	0.9999	0.0018	-0.02249	0.49103	0.68000	0.18897	0.18097
86	0.9999	0.0020	-0.01901	0.49241	0.68800	0.19559	0.18759
87	1.0001	0.0018	0.00706	0.50282	0.69600	0.19318	0.18518
88	1.0005	0.0018	0.07309	0.52913	0.70400	0.17487	0.16687
89	1.0005	0.0018	0.07309	0.52913	0.71200	0.18287	0.17487
90	1.0006	0.0005	0.08870	0.53534	0.72000	0.18466	0.17666
91	1.0008	0.0050	0.12870	0.55120	0.72800	0.17680	0.16880
92	1.0016	0.0041	0.27642	0.60889	0.73600	0.12711	0.11911
93	1.0017	0.0041	0.28511	0.61222	0.74400	0.13178	0.12378
94	1.0022	0.0040	0.37200	0.64505	0.75200	0.10695	0.09895
95	1.0025	0.0040	0.43283	0.66743	0.76000	0.09257	0.08457
96	1.0026	0.0040	0.44499	0.67184	0.76800	0.09616	0.08816
97	1.0027	0.0040	0.45715	0.67622	0.77600	0.09978	0.09178
98	1.0029	0.0041	0.50060	0.69167	0.78400	0.09233	0.08433
99	1.0030	0.0038	0.50755	0.69412	0.79200	0.09788	0.08988
100	1.0031	0.0040	0.52493	0.70018	0.80000	0.09982	0.09182

Case #	k_{adj}	σ_{com}	z_i	F(z)	G(z)	$ F^*(z_i)-G(z_i) $	$ F^*(z_i)-G(z_{i-1}) $
101	1.0032	0.0040	0.54057	0.70560	0.80800	0.10240	0.09440
102	1.0034	0.0040	0.58575	0.72098	0.81600	0.09502	0.08702
103	1.0036	0.0038	0.61704	0.73139	0.82400	0.09261	0.08461
104	1.0036	0.0038	0.61704	0.73139	0.83200	0.10061	0.09261
105	1.0042	0.0040	0.71783	0.76357	0.84000	0.07643	0.06843
106	1.0044	0.0039	0.74737	0.77258	0.84800	0.07542	0.06742
107	1.0044	0.0039	0.74911	0.77310	0.85600	0.08290	0.07490
108	1.0045	0.0039	0.76649	0.77831	0.86400	0.08569	0.07769
109	1.0046	0.0038	0.78213	0.78293	0.87200	0.08907	0.08107
110	1.0046	0.0039	0.78213	0.78293	0.88000	0.09707	0.08907
111	1.0046	0.0040	0.78734	0.78446	0.88800	0.10354	0.09554
112	1.0048	0.0039	0.82731	0.79597	0.89600	0.10003	0.09203
113	1.0060	0.0039	1.03933	0.85067	0.90400	0.05333	0.04533
114	1.0068	0.0039	1.16793	0.87858	0.91200	0.03342	0.02542
115	1.0069	0.0039	1.18704	0.88239	0.92000	0.03761	0.02961
116	1.0072	0.0039	1.24265	0.89300	0.92800	0.03500	0.02700
117	1.0074	0.0039	1.26872	0.89773	0.93600	0.03827	0.03027
118	1.0131	0.0029	2.26133	0.98813	0.94400	0.04413	0.05213
119	1.0138	0.0039	2.38962	0.99157	0.95200	0.03957	0.04757
120	1.0157	0.0041	2.72329	0.99677	0.96000	0.03677	0.04477
121	1.0169	0.0042	2.91966	0.99825	0.96800	0.03025	0.03825
122	1.0170	0.0042	2.94573	0.99839	0.97600	0.02239	0.03039
123	1.0182	0.0042	3.16122	0.99921	0.98400	0.01521	0.02321
124	1.0185	0.0041	3.20814	0.99933	0.99200	0.00733	0.01533
125	1.0197	0.0041	3.40799	0.99967	1.00000	0.00033	0.00767
Lilliefors Test Results							
$\bar{k} = 1.0000$	$s = 0.0058$	$n=125$	$w_{1-\alpha}=0.07925$		$\text{Max } T^*=0.19559$		
<p>$T^* > w_{1-\alpha}$ therefore these cases are probably <i>not</i> from a normal distribution. As such the nonparametric method is used to define the bias as described in Section 5.4.1.</p>			<p>$k_1=0.9804$; $\sigma_1=0.0006$ $\beta = 99.99\%$; NPM (125) = 0 (Table 2.2, NUREG/CR-6698, Ref. [3]) Bias = 0.9804 – 0.0006 Bias = 0.9798</p>				

13. ATTACHMENT E – NORMAL PLOT FIGURES

The following figure is the normal probability plot of results identified in Section 6.1.

