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REVISION HISTORY

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0		Initial issue

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1. Introduction

This report summarizes the previous work done to validate and verify the criticality calculations of MCNP6 (including Version 1.0). MCNP6 performs criticality calculations when the criticality source (KCODE) card [LA-CP-13-00634; Sec. 3.3.4.9] is included in the MCNP6 input deck. When invoked the KCODE card instructs MCNP6 to determine the effective multiplication factor (k_{eff}) for the modeled configuration. The KCODE card also specifies the initial neutron source for the criticality calculation. The most comprehensive documentation for verification and validation (V&V) testing for criticality calculations using the KCODE option in MCNP6 is:

- LA-UR-13-00019, *MCNP6 Release 1.0: Verification & Validation Testing*, HTML included in the MCNP6 Release 1.0 documentation collection on Disk 1, L. J. Cox[1]

This HTML document has test results for four test suites related to criticality calculations:

1. *Criticality Verification Suite*
2. *Criticality Validation Suite*
3. *Expanded Criticality Validation Suite*
4. *SB-CS Criticality Test Suite*

Some of this V&V testing for MCNP6 Version 1.0 is also reported in:

- LA-UR-13-22196, *Verification of MCNP5-1.6 and MCNP6.1 for Criticality Safety Applications*

- LA-UR-13-24008, *MCNP6™ Release 1.0: Creating and Testing the Code Distribution*

- LA-UR-14-22480, *Verification of MCNP 6.1 and MCNP6.1.1 for Criticality Safety Applications*

This report also documents the contents of the installation testing of MCNP6 for criticality safety calculations. In the future, the installation tests will also be used as in-use testing of MCNP6 by the LANL Nuclear Criticality Safety (NCS) Division. The in-use tests will be identical to the installation tests.

This document was written to support the Software Quality Management of MCNP6 by the LANL NCS Division.

2. Verification and Validation Testing

The "correctness" of a computer code is traditionally discussed in terms of the verification and validation processes. The definitions of these terms, as used by the MCNP6 developers, are [LA-UR-13-00019]:

Verification (functionality)	Involves performing a series of calculations to determine whether a code faithfully solves the equations and physical models it was designed to solve.

[1] The HTML document does not include the LA-UR number, however, LA-UR-13-24008 references this HTML as LA-UR 13-00019. On systems with the MCNP6 package installed, the HTML document is entered via file `VnV.htm` in the directory `MCNP_DOCS\MCNP6_VnV\VnVTop`.

Validation (suitability)	Involves a determination of whether the code sufficiently reproduces reality for a particular range of applications of interest.

Verification may involve comparison to other codes, to analytic benchmarks, or to experiments. Validation may involve assessing the verification problems (to ensure that the end-user application is bounded), comparing calculations to relevant experiments, or performance of scoping studies (to ensure that parameter changes produce expected changes in results).

To calculate the random walk of particles and to calculate k_{eff}, MCNP6 relies on the nuclear cross section libraries. A discrepancy in the nuclear data from the actual behavior of a material will be reflected in the MCNP6 results. Therefore, comparing MCNP6 results to experimental measurements is a test of both the software code and the data library. Because differences between MCNP6 results and experimental measurements will occur due to discrepancies in the cross section data, the benchmark suites cannot be an absolute measure of code correctness.

Development of the ENDF/B and MCNP6 nuclear data involves substantial effort separate from the MCNP6 algorithms and coding. A couple of the recent publications for the nuclear data are:

- LA-UR-12-26307, *V&V of MCNP and Data Libraries at Los Alamos*, 2012
- LA-UR-12-20002, *LANL Data Testing Support for ENDF/B-VII.1*, 2012

Additional references can be found on the mcnp.lanl.gov website. However, this report focuses on the V&V of MCNP6 with incidental inclusion of any nuclear data used; the report will not include any testing specific to only the nuclear data.

The stochastic processes in MCNP6 will also generate differences with the benchmark measurements. If the code and data were both perfect, the MCNP6 differences observed with a large number of benchmark measurements (in number of standard deviations) would form a normal distribution. Because it is known that the cross section data is not perfect, the distribution is expected to be only approximately normal.

Additionally, neutron transport methods, such as MCNP6, are never used in a nuclear criticality safety analysis without knowing and accounting for the bias[2] and bias uncertainty[3]. Analysts must determine the upper subcritical limit (USL), a limit on the calculated k_{eff} value to ensure that conditions calculated to be subcritical will actually be subcritical. Therefore, the differences between the MCNP6 results and the relevant benchmark measurements, similar to the V&V test results below, are incorporated into criticality safety analyses. See Section 2.6.1 below for additional information.

Unless otherwise noted, the following (Section 2) information is from LA-UR-13-00019 (i.e., the HTML included in the MCNP6 Release 1.0 documentation collection on Disk 1).

[2] Bias: The systematic difference between calculated results and experimental data somewhat analogous to accuracy.

[3] Bias uncertainty: An estimate attached to a calculated quantity, which characterizes the range of values within which the true value is asserted to lie. This estimation of error contains all known sources of error as well as the error from unknown and/or systemic sources of error. Some sources of bias uncertainty are discrepancies in the real world benchmark from the modeled version, errors in the calculational method, differences in measured cross sections and many other sources. Bias uncertainty is somewhat analogous to precision.

2.1 Criticality Verification Suite

The analytic eigenvalue (k_{eff}) and eigenfunction (flux) solutions to 75 neutron transport equation problems were published in LA-UR-01-03082. The scope of the suite includes the following aspects:

1. Geometry
    a. Infinite
    b. Slab
    c. Cylindrical
    d. Spherical
2. Composition – 1, 2 and 4 materials
3. Scattering Types
    a. Isotropic
    b. Linearly anisotropic
    c. Quadratically anisotropic
4. Energy Groups – 1, 2, 3 and 6 groups

The purpose of the *Criticality Verification Test Suite* (VERIFICATION_KEFF in LA-UR-13-24008) is to verify that transport algorithms and codes can correctly calculate the analytic k_{eff} (and fluxes). MCNP6 inputs were developed using the detailed descriptions found in LA-UR-01-3082. For these verification tests, the cross sections are known precisely. Therefore, any differences between the analytical solution and MCNP6 results cannot be attributed to the cross sections.

The k_{eff} results calculated with MCNP6 were compared to the published analytic results (see Appendix A - Criticality Verification Results). The following table summarizes this comparison.

Criticality Verification Suite Summary Results

Difference	Number of Test Problems	Percentage
< 0.001%	11	14.67
< 1 std. dev.	35	46.67
1 – 2 std. dev.	17	22.67
2 – 3 std. dev.	6	8.00
> 3 std. dev.	6	8.00

LA-UR-08-0567 identifies four problems which have negative values in the scattering probability density function (PDF): 34, 37, 43, and 71. However, negative scattering probabilities are unrealistic and MCNP6 cannot model a PDF with negative values. The ad hoc fix used in the verification tests was to set the PDF negative values to zero and renormalize the positive portion of the PDF. Consequently, the MCNP6 model is a poor simulation of the original analytical problem. These four problems are among the six problems that have a difference greater than 3 standard deviations in Appendix A. However, the differences between the analytical and MCNP6 results are due not to errors in the code, but rather to the different scattering PDFs.

Criticality Verification Suite Problems with Negative Scattering Probabilities

Problem	Identifier Material	Σ_{s0} and Σ_{s1} [LA-UR-01-3082]	Scattering P_1 Equation[4] and Extreme Negative Value
34	PUb-1-1-SL Pu-239 (b)	0.733333 0.333333 [Table 21]	$\Sigma_s(\mu) = \frac{1}{4\pi}[0.733333 + \mu]$ $\Sigma_s(-1) = -0.266667/4\pi$
37	Ub-1-1-CY U-235 (b)	0.248064 0.212160 [Table 23]	$\Sigma_s(\mu) = \frac{1}{4\pi}[0.248064 + 0.636480\mu]$ $\Sigma_s(-1) = -0.38842/4\pi$
43	UD2Oc-1-1-SP U-D_2O (c)	0.464338 -0.27850447 [Table 25]	$\Sigma_s(\mu) = \frac{1}{4\pi}[0.464338 - 0.83551341\,\mu]$ $\Sigma_s(1) = -0.3711754/4\pi$
71	URRa-2-1-SL (fast group)	0.62568 0.27459 [Table 49]	$\Sigma_s(\mu) = \frac{1}{4\pi}[0.62568 + 0.82377\mu]$ $\Sigma_s(-1) = -0.19809/4\pi$
	(slow group)	2.44383 0.83318 [Table 50]	$\Sigma_s(\mu) = \frac{1}{4\pi}[2.44383 + 2.9954\mu]$ $\Sigma_s(-1) = -0.05571/4\pi$

Because of this disparity between the analytical problem and the MCNP6 model, these four problems are removed from consideration in this report. The revised summary is:

Criticality Verification Suite Summary Results
with Negative Scattering Probability Problems Removed

Difference	Number of Test Problems	Percentage
< 0.001%	11	15.49
< 1 std. dev.	35	49.30
1 – 2 std. dev.	17	23.94
2 – 3 std. dev.	6	8.45
> 3 std. dev.	2	2.82

The proportion of cases within 2 standard deviations[5] of the analytical result is 88%. This result is sufficiently close to the proportion predicted by the normal distribution (95.45%) that this test suite indicates that MCNP6 V1.0 is properly calculating k_{eff}.

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[4] Using equation 9 in LA-UR-01-3082.
[5] Two standard deviations are used here because nuclear criticality analyses typically add two standard deviations to the calculated MCNP6 k_{eff} results before a comparison is made to the USL. This is a common practice used to conservatively bound any statistical uncertainty present in the Monte Carlo calculation.

2.2 Criticality Validation Suite

This *Criticality Validation Suite* consists of 31 benchmarks taken from the International Criticality Safety Benchmark Evaluation Project (ICSBEP). Calculated k_{eff} values from MCNP6 are compared to values taken from the ICSBEP. The original documentation for this validation suite is LA-UR-02-0878. When the *Criticality Validation Suite* was developed (up to 2002), ICSBEP was in its early formative stage; hence many of the *Criticality Validation Suite* problems may differ from the current ICSBEP model (private communication from F. Brown).

This suite contains cases for a variety of fuels, including:

- ^{233}U,
- highly enriched uranium (HEU),
- intermediate-enriched uranium (IEU),
- low-enriched uranium (LEU), and
- plutonium.

These fuels are in many different configurations that produce fast, intermediate, and thermal spectra. The fast-spectrum cases include bare spheres, cores reflected by a heavy material (normal U), and cores reflected by a light material (Be or water). The thermal-spectrum cases include lattices of fuel pins as well as homogeneous solutions. The number of experiments with intermediate spectra is much more limited, and those cases were chosen primarily for availability rather than specific attributes. All of the cases are at room temperature and pressure.

The selected benchmarks are listed in Appendix B - Criticality Validation. The k_{eff} results calculated with MCNP6 and the ENDF/B-VII data libraries were compared to the benchmark results (see Appendix B - Criticality Validation). The following table summarizes this comparison.

Criticality Validation Suite Summary Results

Difference	Number of Test Problems	Percentage
< 1 std. dev.	20	64.5
1 – 2 std. dev.	10	32.3
2 – 3 std. dev.	-	-
> 3 std. dev.	1	3.2

The proportion of cases within 2 standard deviations[6] of the analytical result is 96.8%. This result is sufficiently close to (and exceeds) the proportion predicted by the normal distribution (95.45%). Furthermore, in nuclear criticality safety analyses, MCNP6 is used in conjunction with USLs. These USLs quantitatively include the bias and bias uncertainty between MCNP6 and the relevant benchmark experiments; benchmark experiments of the kind used in this validation suite. Based on the favorable comparison of MCNP6 to this test suite and the inclusion of benchmark bias and bias uncertainty in the USLs, MCNP6 is an acceptable neutron transport method for nuclear criticality safety analyses.

[6] Two standard deviations are used here because nuclear criticality analyses typically add two standard deviations to the calculated MCNP6 k_{eff} results before a comparison is made to the USL. This is a common practice used to conservatively bound any statistical uncertainty present in the Monte Carlo calculation.

Along with being old, the *Criticality Validation Suite* is rather small, with only 31 test problems. When the test problems are categorized by principal fuel and energy spectra, as in the following table, the number of test problems in each category is very small. (It is not possible to have a critical assembly of low-enriched uranium (LEU) operating in the fast or intermediate energy ranges.)

Spectral Distribution of Benchmarks in the Criticality Validation Suite

Principal Fuel	Number of Benchmarks			
	Fast	Intermediate	Thermal	Total
^{233}U	3	1	2	6
HEU	4	2	2	8
IEU	3	1	2	6
LEU	N/A	N/A	2	2
Plutonium	6	1	2	9
Total	16	5	10	31

2.2.1 Comparison to the Expanded Criticality Validation Suite

The test cases in the *Criticality Validation Suite* are also used by the *Expanded Criticality Validation Suite*, with the following exceptions and notes/explanations:

1. Although the *Criticality Validation Suite* and the *Expanded Criticality Validation Suite* both model benchmark heu-met-fast-004, the *Criticality Validation Suite* (case GODIVR) corresponds to the 1-D idealization and the *Expanded Criticality Validation Suite* corresponds to the 3-D idealization.

    a. In the *Criticality Validation Suite*, the input model matches the description of the "one-dimensional" idealization: the experiment consists of the sphere of HEU suspended in the center of a sphere of water [2014 ICSBEP Handbook; HEU-MET-FAST-004; pg. 9]. Consequently, the benchmark for GODIVR is 0.9985 [2014 ICSBEP Handbook; HEU-MET-FAST-004; Table 11].

    b. In the *Expanded Criticality Validation Suite*, the input model matches the description of the "three-dimensional" idealization: the experiment contains only the sphere of HEU, the seat of the stand (represented by a flattened, hollow cylinder with the same outer radius and volume as the actual stand), and the cylinder of water [2014 ICSBEP Handbook; HEU-MET-FAST-004; pg. 13]. Consequently, the benchmark In the *Expanded Criticality Validation Suite* is 1.0020 [2014 ICSBEP Handbook; HEU-MET-FAST-004; Table 11].

2. Benchmark ieu-met-fast-007 is in the *Criticality Validation Suite* as case BIG TEN. But benchmark ieu-met-fast-007 is not in the *Expanded Criticality Validation Suite*, except as the new, unapproved benchmark ieu-met-fast-007 case 4.

a. The benchmark results listed for case BIG TEN do not match the ieu-met-fast-007 results in the 2014 ICSBEP Handbook, shown below.

	k_{eff}
Experimental	1.0062 ± 0.0003
Detailed Benchmark Model	1.0045 ± 0.0007
Improved Simplified Benchmark Model	1.0049 ± 0.0008

3. Benchmark mix-met-fast-008 case 7 is included in both the *Criticality Validation Suite* (case Zebra-8H) and the *Expanded Criticality Validation Suite*, but the listed benchmark k_{eff} values are 1.0300 (± 2.5e-03) and 1.0030 (± 2.5e-03), respectively. The 2014 ICSBEP Handbook, through a reference and link to *K-Infinity Measurements in Zebra Core 8*, gives an experimental k_{eff} = 1.0300 ± 0.0024 for case 7 (Core 8H), indicating the *Criticality Validation Suite* is correct.

4. Benchmark leu-sol-therm-007 case 36 is included in both the *Criticality Validation Suite* (case STACY36) and the *Expanded Criticality Validation Suite*, but the listed benchmark k_{eff} uncertainty values are 1.3e-03 and 1.1e-03, respectively. The 2014 ICSBEP Handbook has 0.0011 as the benchmark k_{eff} uncertainty for this case, indicating the *Expanded Criticality Validation Suite* is correct.

5. Benchmark leu-comp-therm-008 case 2 is included in both the *Criticality Validation Suite* (case B&W XI-2) and the *Expanded Criticality Validation Suite*, but the listed benchmark k_{eff} uncertainty values are 1.2e-03 and 1.6e-03, respectively. The 2014 DICE database has 0.0012 as the benchmark k_{eff} uncertainty for this case, indicating the *Criticality Validation Suite* is correct.

Therefore, requiring both the *Criticality Validation Suite* and the *Expanded Criticality Validation Suite* for software testing purposes would be redundant. The *Expanded Criticality Validation Suite* is the more recent and modern test suite.

2.3 Expanded Criticality Validation Suite

The *Expanded Criticality Validation Suite* is thoroughly described in LA-UR-10-06230 and summarized in LA-UR-11-00240. This test suite consists of 118 benchmarks in the ICSBEP Handbook, plus one benchmark that has been submitted for inclusion but has not yet been approved (ieu-met-fast-007-case-4). Each test is named after the identifier for the benchmark evaluation in the ICSBEP Handbook from which it is taken. When an evaluation includes more than one case, the case number is appended to the identifier.

The tests in this *Expanded Criticality Validation Suite* are divided according to the isotope that produces the majority of fissions: ^{233}U, ^{235}U, or ^{239}Pu. The ^{235}U benchmarks are further subdivided by the fractional ^{235}U content in the uranium as HEU, IEU, or LEU. HEU contains 60 weight-percent ($^{w}/_{o}$) or more ^{235}U, and LEU contains 5$^{w}/_{o}$ or less[7]. IEU therefore contains between 5$^{w}/_{o}$ and 60$^{w}/_{o}$ ^{235}U. The ^{239}Pu category is generalized to include all plutonium isotopes and hereafter is referred to simply as plutonium (Pu).

[7] It should be noted that the expanded validation suite uses 5$^{w}/_{o}$ as the dividing line between LEU and IEU, whereas the Handbook uses 10$^{w}/_{o}$. The reason that 5$^{w}/_{o}$ was chosen is that it is the current enrichment limit for fuel used in commercial nuclear reactors in the United States. [LA-UR-10-06230; Sec. 1.2]

The *Expanded Criticality Validation Suite* follows the guidelines from the ICSBEP Handbook in classifying spectra as fast, intermediate, or thermal. Fast benchmarks are those in which the majority of fissions is caused by neutrons with energy greater than 100 keV, and thermal benchmarks are those in which the majority of fissions is caused by neutrons with energies less than 0.625 eV. Benchmarks with intermediate spectra therefore are those in which the majority of fissions are caused by neutrons with energies between 0.625 eV and 100 keV. The spectral distribution of the benchmarks in the expanded validation suite is summarized in the following table. (It is not possible to have a critical assembly of low-enriched uranium (LEU) operating in the fast or intermediate energy ranges.)

Spectral Distribution of Benchmarks in the Expanded Criticality Validation Suite

Principal Fuel	Number of Benchmarks			
	Fast	Intermediate	Thermal	Total
^{233}U	10	1	7	18
HEU	29	5	6	40
IEU	10	1	6	17
LEU	N/A	N/A	8	8
Plutonium	21	1	14	36
Total	70	8	41	119

[LA-UR-10-06230; Table 2]

The k_{eff} results calculated with MCNP6 were compared to the benchmark results (see Appendix C – Expanded Criticality Validation). The following table summarizes this comparison.

Expanded Criticality Validation Suite Summary Results

Difference	Number of Test Problems	Percentage
< 1 std. dev.	72	60.50
1 – 2 std. dev.	26	21.85
2 – 3 std. dev.	13	10.92
> 3 std. dev.	8	6.72

The proportion of cases within 2 standard deviations[8] of the analytical result is 82.4%. This result is sufficiently close to the proportion predicted by the normal distribution (95.45%). Furthermore, in nuclear criticality safety analyses, MCNP6 is used in conjunction with USLs. These USLs quantitatively include the bias and bias uncertainty between MCNP6 and the relevant benchmark experiments; benchmark experiments of the kind used in this validation suite. Based on the favorable comparison of MCNP6 to this test suite and the inclusion of benchmark bias and bias uncertainty in the USLs, MCNP6 is an acceptable neutron transport method for nuclear criticality safety analyses.

[8] Two standard deviations are used here because nuclear criticality analyses typically add two standard deviations to the calculated MCNP6 k_{eff} results before a comparison is made to the USL. This is a common practice used to conservatively bound any statistical uncertainty present in the Monte Carlo calculation.

2.4 SB-CS Criticality Test Suite

The *SB-CS Criticality Test Suite* consists of 194 ICSBEP criticality benchmark problems from the LANL Safety Basis Criticality Safety (SB-CS) Group. This suite was created in 2007 to verify and validate MCNP5 on the Ganglion Cyst computer cluster using the ENDF/B-VI and ENDF/B-V nuclear data libraries[9] [NCS-TECH-07-002].

The k_{eff} results calculated with MCNP6 were compared to the benchmark results (see Appendix D – SB-CS Criticality Test Suite). The following table summarizes this comparison.

SB-CS Criticality Validation Suite Summary Results

Difference	Number of Test Problems	Percentage
< 1 std. dev.	93	47.94
1 – 2 std. dev.	45	23.20
2 – 3 std. dev.	21	10.82
> 3 std. dev.	35	18.04

The proportion of cases within 2 standard deviations of the analytical result is 71.1%. The *SB-CS Validation Suite* is further from the normal distribution[10] than the previous test suites. This indicates that these results are strongly influenced by something other than random behavior. Although this test suite was included in LA-UR-13-00019, it would be difficult to justify the verification and validation of MCNP6 with the *SB-CS Validation Suite*. Fortunately, the USLs used in nuclear criticality safety analyses quantitatively include the bias and bias uncertainty between MCNP6 and the relevant benchmark experiments; benchmark experiments of the kind used in this validation suite.

2.5 Comparison

If the differences between the computational and reference k_{eff} were solely due to random factors, the differences would follow a normal distribution. Figure 1 compares the results for the four test suites against the cumulative probability distribution. The *Criticality Validation Suite* is the closest to the cumulative probability distribution; although it has the abnormal behavior of no results between 2 and 3 standard deviations from the reference values. The *Expanded Criticality Validation Suite* and *Criticality Verification Suite* are the next closest to the cumulative probability distribution, although the *Expanded Criticality Validation Suite* is ~13% less so than the cumulative probability distribution at two standard deviations. The *SB-CS Validation Suite* is furthest from the cumulative probability distribution; the indication is that these results are strongly influenced by something other than random behavior. The SB-CS Validation Suite has the general shape of the cumulative probability distribution but is considerably offset (~20%); as stated in Section 2.4 above, it would be difficult to justify the verification and validation of MCNP6 with the *SB-CS Validation Suite.*

[9] ENDF/B-VI and ENDF/B-V are older nuclear data libraries and are generally superceded by the newer, more accurate ENDF libraries.
[10] The normal distribution would have 68.3%, 95.5%, and 99.7% of the results within 1, 2, and 3 standard deviations, respectively.