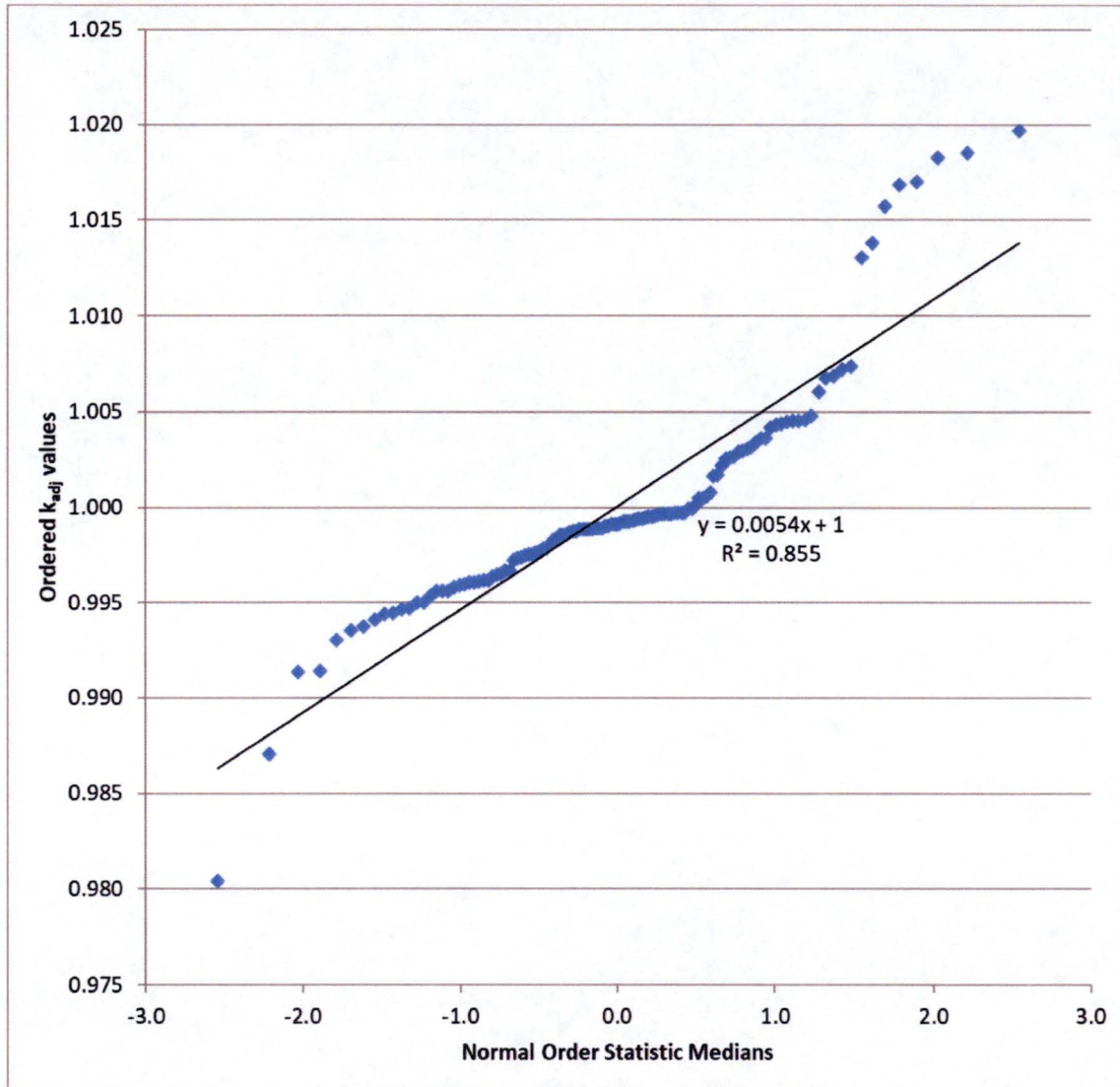


Figure 1: Normal Probability Plot for LEU k_{adj} Results

14. ATTACHMENT F – TREND ANALYSIS FIGURES

The following figures present the results of the trend analysis performed on the k_{adj} values over the range of ANECF and enrichment. The data is fitted to a linear, a 3rd order polynomial, and a power function. The best fit of these functions is shown in the figures along with the determined value of R^2 .