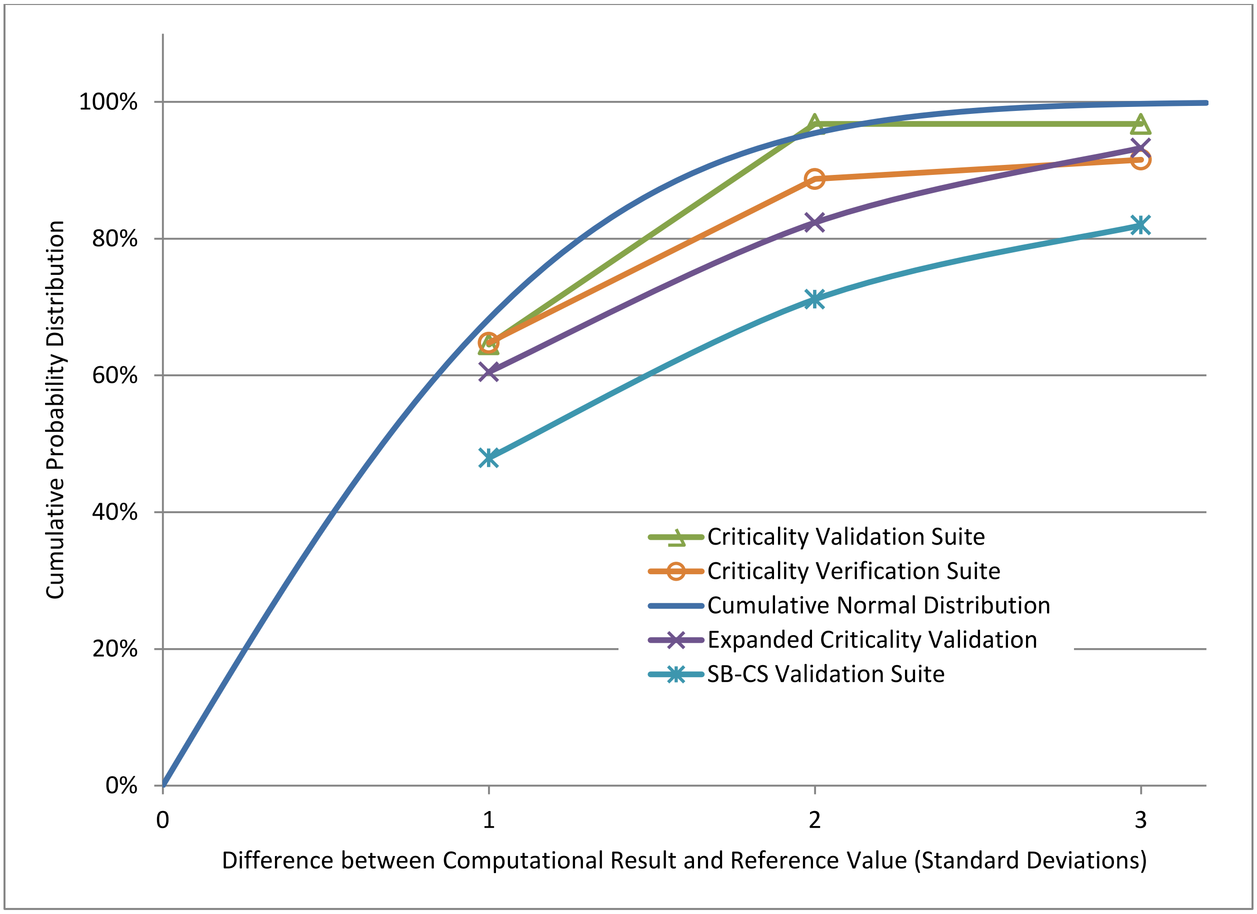

Figure 1 – Distribution of Test Suite Results

2.6 Conclusions

The general conclusion from this testing is MCNP6 V1.0 performs correctly for criticality safety applications [LA-UR-13-22196; Sec. IV] [LA-UR-14-22480; Sec. VII]. For each test suite, the majority of the calculated k_{eff} values are within two standard deviations of the analytical result.

2.6.1 Application of MCNP6 in Nuclear Criticality Safety Analyses

Although the conclusion of the V&V efforts is that MCNP6 V1.0 performs correctly for criticality safety applications, the differences between calculated results and experimental data is not ignored in Nuclear Criticality Safety analyses. For NCS analyses, computer code systems (hardware and software) must be validated according to the following standards:

- ANSI/ANS-8.1, *Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors*
- ANS/ANS-8.24, *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations*

In these standards, validation is the "process of quantifying (e.g., establishing the appropriate bias and bias uncertainty) the suitability of a computer code system for use in nuclear criticality safety analyses." This validation includes determining the calculational margin: an allowance for bias and bias uncertainty plus considerations of uncertainties related to interpolation, extrapolation, and trending. The calculational margin is used to determine the USL, a limit on the calculated k-effective value established to ensure modeled conditions calculated to be subcritical will actually be subcritical in the real world with a very high degree of confidence.

3. NCS Installation Test Suite

The NCS installation test suite for MCNP6 Version 1.0 consists of the regression test suite and ten of the *Criticality Verification Test Suite* cases. The results of the MCNP6 installation tests shall be documented in a separate report (e.g., NCS-SQM-MCNP6-INSTALL).

3.1 Regression Test Suite

The regression test suite contains 147 problems [LA-UR-13-24008], including twenty-one (21) input decks performing criticality (KCODE) calculations. Due to continuation input decks and duplication, there are fifteen (15) unique criticality problems listed below. The regression tests do not verify code correctness; they are used only for detecting unintended changes to the code and for installation testing [LA-UR-12-26631; Sec. VI.L].

Test Problem #9 and #26

Test problem #9 is a KCODE calculation with complicated cells and source definition (sdef). Comments indicate this input file tests a previous bug in MCNP4.2 (trouble with rotating a cone). The fissile material is ^{235}U but an older library (50d) is specified. Test problem #26 runs a continuation of problem #26.

Test Problem #17 and #123

Test problem #17 is a KCODE calculation with a rectangular finite lattice. Comments indicate this input file tests a previous bug in MCNP4.2 (finite lattice fails in MCNP4.2). The fissile material is ^{235}U but an older library (50m) is specified. Except for one additional tally, test problem #123 is identical to test problem #17.

Test Problem #18

Test problem #18 is a KCODE calculation with a hexagonal prism lattice. The fissile material is ^{235}U but an older library (50d) is specified.

Test Problem #24 and # 25

Test problem #24 is a KCODE calculation with a reflecting lattice (15×15 at 3.75 w/o U-235 enrichment). The fissile material is ^{235}U but an older library (50d) is specified. Comments indicate this input file tests a previous bug in MCNP4.2 (heating in cells with void material causes a fatal error). Test problem #25 runs a continuation of problem #24.

Test Problem #32

Test problem #32 is a KCODE calculation with a modified BIG TEN model. The fissile material is ^{235}U but an older library (50d) is specified.

Test Problem #42

Test problem #42 is a KCODE calculation with the GODIVA reactor separated into two regions. The input deck also tests tally perturbations by the differential operator technique. The fissile material is ^{235}U with the default library.

Test Problem #108

Test problem #108 is a KCODE calculation whose purpose is to test the stochastic geometry for HTGRs (URAN card). The fissile material is ^{235}U with the default library.

Test Problem #111 and #112

Test problem #111 and #112 are KCODE calculation with the GODIVA reactor. The outer surface radius and the material is similar to, but not identical to, test problem #42. The input decks also test other aspects of MCNP, e.g., very large identifying numbers for cells, surfaces, and materials. The fissile material is ^{235}U with the default library.

Test Problem #113

Test problem #113 and #114 are KCODE calculations to test the kinetics parameters. The fissile material is ^{235}U with the default library.

Test Problem #115

Test problem #115 is a KCODE calculation of coupled spheres with a deterministic transport sphere (DXT card). The fissile material is ^{239}Pu with the default library.

Test Problem #124

Test problem #124 is a KCODE and sensitivity coefficient calculation. The fissile material is ^{235}U with the default library.

Test Problem #125

Test problem #125 is a KCODE and adjoint-weighted perturbation calculation. The fissile material is ^{239}Pu with the default library.

Test Problem #1005

Test problem #1005 is a KCODE calculation of the GODIVA reactor (heu-met-fast-001) with an unstructured mesh. The fissile material is ^{235}U with the default library. Although this problem has same material composition and density as the GODIVA/heu-met-fast-001 cases in the *Criticality Validation Suite* and *Expanded Criticality Validation Suite*, the size of the reactor (sphere) is different.

Test Problem #1008 and #1009

Test problem #1008 is a KCODE calculation with an unstructured mesh. The fissile material is ^{235}U with the default library. Test problem #1009 runs a continuation of problem #1008.

Test Problem #1013

Test problem #1013 is a KCODE calculation of a simple rectangular lattice with an unstructured mesh. The fissile material is ^{235}U with the default library.

3.2 Ten Criticality Verification Test Cases

For criticality safety applications, ten of the *Criticality Verification Test Suite* cases have been adopted as installation test problems (in addition to the regression test problems). These ten cases are:

Case	Name	Analytic k_{eff}	MCNP6 V1.0 Benchmark		Difference (std. dev.)
			k_{eff}	Std. Dev.	
prob11	Ua-1-0-IN	2.25000	2.25000	0.00000	< 1
prob14	Ua-1-0-SP	1.00000	1.00006	0.00010	< 1
prob18	Uc-H2O(2)-1-0-SP	1.00000	1.00005	0.00011	< 1
prob23	UD2O-1-0-CY	1.00000	1.00000	0.00006	< 1
prob32	PUa-1-1-SL	1.00000	0.99995	0.00011	< 1
prob41	UD2Ob-1-1-SP	1.00000	1.00003	0.00007	< 1
prob44	PU-2-0-IN	2.68377	2.68377	0.00003	< 1
prob54	URRa-2-0-SL	1.00000	1.00007	0.00013	< 1
prob63	URRd-H2Ob(1)-2-0-ISLC	1.00000	0.99993	0.00006	1 – 2
prob75	URR-6-0-IN	1.60000	1.59999	0.00001	1 – 2

The MCNP developers have even automated the execution of these ten problems. The problems can be executed by the following command in the VERIFICATION_KEFF directory:

```
make ten
```

Note: For high performance computers with front-end and computational nodes (such as Moonlight and Luna), it may be inappropriate to execute this command on a front-end node.

4. NCS In-Use Test Suite

The NCS in-use test suite is identical to the NCS installation test suite. The methods and steps for performing the MCNP6 in-use testing, including record keeping, will be in a written procedure separate from this document.

5. References

ANSI/ANS-8.1-2014, *Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors*

ANS/ANS-8.24-2007, *Validation of Neutron transport Methods for Nuclear Criticality Safety Calculations*

J. B. Briggs (Ed.), "International Handbook of Evaluated Criticality Safety Benchmark Experiments", Nuclear Energy Agency, NEA/NSC/DOC(95)03/I, Paris, France (2004).

LA-CP-13-00634, Rev. 0, *MCNP6 User's Manual*, Version 1.0, May 2013

LA-UR-01-3082, *Analytical Benchmark Tests for Criticality Code Verification*[11]

LA-UR-02-0878, *Validation Suites for MCNP*

LA-UR-08-0567, *One-group MCNP5 Criticality Calculations with Anisotropic Scattering*

LA-UR-10-06230, *An Expanded Criticality Validation Suite for MCNP*

LA-UR-11-00240, *An Expanded Criticality Validation Suite for MCNP*

LA-UR-12-26631, *Initial MCNP6 Release Overview – MCNP6 Beta 3*

LA-UR-13-00019, *MCNP6 Release 1.0: Verification & Validation Testing*, HTML included in the MCNP6 Release 1.0 documentation collection on Disk 1, L. J. Cox[12]

LA-UR-13-22196, *Verification of MCNP5-1.6 and MCNP6.1 for Criticality Safety Applications*

LA-UR-13-24008, *MCNP6™ Release 1.0: Creating and Testing the Code Distribution*

LA-UR-14-22480, *Verification of MCNP 6.1 and MCNP6.1.1 for Criticality Safety Applications*

NCS-TECH-07-002, *Validation of MCNP5 on the Ganglion Cyst Computer cluster with various Cross-Section Libraries*, 18 September 2007

[11] Also published in *Progress in Nuclear Energy*, Vol. 42, No. 1, pp. 55-106, 2003

[12] LA-UR-13-24008 references this HTML as LA-UR 13-00019.

Appendix A - Criticality Verification Results

The following results tables list the case name (see LA-UR-01-3082 Section 1.3 for the algorithms used to generate the case names), the analytical solution for k_{eff}, and the k_{eff} calculated by MCNP6 Version 1.0. The next column (std) lists the standard deviation unless the "note" column is "diff", in which case the difference between the analytical and computational results is listed. The "note" column is explained in the table following the results tables. The appendix ends with a cross-reference table between the filename, case name, and description.

30 Tests for "1 Group, Isotropic"

case	Analytic keff	MCNP6		
		keff	std[13]	note
PUa-1-0-IN	2.6129	2.6129	3.0e-06	diff
PUa-1-0-SL	1.0000	0.9999	1.2e-04	
PUa-H2O(1)-1-0-SL	1.0000	1.0001	1.2e-04	*
PUa-H2O(0.5)-1-0-SL	1.0000	1.0001	1.3e-04	
PUb-1-0-IN	2.2903	2.2903	3.0e-06	diff
PUb-1-0-SL	1.0000	1.0000	1.1e-04	
PUb-1-0-CY	1.0000	0.9991	1.1e-04	***
PUb-1-0-SP	1.0000	0.9998	1.0e-04	*
PUb-H2O(1)-1-0-CY	1.0000	1.0000	1.1e-04	
PUb-H2O(10)-1-0-CY	1.0000	1.0000	1.1e-04	
Ua-1-0-IN	2.2500	2.2500	0.0e+00	diff
Ua-1-0-SL	1.0000	1.0000	1.1e-04	
Ua-1-0-CY	1.0000	1.0002	1.0e-04	*
Ua-1-0-SP	1.0000	1.0001	1.0e-04	
Ub-1-0-IN	2.3309	2.3309	2.6e-04	
Ub-H2O(1)-1-0-SP	1.0000	1.0001	1.3e-04	
Uc-1-0-IN	2.2561	2.2561	7.0e-06	diff
Uc-H2O(2)-1-0-SP	1.0000	1.0001	1.1e-04	
Ud-1-0-IN	2.2327	2.2327	7.0e-06	diff
Ud-H2O(3)-1-0-SP	1.0000	1.0000	1.1e-04	
UD2O-1-0-IN	1.1333	1.1333	3.0e-06	diff
UD2O-1-0-SL	1.0000	1.0001	6.0e-05	
UD2O-1-0-CY	1.0000	1.0000	6.0e-05	
UD2O-1-0-SP	1.0000	1.0001	6.0e-05	
UD2O-H2O(1)-1-0-SL	1.0000	1.0002	6.0e-05	**
UD2O-H2O(10)-1-0-SL	1.0000	1.0000	6.0e-05	
UD2O-H2O(1)-1-0-CY	1.0000	1.0000	6.0e-05	
UD2O-H2O(10)-1-0-CY	1.0000	0.9999	6.0e-05	*
Ue-1-0-IN	2.1807	2.1807	3.0e-06	diff

[13] Except when the note is "diff", in which case the difference between the analytical and computational results is listed.

Ue-Fe-Na-1-0-SL	1.0000	1.0000	1.1e-04	

14 Tests for "1 Group, Anisotropic"

case	Analytic keff	MCNP6		
		keff	std	note
PU-1-1-IN	2.5000	2.5000	0.0e+00	diff
PUa-1-1-SL	1.0000	1.0000	1.1e-04	
PUa-1-2-SL	1.0000	1.0002	1.1e-04	*
PUb-1-1-SL[14]	1.0000	1.0027	1.2e-04	***
PUb-1-2-SL	1.0000	1.0002	1.1e-04	*
Ua-1-1-CY	1.0000	1.0001	1.0e-04	*
Ub-1-1-CY[14]	1.0000	1.0620	1.0e-04	***
UD2Oa-1-1-IN	1.2056	1.2056	3.0e-06	diff
UD2Oa-1-1-SP	1.0000	1.0000	7.0e-05	
UD2Ob-1-1-IN	1.2274	1.2274	1.0e-06	diff
UD2Ob-1-1-SP	1.0000	1.0000	7.0e-05	
UD2Oc-1-1-IN	1.1309	1.1309	3.0e-06	diff
UD2Oc-1-1-SP[14]	1.0000	0.9968	6.0e-05	***
UD2O-2-1-IN[15]	1.0002	1.0002	9.0e-05	

26 Tests for "2 Group, Isotropic"

case	Analytic keff	MCNP6		
		keff	std	note
PU-2-0-IN	2.6838	2.6838	3.0e-05	
PU-2-0-SL	1.0000	1.0000	1.2e-04	
PU-2-0-SP	1.0000	0.9999	1.0e-04	*
U-2-0-IN	2.2163	2.2164	3.0e-05	**
U-2-0-SL	1.0000	1.0001	1.1e-04	*
U-2-0-SP	1.0000	1.0000	1.0e-04	
UAL-2-0-IN	2.6617	2.6624	4.0e-05	***
UAL-2-0-IN[16]	2.6624	2.6624	4.0e-05	*[17]
UAL-2-0-SL	1.0000	1.0000	2.1e-04	

[14] LA-UR-08-0567 explains that MCNP is incapable of modeling this analytical problem. The differences between the analytical result and MCNP6 are due not to errors in the code, but rather to difficulties with the negative values in the scattering probability density function.

[15] Case name from LA-UR-13-00019 was revised to be consistent with LA-UR-01-3082.

[16] LA-UR-13-00019 table value replaced with LA-UR-01-3082 reported result.

[17] With a standard deviation of 4.0e-05, the difference between the results (identical to four decimal places) will be within one or two standard deviations. Two standard deviations is conservatively assumed.

UAL-2-0-SP	1.0000	0.9997	2.2e-04	*
URRa-2-0-IN	1.6315	1.6315	1.0e-05	
URRa-2-0-SL	1.0000	1.0001	1.3e-04	
URRa-2-0-SP[18]	1.0000	1.0001	1.5e-04	
URRb-2-0-IN	1.3658	1.3658	1.0e-05	**
URRc-2-0-IN	1.6334	1.6334	1.0e-05	
URRb-H2Oa(1)-2-0-SL	1.0000	1.0000	1.0e-04	
URRb-H2Oa(5)-2-0-SL	1.0000	0.9998	9.0e-05	**
URRb-H2Oa(IN)-2-0-SL	1.0000	0.9999	1.0e-04	
URRc-H2Oa(IN)-2-0-SL	1.0000	0.9999	1.3e-04	
URRd-2-0-IN	1.0350	1.0350	2.0e-05	**
URRd-H2Ob(1)-2-0-ISLC	1.0000	0.9999	6.0e-05	*
URRd-H2Ob(10)-2-0-ISLC	1.0000	1.0002	5.0e-05	***
URRd-H2Oc(1)-2-0-ISLC	1.0000	1.0001	6.0e-05	
URRd-H2Oc(10)-2-0-ISLC	1.0000	1.0000	4.0e-05	
UD2O-2-0-IN	1.0002	1.0001	9.0e-05	*
UD2O-2-0-SL	1.0000	1.0002	1.0e-04	*
UD2O-2-0-SP	1.0000	1.0002	1.0e-04	*

3 Tests for "2 Group, Anisotropic"

case	**Analytic keff**	**MCNP6**		
		keff	**std**	**note**
URRa-2-1-IN	1.6315	1.6315	1.0e-05	
URRa-2-1-SL[19]	1.0000	1.0021	1.3e-04	***
UD2O-2-1-SL	1.0000	1.0002	1.0e-04	*

2 Tests for "Other, Isotropic"

case	**Analytic keff**	**MCNP6**		
		keff	**std**	**note**
URR-3-0-IN	1.6000	1.6000	1.0e-05	**
URR-6-0-IN	1.6000	1.6000	1.0e-05	*

[18] Case name from LA-UR-13-00019 was revised to be consistent with LA-UR-01-3082.
[19] LA-UR-08-0567 explains that MCNP is incapable of modeling this analytical problem. The differences between the analytical result and MCNP6 are due not to errors in the code, but rather to difficulties with the negative values in the scattering probability density function.

Notes

	LA-UR-13-00019 original text	**w/ Revised UAL-2-0-IN**
RMS difference	0.72 % for 75 completed tests	
	(35) differ by <1 std dev	(35) differ by <1 std dev
*	(16) differ by 1-2 std dev	(17) differ by 1-2 std dev
**	(6) differ by 2-3 std dev	(6) differ by 2-3 std dev
***	(7) differ by >3 std dev	(6) differ by >3 std dev
diff	(11) delta reported in std dev column	(11) delta reported in std dev column

LA-UR-01-3082 labels the benchmark problems with both a problem number and case name. (See LA-UR-01-3082 Section 1.3 for the algorithms used to generate the case names.) The tables above use the case name, but the computer files use the problem number. The following table is a cross-reference between the computer files (problem number) and the case name.

Filename	Case Name[20]	Description
prob01	PUa-1-0-IN	infinite sphere
prob02	PUa-1-0-SL	semi-infinite slab
prob03	PUa-H2O(1)-1-0-SL	semi_infinite slab and reflector
prob04	PUa-H2O(0.5)-1-0-SL	semi-infinite slab w/ reflectors on both sides
prob05	PUb-1-0-IN	infinite sphere
prob06	PUb-1-0-SL	semi-infinite slab
prob07	PUb-1-0-CY	semi-infinite cylinder
prob08	PUb-1-0-SP	sphere
prob09	PUb-H2O(1)-1-0-CY	semi-infinite cylinder with reflector
prob10	PUb-H2O(10)-1-0-CY	semi-infinite cylinder with reflector
prob11	Ua-1-0-IN	infinite sphere
prob12	Ua-1-0-SL	semi-infinite slab
prob13	Ua-1-0-CY	semi-infinite cylinder
prob14	Ua-1-0-SP	sphere
prob15	Ub-1-0-IN	infinite sphere
prob16	Ub-H2O(1)-1-0-SP	sphere with reflector
prob17	Uc-1-0-IN	infinite sphere
prob18	Uc-H2O(2)-1-0-SP	sphere with reflector
prob19	Ud-1-0-IN	infinite sphere
prob20	Ud-H2O(3)-1-0-SP	sphere with reflector

[20] The case names from file VERIFICATION_KEFF/README were corrected according to LA-UR-01-3082.

Filename	Case Name[20]	Description
prob21	UD2O-1-0-IN	infinite sphere
prob22	UD2O-1-0-SL	semi-infinite slab
prob23	UD2O-1-0-CY	semi-infinite cylinder
prob24	UD2O-1-0-SP	sphere
prob25	UD2O-H2O(1)-1-0-SL	semi-infinite slab w/ reflectors on both sides
prob26	UD2O-H2O(10)-1-0-SL	semi-infinite slab w/ reflectors on both sides
prob27	UD2O-H2O(1)-1-0-CY	semi-infinite cylinder with reflector
prob28	UD2O-H2O(10)-1-0-CY	semi-infinite cylinder with reflector
prob29	Ue-1-0-IN	infinite sphere
prob30	Ue-Fe-Na-1-0-SL	semi-infinite slab with moderator on one side and reflector on both
prob31	PU-1-1-IN	infinite sphere
prob32	PUa-1-1-SL	semi-infinite slab
prob33	PUa-1-2-SL	semi-infinite slab
prob34	PUb-1-1-SL	semi-infinite slab
prob35	PUb-1-2-SL	semi-infinite slab
prob36	Ua-1-1-CY	semi-infinite cylinder
prob37	Ub-1-1-CY	semi-infinite cylinder
prob38	UD2Oa-1-1-IN	infinite sphere
prob39	UD2Oa-1-I-SP	sphere
prob40	UD2Ob-1-1-IN	infinite sphere
prob41	UD2Ob-1-I-SP	sphere
prob42	UD2Oc-1-1-IN	infinite sphere
prob43	UD2Oc-1-I-SP	sphere
prob44	PU-2-0-IN	infinite sphere
prob45	PU-2-0-SL	semi-infinite slab
prob46	PU-2-0-SP	sphere
prob47	U-2-0-IN	infinite sphere
prob48	U-2-0-SL	semi-infinite slab
prob49	U-2-0-SP	sphere
prob50	UAL-2-0-IN	infinite sphere
prob51	UAL-2-0-SL	semi-infinite slab
prob52	UAL-2-0-SP	sphere

Filename	Case Name[20]	Description
prob53	URRa-2-0-IN	infinite sphere
prob54	URRa-2-0-SL	semi-infinite slab
prob55	URRa-2-0-SP	sphere
prob56	URRb-2-0-IN	infinite sphere
prob57	URRc-2-0-IN	infinite sphere
prob58	URRb-H2Oa(1)-2-0-SL	semi-infinite slab with reflector
prob59	URRb-H2Oa(5)-2-0-SL	semi-infinite slab with reflector
prob60	URRb-H2Oa(IN)-2-0-SL	semi-infinite slab with reflector
prob61	URRc-H2Oa(IN)-2-0-SL	semi-infinite slab with reflector
prob62	URRd-2-0-IN	infinite sphere
prob63	URRd-H2Ob(1)-2-0-ISLC	semi-infinite slab with reflector
prob64	URRd-H2Ob(10)-2-0-ISLC	semi-infinite slab with reflector
prob65	URRd-H2Oc(1)-2-0-ISLC	semi-infinite slab with reflector
prob66	URRd-H2Oc(10)-2-0-ISLC	semi-infinite slab with reflector
prob67	UD2O-2-0-IN	infinite sphere
prob68	UD2O-2-0-SL	semi-infinite slab
prob69	UD2O-2-0-SP	sphere
prob70	URRa-2-1-IN	infinite sphere
prob71	URRa-2-1-SL	semi-infinite slab
prob72	UD2O-2-1-IN	infinite sphere
prob73	UD2O-2-1-SL	semi-infinite slab
prob74	URR-3-0-IN	infinite sphere
prob75	URR-6-0-IN	infinite sphere

Appendix B - Criticality Validation

This appendix begins with a cross-reference table of case name, spectrum, identifier, and description. The results tables list the k_{eff} and standard deviation values from the benchmark experiment and calculated by MCNP6 Version 1.0. The notes in the results tables are explained by the last table in the appendix.