The largest R^2 value was 0.2 for the k_{adj} vs. enrichment data fitted to a 3rd order polynomial. None of the data resulted in a R^2 value greater than 0.8 which indicates that none of the data demonstrated a good correlation with the various assumed functions. Therefore, none of the data is considered to demonstrate any significant or relevant trend that would need to be compensated for in the bias.

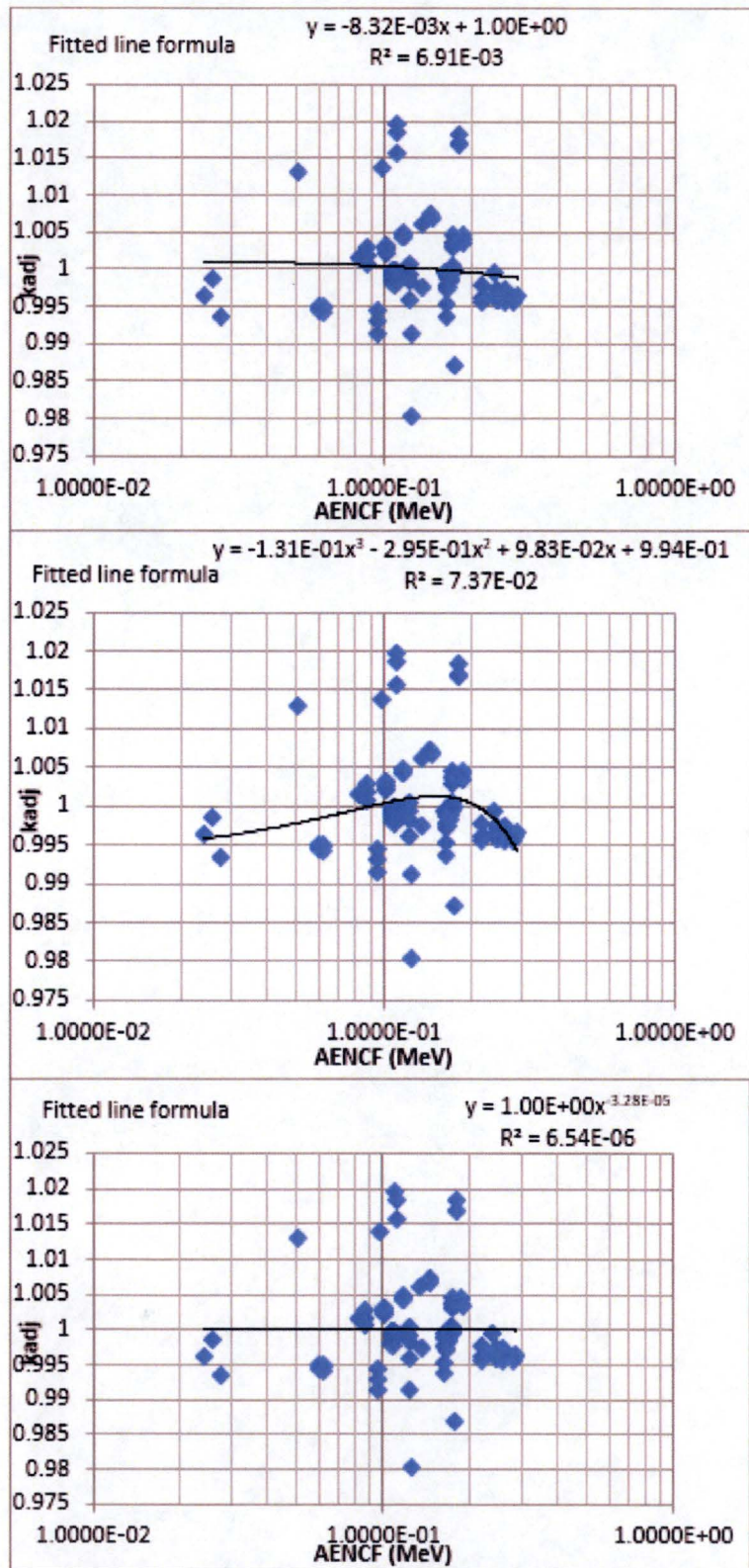


Figure 2: ANECF Trend Analysis Plots for LEU

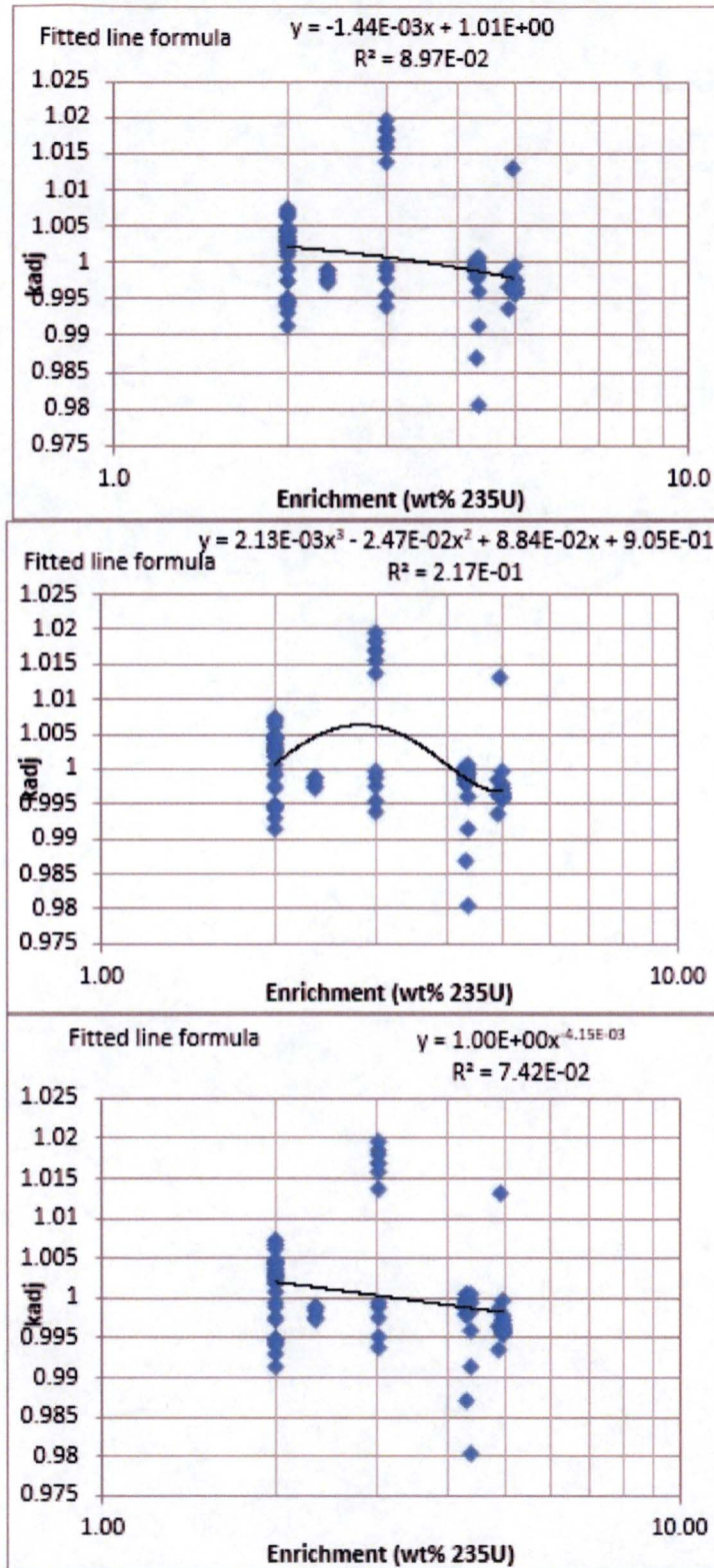


Figure 3: Enrichment Trend Analysis Plots for LEU