Case	Spectrum	Identifier	Description
Jezebel-233	Fast	U233-MET-FAST-001	Bare ^{233}U sphere
Flattop-23	Fast	U233-MET-FAST-006	Sphere of ^{233}U reflected by normal U
U233-MF-05	Fast	U233-MET-FAST-005,c2	Sphere of ^{233}U reflected by beryllium
Falstaff-1	Intmed	U233-SOL-INTER-001,c1	Sphere of uranyl fluoride solution enriched in ^{233}U
SB-2 1/2	Thermal	U233-COMP-THERM-001,c3	Lattice of ^{233}U fuel pins in water
ORNL-11	Thermal	U233-SOL-THERM-008	Large sphere of uranyl nitrate solution enriched in ^{233}U
Godiva	Fast	HEU-MET-FAST-001	Bare HEU sphere
Tinkertoy-2	Fast	HEU-MET-FAST-026,cC-11	3x3x3 array of HEU cylinders in paraffin box
Flattop-25	Fast	HEU-MET-FAST-028	HEU sphere reflected by normal U
Godivr	Fast	HEU-MET-FAST-004	HEU sphere reflected by water
Zeus-2	Intmed	HEU-MET-INTER-006,c2	HEU platters moderated by graphite and reflected by copper
UH3	Intmed	HEU-COMP-INTER-003,c6	UH3 cylinders reflected by depleted uranium
SB-5	Thermal	U233-COMP-THERM-001,c6	Lattice of HEU fuel pins in water, with blanket of ThO2 pins
ORNL-10	Thermal	HEU-SOL-THERM-032	Large sphere of HEU nitrate solution
IEU-MF-03	Fast	IEU-MET-FAST-003	Bare IEU sphere (36 wt.%)
BIG TEN	Fast	IEU-MET-FAST-007	Cylinder of IEU (10 wt.%) reflected by normal uranium

Case	Spectrum	Identifier	Description
IEU-MF-04	Fast	IEU-MET-FAST-004	Sphere of IEU (36 wt.%) reflected by graphite
Zebra-8H	Intmed	MIX-MET-FAST-008,c7	IEU (37.5 wt.%) reflected by normal U and steel
IEU-CT-02	Thermal	IEU-COMP-THERM-002,c3	Lattice of IEU (17 wt.%) fuel rods in water
STACY-36	Thermal	LEU-SOL-THERM-007,c36	Cylinder of IEU (9.97 wt.%) uranyl nitrate solution
B&W XI-2	Thermal	LEU-COMP-THERM-008,c2	Large lattice of LEU (2.46 wt.%) fuel pins in borated water
LEU-ST-02	Thermal	LEU-SOL-THERM-002,c2	Sphere of LEU (4.9 wt.%) uranyl fluoride solution
Jezebel	Fast	PU-MET-FAST-001	Bare plutonium sphere
Jezebel-240	Fast	PU-MET-FAST-002	Bare plutonium sphere (20.1 atom% ^{240}Pu)
Pu Buttons	Fast	PU-MET-FAST-003,c103	3 x 3 x 3 array of small cylinders of plutonium
Flattop-Pu	Fast	PU-MET-FAST-006	Plutonium sphere reflected by normal U
THOR	Fast	PU-MET-FAST-008[21]	Plutonium sphere reflected by thorium
PU-MF-11	Fast	PU-MET-FAST-011	Plutonium sphere reflected by water
HISS/HPG	Intmed	PU-COMP-INTER-001	Infinite, homog. mixture of plutonium, hydrogen, & graphite
PNL-33	Thermal	MIX-COMP-THERM-002,c4	Lattice of mixed-oxide fuel pins in borated water
PNL-2	Thermal	PU-SOL-THERM-021,c3	Sphere of plutonium nitrate solution

[21] Benchmark identifier corrected according to the DICE database and the description.

8 Tests for "HEU Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
GODIVA	1.0000	1.0e-03	0.9995	5.9e-04	
TT2C11	1.0000	3.8e-03	1.0008	7.2e-04	
FLAT25	1.0000	3.0e-03	1.0034	6.6e-04	
GODIVR[22]	0.9985	1.1e-03	0.9990	6.9e-04	
UH3C6	1.0000	4.7e-03	0.9950	8.1e-04	
ZEUS2	0.9997	8.0e-04	0.9972	7.4e-04	*
SB5RN3	1.0015	2.8e-03	0.9985	1.3e-03	
ORNL10	1.0015	2.6e-03	0.9993	3.7e-04	

6 Tests for "IEU Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
IMF03	1.0000	1.7e-03	1.0029	5.9e-04	*
BIGTEN[23]	0.9948	1.3e-03	0.9945	4.7e-04	
IMF04	1.0000	3.0e-03	1.0067	6.5e-04	*
ZEBR8H	1.0300	2.5e-03	1.0195	5.3e-04	***
ICT2C3	1.0017	4.4e-03	1.0037	7.0e-04	
STACY36	0.9988	1.3e-03	0.9994	5.8e-04	
STACY36[24,25]	0.9988	1.1e-03	0.9994	5.8e-04	

[22] The listed benchmark result is for the 1-D idealization of heu-met-fast-004 [2014 ICSBEP Handbook; HEU-MET-FAST-004; Table 11]. The input model matches the the description of the "one-dimensional" idealization: the experiment consists of the sphere of HEU suspended in the center of a sphere of water [2014 ICSBEP Handbook; HEU-MET-FAST-004; pg. 9].

[23] The benchmark results listed for case BIG TEN do not match the ieu-met-fast-007 results in the 2014 ICSBEP Handbook, shown below.

	k_{eff}
Experimental	1.0062 ± 0.0003
Detailed Benchmark Model	1.0045 ± 0.0007
Improved Simplified Benchmark Model	1.0049 ± 0.0008

[24] $5^{w}/_{o}$ is the dividing line between LEU and IEU, whereas the Handbook uses $10^{w}/_{o}$. [LA-UR-10-06230; Sec. 1.2]

[25] LA-UR-13-00019 table uncertainty value replaced with 2014 ICSBEP Handbook reported result (which is used in the *Expanded Criticality Validation Suite* results of LA-UR-13-00019). The difference between the experimental and computational results remains < 1 standard deviations.

2 Tests for "LEU Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
BAWXI2	1.0007	1.2e-03	1.0013	6.9e-04	
LST2C2	1.0024	3.7e-03	0.9940	6.2e-04	*

9 Tests for "Pu Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
JEZPU	1.0000	2.0e-03	1.0002	5.9e-04	
JEZ240	1.0000	2.0e-03	1.0002	5.5e-04	
PUBTNS	1.0000	3.0e-03	0.9996	6.4e-04	
FLATPU	1.0000	3.0e-03	1.0005	7.0e-04	
THOR	1.0000	6.0e-04	0.9980	6.9e-04	*
PU-MF-11	1.0000	1.0e-03	1.0012	7.2e-04	
HISHPG	1.0000	1.1e-02	1.0118	5.5e-04	*
PNL2	1.0000	6.5e-03	1.0046	9.5e-04	
PNL33	1.0024	2.1e-03	1.0065	7.4e-04	*

6 Tests for "U233 Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
JEZ233	1.0000	1.0e-03	0.9989	5.5e-04	
FLAT23	1.0000	1.4e-03	0.9990	7.2e-04	
UMF5C2	1.0000	3.0e-03	0.9931	6.4e-04	*
FLSTF1	1.0000	8.3e-03	0.9830	1.1e-03	*
SB25	1.0000	2.4e-03	1.0053	1.0e-03	*
ORNL11	1.0006	2.9e-03	1.0018	3.7e-04	

Notes

RMS difference	0.52 % for 31 completed tests
	(20) differ by <1 std dev
*	(10) differ by 1-2 std dev
***	(1) differ by >3 std dev

Appendix C – Expanded Criticality Validation

The following results tables list the k_{eff} and standard deviation values from the benchmark experiment and calculated by MCNP6 Version 1.0. The notes in the results tables are explained by the last table in the appendix. Each results table is followed by a table (or two) of the benchmark characteristics (spectrum, form, shape, and reflector).

40 Tests for "HEU Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
heu-met-fast-001	1.0000	1.0e-03	0.9993	2.5e-04	
heu-met-fast-008	0.9989	1.6e-03	0.9957	2.6e-04	*
heu-met-fast-018-case-2	1.0000	1.4e-03	0.9999	2.6e-04	
heu-met-fast-003-case-1	1.0000	5.0e-03	0.9954	2.8e-04	
heu-met-fast-003-case-2	1.0000	5.0e-03	0.9942	2.8e-04	*
heu-met-fast-003-case-3	1.0000	5.0e-03	0.9994	2.7e-04	
heu-met-fast-003-case-4	1.0000	3.0e-03	0.9971	2.9e-04	
heu-met-fast-003-case-5	1.0000	3.0e-03	1.0008	2.8e-04	
heu-met-fast-003-case-6	1.0000	3.0e-03	1.0017	3.0e-04	
heu-met-fast-003-case-7	1.0000	3.0e-03	1.0027	2.9e-04	
heu-met-fast-028	1.0000	3.0e-03	1.0032	3.0e-04	
heu-met-fast-014	0.9989	1.7e-03	0.9978	2.8e-04	
heu-met-fast-003-case-8	1.0000	5.0e-03	1.0081	2.9e-04	*
heu-met-fast-003-case-9	1.0000	5.0e-03	1.0095	2.9e-04	*
heu-met-fast-003-case-10	1.0000	5.0e-03	1.0129	3.0e-04	**
heu-met-fast-003-case-11	1.0000	5.0e-03	1.0166	2.9e-04	***
heu-met-fast-003-case-12	1.0000	3.0e-03	1.0083	2.9e-04	**
heu-met-fast-013	0.9990	1.5e-03	0.9975	2.8e-04	
heu-met-fast-021-case-2	1.0000	2.4e-03	0.9969	2.7e-04	*
heu-met-fast-022-case-2	1.0000	1.9e-03	0.9977	2.7e-04	*
heu-met-fast-012	0.9992	1.8e-03	0.9982	2.7e-04	
heu-met-fast-019-case-2	1.0000	2.8e-03	1.0074	2.9e-04	**
heu-met-fast-009-case-2	0.9992	1.5e-03	0.9955	2.9e-04	**
heu-met-fast-009-case-1	0.9992	1.5e-03	0.9957	2.8e-04	*
heu-met-fast-011	0.9989	1.5e-03	0.9984	3.5e-04	
heu-met-fast-020-case-2	1.0000	2.8e-03	1.0008	2.9e-04	
heu-met-fast-004-case-1[26]	1.0020	1.0e-03	1.0028	3.5e-04	
heu-met-fast-015	0.9996	1.7e-03	0.9943	2.7e-04	**
heu-met-fast-026-case-c-11	1.0000	3.8e-03	1.0038	3.5e-04	
heu-comp-inter-003-case-6	1.0000	4.7e-03	0.9950	3.3e-04	

[26] In DICE, benchmark heu-met-fast-004 has only one case, although, there are two models (1-D and 3-D). Therefore, other documents (such as the Criticality Validation Suite) identify this benchmark by only “heu-met-fast-004”.

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
heu-met-inter-006-case-1	0.9977	8.0e-04	0.9925	3.5e-04	***
heu-met-inter-006-case-2	0.9997	8.0e-04	0.9971	3.2e-04	**
heu-met-inter-006-case-3	1.0015	9.0e-04	1.0011	3.4e-04	
heu-met-inter-006-case-4	1.0016	8.0e-04	1.0075	3.1e-04	***
u233-comp-therm-001-case-6	1.0015	2.8e-03	0.9997	4.2e-04	
heu-sol-therm-013-case-1	1.0012	2.6e-03	0.9985	2.6e-04	
heu-sol-therm-013-case-2	1.0007	3.6e-03	0.9975	2.6e-04	
heu-sol-therm-013-case-3	1.0009	3.6e-03	0.9942	2.8e-04	*
heu-sol-therm-013-case-4	1.0003	3.6e-03	0.9957	3.0e-04	*
heu-sol-therm-032	1.0015	2.6e-03	0.9991	1.7e-04	

HEU Benchmark Characteristics

Spectrum	Form	Shape	Reflector	Benchmark(s)
Fast	Metal	Sphere	Unreflected	heu-met-fast-001 heu-met-fast-008 heu-met-fast-018-case-2
			Normal uranium	heu-met-fast-003-case-1 heu-met-fast-003-case-2 heu-met-fast-003-case-3 heu-met-fast-003-case-4 heu-met-fast-003-case-5 heu-met-fast-003-case-6 heu-met-fast-003-case-7 heu-met-fast-028
			Depleted uranium	heu-met-fast-014
			Tungsten carbide	heu-met-fast-003-case-8 heu-met-fast-003-case-9 heu-met-fast-003-case-10 heu-met-fast-003-case-11
			Nickel	heu-met-fast-003-case-12
			Steel	heu-met-fast-013 heu-met-fast-021-case-2
			Duralumin	heu-met-fast-022-case-2
			Aluminum	heu-met-fast-012
			Graphite	heu-met-fast-019-case-2
			Beryllium oxide	heu-met-fast-009-case-2
			Beryllium	heu-met-fast-009-case-1
			Polyethylene	heu-met-fast-011 heu-met-fast-020-case-2
			Water	heu-met-fast-004-case-1
		Cylinder	Unreflected	heu-met-fast-015
		Lattice	Paraffin	heu-met-fast-026-case-c-11

Ref.: LA-UR-11-00240; Table IV

Spectrum	Form	Shape	Reflector, Moderator and/or Buffer	Benchmark(s)
Intermediate	UH_3	Cylinders	Natural uranium	heu-comp-inter-003, case-6
	Metal	Cylinders	Graphite, copper	heu-met-inter-006-case-1 heu-met-inter-006-case-2 heu-met-inter-006-case-3 heu-met-inter-006-case-4
Thermal	$UO_2 + ZrO_2$	Lattice	Water, ThO_2	u233-comp-inter-001-case-6
	Solution	Sphere	Unreflected	heu-sol-therm-013-case-1 heu-sol-therm-013-case-2 heu-sol-therm-013-case-3 heu-sol-therm-013-case-4 heu-sol-therm-032

Ref.: LA-UR-11-00240; Table V

17 Tests for "IEU Benchmarks"[27]

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
ieu-met-fast-003-case-2[28]	1.0000	1.7e-03	1.0029	2.7e-04	*
ieu-met-fast-005-case-2	1.0000	2.1e-03	1.0018	2.7e-04	
ieu-met-fast-006-case-2	1.0000	2.3e-03	0.9957	2.7e-04	*
ieu-met-fast-004-case-2[29]	1.0000	3.0e-03	1.0075	2.8e-04	**
ieu-met-fast-001-case-1	0.9989	1.0e-03	1.0009	2.7e-04	*
ieu-met-fast-001-case-2	0.9997	1.0e-03	1.0013	2.6e-04	*
ieu-met-fast-001-case-3	0.9993	5.0e-04	1.0014	2.7e-04	**
ieu-met-fast-001-case-4	1.0002	5.0e-04	1.0015	2.6e-04	*
ieu-met-fast-002	1.0000	3.0e-03	0.9991	2.5e-04	
ieu-met-fast-007-case-4[30]	1.0049	8.0e-04	1.0049	2.4e-04	
mix-met-fast-008-case-7	1.0030	2.5e-03	1.0191	1.8e-04	***
mix-met-fast-008-case-7[31]	1.0300	2.5e-03	1.0191	1.8e-04	***
ieu-comp-therm-002-case-3	1.0017	4.4e-03	1.0042	3.5e-04	
leu-sol-therm-007-case-14	0.9961	9.0e-04	0.9950	3.0e-04	
leu-sol-therm-007-case-30	0.9973	9.0e-04	0.9977	3.1e-04	
leu-sol-therm-007-case-32	0.9985	1.0e-03	0.9958	2.9e-04	**
leu-sol-therm-007-case-36	0.9988	1.1e-03	0.9986	2.7e-04	
leu-sol-therm-007-case-49	0.9983	1.1e-03	0.9975	2.8e-04	

[27] The expanded validation suite uses 5^{w}/$_{o}$ as the dividing line between LEU and IEU, whereas the Handbook uses 10^{w}/$_{o}$. [LA-UR-10-06230; Sec. 1.2]

[28] In DICE, benchmark ieu-met-fast-003 has only one case, although, there are two models (detailed and simplified). Therefore, other documents (such as the Criticality Validation Suite) identify this benchmark by only "ieu-met-fast-003".

[29] In DICE, benchmark ieu-met-fast-004 has only one case, although, there are two models (detailed and simplified). Therefore, other documents (such as the Criticality Validation Suite) identify this benchmark by only "ieu-met-fast-004".

[30] Benchmark ieu-met-fast-007-case-4 has been submitted for inclusion in the ICSBEP Handbook but has not yet been approved.

[31] LA-UR-13-00019 table value replaced with 2014 ICSBEP Handbook reported result (which is used in the *Criticality Validation Suite* results of LA-UR-13-00019). The difference between the experimental and computational results remains > 3 standard deviations.

IEU Benchmark Characteristics

Spectrum	Form	Shape	Reflector and/or Buffer	Benchmark(s)
Fast	Metal	Sphere	Unreflected	ieu-met-fast-003-case-2
			Steel	ieu-met-fast-005-case-2
			Duralumin	ieu-met-fast-006-case-2
			Graphite	ieu-met-fast-004-case-2
		Cylinders	Unreflected	ieu-met-fast-001-case-1 ieu-met-fast-001-case-2 ieu-met-fast-001-case-3 ieu-met-fast-001-case-4
			Normal uranium	ieu-met-fast-002
			Depleted uranium	ieu-met-fast-007-case-4
Intermediate	Plate	Lattice	Normal uranium, steel	mix-met-fast-008-case-7
Thermal	UO_2	Lattice	Water	ieu-comp-therm-002-case-3
	Solution	Cylinder	Unreflected	leu-sol-therm-027-case-14 leu-sol-therm-027-case-30 leu-sol-therm-027-case-32 leu-sol-therm-027-case-36 leu-sol-therm-027-case-49

Ref.: LA-UR-11-00240; Table VI

8 Tests for "LEU Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
leu-comp-therm-008-case-1	1.0007	1.6e-03	1.0012	2.9e-04	
leu-comp-therm-008-case-2	1.0007	1.6e-03	1.0013	3.0e-04	
leu-comp-therm-008-case-2[32]	1.0007	1.2e-03	1.0013	3.0e-04	
leu-comp-therm-008-case-5	1.0007	1.6e-03	1.0006	2.9e-04	
leu-comp-therm-008-case-7	1.0007	1.6e-03	1.0003	3.0e-04	
leu-comp-therm-008-case-8	1.0007	1.6e-03	1.0007	3.0e-04	
leu-comp-therm-008-case-11	1.0007	1.6e-03	1.0020	2.9e-04	
leu-sol-therm-002-case-1	1.0038	4.0e-03	1.0000	2.5e-04	
leu-sol-therm-002-case-2	1.0024	3.7e-03	0.9959	2.8e-04	*

LEU Benchmark Characteristics

Spectrum	Form	Shape	Buffer and/or Reflector	Benchmark(s)
Thermal	UO_2	Lattice	UO_2 Rods, Water	leu-comp-therm-008-case-1 leu-comp-therm-008-case-2 leu-comp-therm-008-case-5 leu-comp-therm-008-case-7 leu-comp-therm-008-case-8 leu-comp-therm-008-case-11
	Solution	Sphere	Water	leu-sol-therm-002-case-1
			Unreflected	leu-sol-therm-002-case-2

Ref.: LA-UR-11-00240; Table VII

[32] LA-UR-13-00019 table value replaced with 2014 ICSBEP Handbook reported result (which is used in the *Criticality Validation Suite* results of LA-UR-13-00019). The difference between the experimental and computational results remains < 1 standard deviations.

36 Tests for "Pu Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
pu-met-fast-001	1.0000	2.0e-03	1.0000	2.6e-04	
pu-met-fast-002	1.0000	2.0e-03	0.9999	2.6e-04	
pu-met-fast-022-case-2	1.0000	2.1e-03	0.9983	2.8e-04	
mix-met-fast-001	1.0000	1.6e-03	0.9993	2.6e-04	
mix-met-fast-003	0.9993	1.6e-03	1.0008	2.8e-04	
pu-met-fast-006	1.0000	3.0e-03	0.9995	3.0e-04	
pu-met-fast-010	1.0000	1.8e-03	1.0001	2.9e-04	
pu-met-fast-020	0.9993	1.7e-03	0.9981	2.9e-04	
pu-met-fast-008-case-2	1.0000	6.0e-04	0.9977	2.7e-04	**
pu-met-fast-005	1.0000	1.3e-03	1.0092	2.9e-04	***
pu-met-fast-025-case-2	1.0000	2.0e-03	0.9988	2.7e-04	
pu-met-fast-026-case-2	1.0000	2.4e-03	0.9985	2.9e-04	
pu-met-fast-009	1.0000	2.7e-03	1.0053	2.8e-04	*
pu-met-fast-023-case-2	1.0000	2.0e-03	0.9993	2.9e-04	
pu-met-fast-018	1.0000	3.0e-03	0.9964	2.8e-04	*
pu-met-fast-019	0.9992	1.5e-03	0.9975	2.9e-04	
pu-met-fast-024-case-2	1.0000	2.0e-03	1.0019	2.9e-04	
pu-met-fast-011	1.0000	1.0e-03	1.0006	3.4e-04	
pu-met-fast-021-case-2	1.0000	2.6e-03	0.9931	2.9e-04	**
pu-met-fast-021-case-1	1.0000	2.6e-03	1.0021	2.8e-04	
pu-met-fast-003-case-103	1.0000	3.0e-03	0.9981	2.9e-04	
pu-comp-inter-001	1.0000	1.1e-02	1.0121	2.5e-04	*
mix-comp-therm-002-case-pnl30	1.0024	6.0e-03	1.0011	3.4e-04	
mix-comp-therm-002-case-pnl31	1.0009	4.7e-03	1.0025	3.4e-04	
mix-comp-therm-002-case-pnl32	1.0042	3.1e-03	1.0031	3.3e-04	
mix-comp-therm-002-case-pnl33	1.0024	2.1e-03	1.0079	3.1e-04	**
mix-comp-therm-002-case-pnl34	1.0038	2.5e-03	1.0042	3.2e-04	
mix-comp-therm-002-case-pnl35	1.0029	2.7e-03	1.0066	3.2e-04	*
pu-sol-therm-009-case-3a	1.0000	3.3e-03	1.0190	1.7e-04	***
pu-sol-therm-011-case-16-5	1.0000	5.2e-03	1.0060	4.1e-04	*
pu-sol-therm-011-case-18-1	1.0000	5.2e-03	0.9943	3.6e-04	*
pu-sol-therm-011-case-18-6	1.0000	5.2e-03	0.9996	3.8e-04	
pu-sol-therm-021-case-1	1.0000	3.2e-03	1.0043	4.0e-04	*
pu-sol-therm-021-case-3	1.0000	6.5e-03	1.0044	4.6e-04	
pu-sol-therm-018-case-9	1.0000	3.4e-03	1.0031	3.2e-04	
pu-sol-therm-034-case-1	1.0000	6.2e-03	0.9999	4.1e-04	

Pu Benchmark Characteristics

Spectrum	Form	Shape	Reflector and/or Buffer	Benchmark(s)
Fast	Metal	Sphere	Unreflected	pu-met-fast-001 pu-met-fast-002 pu-met-fast-022-case-2
			HEU	mix-met-fast-001 mix-met-fast-003
			Normal uranium	pu-met-fast-006 pu-met-fast-010
			Depleted uranium	pu-met-fast-020
			Thorium	pu-met-fast-008-case-2
			Tungsten	pu-met-fast-005
			Steel	pu-met-fast-025-case-2 pu-met-fast-026-case-2
			Aluminum	pu-met-fast-009
			Graphite	pu-met-fast-023-case-2
			Beryllium	pu-met-fast-018 pu-met-fast-019
			Polyethylene	pu-met-fast-024-case-2
			Water	pu-met-fast-011
		Cylinders	Beryllium oxide	pu-met-fast-021-case-2
			Beryllium	pu-met-fast-021-case-1
		Lattice	Unreflected	pu-met-fast-003-case-103

Ref.: LA-UR-11-00240; Table VIII

Spectrum	Form	Shape	Reflector and/or Moderator	Benchmark(s)
Intermediate	Mixture	Homogeneous	Hydrogen, graphite	pu-comp-inter-001
Thermal	MOX	Lattice	Water	mix-comp-therm-002-case-pnl-30 mix-comp-therm-002-case-pnl-31 mix-comp-therm-002-case-pnl-32 mix-comp-therm-002-case-pnl-33 mix-comp-therm-002-case-pnl-34 mix-comp-therm-002-case-pnl-35
	Solution	Sphere	Unreflected	pu-sol-therm-009-case-3a pu-sol-therm-011-case-16-5 pu-sol-therm-011-case-18-1 pu-sol-therm-011-case-18-6 pu-sol-therm-021-case-1 pu-sol-therm-021-case-3
		Cylinder	Water	pu-sol-therm-018-case-9 pu-sol-therm-034-case-1

Ref.: LA-UR-11-00240; Table IX

18 Tests for "U233 Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
u233-met-fast-001	1.0000	1.0e-03	0.9993	2.6e-04	
u233-met-fast-002-case-1	1.0000	1.0e-03	0.9987	2.6e-04	*
u233-met-fast-002-case-2	1.0000	1.1e-03	1.0005	2.9e-04	
u233-met-fast-003-case-1	1.0000	1.0e-03	0.9997	2.7e-04	
u233-met-fast-003-case-2	1.0000	1.0e-03	1.0001	2.8e-04	
u233-met-fast-006	1.0000	1.4e-03	0.9994	3.0e-04	
u233-met-fast-004-case-1	1.0000	7.0e-04	1.0051	2.8e-04	***
u233-met-fast-004-case-2	1.0000	8.0e-04	1.0051	2.9e-04	***
u233-met-fast-005-case-1	1.0000	3.0e-03	0.9944	2.7e-04	*
u233-met-fast-005-case-2	1.0000	3.0e-03	0.9925	3.0e-04	**
u233-sol-inter-001-case-1	1.0000	8.3e-03	0.9848	5.0e-04	*
u233-comp-therm-001-case-3	1.0000	2.4e-03	1.0046	4.6e-04	*
u233-sol-therm-001-case-1	1.0000	3.1e-03	1.0015	2.5e-04	
u233-sol-therm-001-case-2	1.0000	3.3e-03	1.0011	2.7e-04	
u233-sol-therm-001-case-3	1.0000	3.3e-03	1.0009	2.5e-04	
u233-sol-therm-001-case-4	1.0000	3.3e-03	1.0019	2.7e-04	
u233-sol-therm-001-case-5	1.0000	3.3e-03	0.9996	2.7e-04	
u233-sol-therm-008	1.0000	2.9e-03	1.0014	1.7e-04	

U-233 Benchmark Characteristics

Spectrum	Form	Shape	Moderator and /or Reflector	Benchmark(s)
Fast	Metal	Sphere	Unreflected	u233-met-fast-001
			HEU	u233-met-fast-002-case-1 u233-met-fast-002-case-2
			Normal uranium	u233-met-fast-003-case-1 u233-met-fast-003-case-2 u233-met-fast-006
			Tungsten	u233-met-fast-004-case-1 u233-met-fast-004-case-2
			Beryllium	u233-met-fast-005-case-1 u233-met-fast-005-case-2
Intermediate	Solution	Sphere	Beryllium	u233-sol-inter-001-case-1
Thermal	$UO_2 + ZrO_2$	Lattice	Water	u233-comp-therm-001-case-3
	Solution	Sphere	Unreflected	u233-sol-therm-001-case-1 u233-sol-therm-001-case-2 u233-sol-therm-001-case-3 u233-sol-therm-001-case-4 u233-sol-therm-001-case-5 u233-sol-therm-008

Ref.: LA-UR-11-00240; Table III

Notes

RMS difference	0.49 % for 119 completed tests
	(72) differ by <1 std dev
*	(26) differ by 1-2 std dev
**	(13) differ by 2-3 std dev
***	(8) differ by >3 std dev

Appendix D – SB-CS Criticality Test Suite

The following results tables list the k_{eff} and standard deviation values from the benchmark experiment and calculated by MCNP6 Version 1.0. The notes in the results tables are explained by the table after the results tables. The last table in the appendix lists the areas of applicability.

25 Tests for "HEU-comp-therm Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
heu-comp-therm-002-001	1.0011	6.9e-03	1.0088	9.7e-04	
heu-comp-therm-002-002	1.0011	6.9e-03	1.0132	8.4e-04	*
heu-comp-therm-002-003	1.0011	6.9e-03	1.0142	9.1e-04	*
heu-comp-therm-002-004	1.0011	6.9e-03	1.0154	7.9e-04	*
heu-comp-therm-002-005	1.0011	6.9e-03	1.0143	8.8e-04	*
heu-comp-therm-002-006	1.0011	6.9e-03	1.0155	7.7e-04	*
heu-comp-therm-002-007	1.0011	6.9e-03	1.0158	7.7e-04	*
heu-comp-therm-002-008	1.0011	6.9e-03	1.0138	7.1e-04	*
heu-comp-therm-002-009	1.0011	6.9e-03	1.0155	7.2e-04	*
heu-comp-therm-002-010	1.0011	6.9e-03	1.0111	7.3e-04	*
heu-comp-therm-002-011	1.0011	5.3e-03	1.0118	8.8e-04	*
heu-comp-therm-002-012	1.0011	5.5e-03	1.0111	8.5e-04	*
heu-comp-therm-002-013	1.0011	5.5e-03	1.0148	8.8e-04	**
heu-comp-therm-002-014	1.0011	5.5e-03	1.0156	7.9e-04	**
heu-comp-therm-002-015	1.0011	5.5e-03	1.0171	7.6e-04	**
heu-comp-therm-002-016	1.0011	5.3e-03	1.0148	7.7e-04	**
heu-comp-therm-002-017	1.0011	5.3e-03	1.0201	6.6e-04	***
heu-comp-therm-002-018	1.0020	4.3e-03	1.0136	9.2e-04	**
heu-comp-therm-002-019	1.0020	4.3e-03	1.0115	8.6e-04	*
heu-comp-therm-002-020	1.0020	4.3e-03	1.0130	8.4e-04	**
heu-comp-therm-002-021	1.0020	4.3e-03	1.0141	7.9e-04	**
heu-comp-therm-002-022	1.0020	4.3e-03	1.0134	7.5e-04	**
heu-comp-therm-002-023	1.0008	8.5e-03	1.0134	8.9e-04	*
heu-comp-therm-002-024	1.0008	8.5e-03	1.0121	8.4e-04	*
heu-comp-therm-002-025	1.0008	8.5e-03	1.0107	8.5e-04	*

76 Tests for "HEU-met-fast Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
heu-met-fast-001-001	1.0000	1.0e-03	0.9967	6.6e-04	*
heu-met-fast-002-001	1.0000	3.0e-03	1.0000	6.2e-04	
heu-met-fast-002-002	1.0000	3.0e-03	1.0009	7.4e-04	
heu-met-fast-002-003	1.0000	3.0e-03	0.9996	6.2e-04	
heu-met-fast-002-004	1.0000	3.0e-03	0.9990	6.3e-04	
heu-met-fast-002-005	1.0000	3.0e-03	0.9995	6.6e-04	
heu-met-fast-002-006	1.0000	3.0e-03	1.0009	6.2e-04	
heu-met-fast-003-001	1.0000	5.0e-03	0.9921	6.5e-04	*
heu-met-fast-003-002	1.0000	5.0e-03	0.9902	5.6e-04	*
heu-met-fast-003-003	1.0000	5.0e-03	0.9969	6.2e-04	
heu-met-fast-003-004	1.0000	3.0e-03	0.9961	6.6e-04	*
heu-met-fast-003-005	1.0000	3.0e-03	0.9992	6.4e-04	
heu-met-fast-003-006	1.0000	3.0e-03	1.0000	6.2e-04	
heu-met-fast-003-007	1.0000	3.0e-03	1.0007	6.7e-04	
heu-met-fast-003-008	1.0000	5.0e-03	1.0040	7.1e-04	
heu-met-fast-003-009	1.0000	5.0e-03	1.0052	7.0e-04	
heu-met-fast-003-010	1.0000	5.0e-03	1.0080	6.1e-04	*
heu-met-fast-003-011	1.0000	5.0e-03	1.0124	5.9e-04	**
heu-met-fast-003-012	1.0000	3.0e-03	1.0050	6.2e-04	*
heu-met-fast-004-001	0.9985	0.0e+00	0.9888	7.3e-04	***
heu-met-fast-007-001	0.9971	1.0e-04	0.9895	6.2e-04	***
heu-met-fast-007-002	0.9986	1.0e-04	0.9955	6.8e-04	***
heu-met-fast-007-003	1.0012	1.0e-04	0.9970	7.1e-04	***
heu-met-fast-007-004	0.9970	1.0e-04	0.9954	6.4e-04	**
heu-met-fast-007-005	1.0000	1.0e-04	0.9957	6.8e-04	***
heu-met-fast-007-006	1.0028	1.0e-04	1.0019	7.8e-04	*
heu-met-fast-007-007	0.9996	1.0e-04	0.9967	7.0e-04	***
heu-met-fast-007-008	0.9992	1.0e-04	0.9962	7.1e-04	***
heu-met-fast-007-009	1.0017	8.0e-04	0.9978	7.1e-04	**
heu-met-fast-007-010	1.0000	1.0e-04	0.9961	8.0e-04	***
heu-met-fast-007-011	0.9982	1.0e-04	0.9954	8.4e-04	**
heu-met-fast-007-012	0.9951	1.0e-04	0.9899	7.9e-04	***
heu-met-fast-007-013	1.0009	1.0e-04	0.9968	8.3e-04	***
heu-met-fast-007-014	0.9983	1.0e-04	0.9934	8.3e-04	***
heu-met-fast-007-015	0.9978	1.0e-04	0.9931	7.5e-04	***
heu-met-fast-007-016	0.9988	1.0e-04	0.9935	8.5e-04	***
heu-met-fast-007-017	0.9972	1.0e-04	0.9937	8.6e-04	***
heu-met-fast-007-018	0.9991	1.0e-04	0.9966	9.1e-04	**
heu-met-fast-007-019	0.9983	1.0e-04	0.9923	6.5e-04	***

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
heu-met-fast-007-020	0.9981	1.0e-04	0.9938	7.4e-04	***
heu-met-fast-007-021	0.9987	1.0e-04	0.9937	7.6e-04	***
heu-met-fast-007-022	0.9994	1.0e-04	0.9950	7.2e-04	***
heu-met-fast-007-023	0.9993	1.0e-04	0.9955	7.6e-04	***
heu-met-fast-007-024	1.0001	1.0e-04	0.9965	8.1e-04	***
heu-met-fast-007-025	0.9990	1.0e-04	0.9941	8.3e-04	***
heu-met-fast-007-026	0.9997	1.0e-04	0.9952	7.6e-04	***
heu-met-fast-007-027	0.9965	2.0e-04	0.9939	7.1e-04	**
heu-met-fast-007-028	0.9987	2.0e-04	0.9947	6.4e-04	***
heu-met-fast-007-029	0.9978	2.0e-04	0.9941	7.2e-04	***
heu-met-fast-007-030	0.9981	2.0e-04	0.9932	8.9e-04	***
heu-met-fast-007-031	1.0013	2.0e-04	0.9963	8.3e-04	***
heu-met-fast-007-032	0.9959	1.0e-04	1.0016	6.7e-04	***
heu-met-fast-007-033	0.9995	1.0e-04	1.0124	6.6e-04	***
heu-met-fast-007-034	0.9977	1.0e-04	1.0169	6.6e-04	***
heu-met-fast-007-035	1.0011	1.0e-04	0.9906	7.4e-04	***
heu-met-fast-007-036	0.9999	1.0e-04	1.0001	8.1e-04	
heu-met-fast-007-037	0.9988	1.0e-04	0.9993	7.6e-04	
heu-met-fast-007-038	1.0000	1.0e-04	0.9979	8.7e-04	**
heu-met-fast-007-039	1.0018	1.0e-04	1.0025	8.3e-04	
heu-met-fast-007-040	1.0013	1.0e-04	1.0023	8.6e-04	
heu-met-fast-007-041	0.9994	1.0e-04	0.9977	8.4e-04	*
heu-met-fast-007-042	1.0016	1.0e-04	1.0002	7.7e-04	*
heu-met-fast-007-043	0.9998	1.0e-04	0.9985	8.6e-04	*
heu-met-fast-008-001	0.9989	1.6e-03	0.9930	5.0e-04	**
heu-met-fast-017-001	0.9993	1.4e-03	0.9989	6.9e-04	
heu-met-fast-019-001	1.0000	3.0e-03	1.0022	6.2e-04	
heu-met-fast-028-001	1.0000	3.0e-03	1.0013	6.6e-04	
heu-met-fast-030-001	1.0000	9.0e-04	1.0045	6.5e-04	**
heu-met-fast-041-001	1.0013	3.0e-03	1.0052	6.7e-04	*
heu-met-fast-041-002	1.0022	4.3e-03	1.0036	6.8e-04	
heu-met-fast-041-003	1.0006	2.9e-03	0.9983	6.2e-04	
heu-met-fast-041-004	1.0006	2.5e-03	1.0028	6.5e-04	
heu-met-fast-041-005	1.0006	3.1e-03	0.9997	6.7e-04	
heu-met-fast-041-006	1.0006	4.5e-03	1.0010	6.8e-04	
heu-met-fast-067-001	1.0086	4.0e-04	1.0113	6.2e-04	**
heu-met-fast-067-002	0.9938	2.4e-03	1.0078	6.0e-04	***

10 Tests for "HEU-sol-therm Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
heu-sol-therm-001-001	1.0000	2.5e-03	0.9984	1.1e-03	
heu-sol-therm-001-002	1.0000	2.5e-03	0.9952	1.1e-03	*
heu-sol-therm-001-003	1.0000	2.5e-03	1.0015	1.0e-03	
heu-sol-therm-001-004	1.0000	2.5e-03	0.9986	1.0e-03	
heu-sol-therm-001-005	1.0000	2.5e-03	1.0020	8.5e-04	
heu-sol-therm-001-006	1.0000	2.5e-03	1.0028	9.2e-04	
heu-sol-therm-001-007	1.0000	2.5e-03	1.0003	1.0e-03	
heu-sol-therm-001-008	1.0000	2.5e-03	1.0010	1.0e-03	
heu-sol-therm-001-009	1.0000	2.5e-03	0.9950	1.1e-03	*
heu-sol-therm-001-010	1.0000	2.5e-03	0.9935	9.3e-04	*

4 Tests for "mix-met-fast Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
mix-met-fast-001-001	1.0000	1.6e-03	0.9961	6.4e-04	*
mix-met-fast-002-001	1.0000	4.2e-03	1.0040	6.5e-04	
mix-met-fast-002-002	1.0000	4.4e-03	1.0060	7.4e-04	*
mix-met-fast-002-003	1.0000	4.8e-03	1.0041	6.8e-04	

35 Tests for "pu-met-fast Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
pu-met-fast-001-001	1.0000	2.0e-03	0.9976	5.7e-04	
pu-met-fast-002-001	1.0000	2.0e-03	0.9992	5.7e-04	
pu-met-fast-005-001	1.0000	1.3e-03	1.0073	6.9e-04	***
pu-met-fast-006-001	1.0000	3.0e-03	1.0024	6.9e-04	
pu-met-fast-008-001	1.0000	6.0e-04	1.0065	6.0e-04	***
pu-met-fast-009-001	1.0000	2.7e-03	1.0017	6.2e-04	
pu-met-fast-010-001	1.0000	1.8e-03	0.9995	5.9e-04	
pu-met-fast-011-001	1.0000	1.0e-03	0.9956	6.7e-04	**
pu-met-fast-012-001	1.0009	2.1e-03	1.0050	7.2e-04	*
pu-met-fast-013-001	1.0034	2.3e-03	1.0059	6.9e-04	
pu-met-fast-014-001	1.0037	3.1e-03	1.0047	6.1e-04	
pu-met-fast-015-001	1.0041	2.6e-03	0.9999	7.0e-04	*
pu-met-fast-018-001	1.0000	3.0e-03	1.0003	6.3e-04	
pu-met-fast-019-001	0.9992	1.5e-03	1.0015	6.2e-04	*
pu-met-fast-020-001	0.9993	1.7e-03	0.9969	6.7e-04	
pu-met-fast-021-001	1.0000	2.6e-03	1.0035	7.1e-04	*
pu-met-fast-021-002	1.0000	2.6e-03	0.9907	6.4e-04	**
pu-met-fast-023-001	1.0000	2.2e-03	0.9976	6.0e-04	
pu-met-fast-024-001	1.0000	2.2e-03	1.0002	6.4e-04	
pu-met-fast-025-001	1.0000	2.2e-03	0.9961	6.9e-04	*
pu-met-fast-026-001	1.0000	2.2e-03	0.9962	6.5e-04	*
pu-met-fast-027-001	1.0000	2.4e-03	1.0012	8.2e-04	
pu-met-fast-028-001	1.0000	2.4e-03	0.9971	6.6e-04	
pu-met-fast-029-001	1.0000	2.4e-03	0.9939	6.0e-04	**
pu-met-fast-030-001	1.0000	2.3e-03	1.0011	6.1e-04	
pu-met-fast-031-001	1.0000	2.3e-03	1.0013	7.2e-04	
pu-met-fast-032-001	1.0000	2.2e-03	0.9962	6.3e-04	*
pu-met-fast-035-001	1.0000	1.6e-03	1.0074	6.5e-04	***
pu-met-fast-045-001	1.0000	4.7e-03	0.9979	7.1e-04	
pu-met-fast-045-002	1.0000	4.6e-03	1.0030	7.2e-04	
pu-met-fast-045-003	1.0000	4.4e-03	1.0019	6.1e-04	
pu-met-fast-045-004	1.0000	4.6e-03	1.0007	6.5e-04	
pu-met-fast-045-005	1.0000	4.5e-03	1.0058	6.5e-04	*
pu-met-fast-045-006	1.0000	4.9e-03	1.0020	6.9e-04	
pu-met-fast-045-007	1.0000	5.0e-03	1.0019	6.4e-04	

44 Tests for "pu-sol-therm Benchmarks"

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
pu-sol-therm-001-001	1.0000	5.0e-03	1.0041	9.8e-04	
pu-sol-therm-001-002	1.0000	5.0e-03	1.0059	9.1e-04	*
pu-sol-therm-001-003	1.0000	5.0e-03	1.0069	9.9e-04	*
pu-sol-therm-001-004	1.0000	5.0e-03	1.0010	9.2e-04	
pu-sol-therm-001-005	1.0000	5.0e-03	1.0045	9.1e-04	
pu-sol-therm-001-006	1.0000	5.0e-03	1.0067	9.2e-04	*
pu-sol-therm-002-001	1.0000	4.7e-03	1.0024	8.4e-04	
pu-sol-therm-002-002	1.0000	4.7e-03	1.0025	8.6e-04	
pu-sol-therm-002-003	1.0000	4.7e-03	1.0017	8.4e-04	
pu-sol-therm-002-004	1.0000	4.7e-03	1.0030	8.3e-04	
pu-sol-therm-002-005	1.0000	4.7e-03	1.0073	9.0e-04	*
pu-sol-therm-002-006	1.0000	4.7e-03	1.0051	8.5e-04	
pu-sol-therm-002-007	1.0000	4.7e-03	1.0056	8.9e-04	
pu-sol-therm-003-001	1.0000	4.7e-03	1.0021	7.9e-04	
pu-sol-therm-003-002	1.0000	4.7e-03	1.0017	8.9e-04	
pu-sol-therm-003-003	1.0000	4.7e-03	1.0055	8.6e-04	
pu-sol-therm-003-004	1.0000	4.7e-03	1.0022	8.1e-04	
pu-sol-therm-003-005	1.0000	4.7e-03	1.0042	8.8e-04	
pu-sol-therm-003-006	1.0000	4.7e-03	1.0042	7.8e-04	
pu-sol-therm-004-001	1.0000	4.7e-03	1.0042	7.9e-04	
pu-sol-therm-004-002	1.0000	4.7e-03	0.9990	7.7e-04	
pu-sol-therm-004-003	1.0000	4.7e-03	1.0021	8.1e-04	
pu-sol-therm-004-004	1.0000	4.7e-03	0.9992	7.8e-04	
pu-sol-therm-004-005	1.0000	4.7e-03	0.9992	8.5e-04	
pu-sol-therm-004-006	1.0000	4.7e-03	1.0011	8.0e-04	
pu-sol-therm-004-007	1.0000	4.7e-03	1.0063	7.1e-04	*
pu-sol-therm-004-008	1.0000	4.7e-03	1.0002	7.5e-04	
pu-sol-therm-004-009	1.0000	4.7e-03	0.9992	8.3e-04	
pu-sol-therm-004-010	1.0000	4.7e-03	1.0012	8.6e-04	
pu-sol-therm-004-011	1.0000	4.7e-03	1.0000	7.6e-04	
pu-sol-therm-004-012	1.0000	4.7e-03	1.0007	8.0e-04	
pu-sol-therm-004-013	1.0000	4.7e-03	1.0001	7.3e-04	
pu-sol-therm-005-001	1.0000	4.7e-03	1.0011	7.8e-04	
pu-sol-therm-005-002	1.0000	4.7e-03	1.0020	8.1e-04	
pu-sol-therm-005-003	1.0000	4.7e-03	1.0020	8.0e-04	
pu-sol-therm-005-004	1.0000	4.7e-03	1.0064	7.2e-04	*
pu-sol-therm-005-005	1.0000	4.7e-03	1.0044	7.8e-04	
pu-sol-therm-005-006	1.0000	4.7e-03	1.0050	8.3e-04	
pu-sol-therm-005-007	1.0000	4.7e-03	1.0020	8.0e-04	

case	Benchmark Results		MCNP6 V1.0		
	keff	std	keff	std	note
pu-sol-therm-005-008	1.0000	4.7e-03	0.9992	8.6e-04	
pu-sol-therm-005-009	1.0000	4.7e-03	1.0020	7.7e-04	
pu-sol-therm-006-001	1.0000	3.5e-03	0.9997	7.4e-04	
pu-sol-therm-006-002	1.0000	3.5e-03	1.0016	7.6e-04	
pu-sol-therm-006-003	1.0000	3.5e-03	1.0016	7.2e-04	

Notes

RMS difference	0.62 % for 194 completed tests
	(93) differ by <1 std dev
*	(45) differ by 1-2 std dev
**	(21) differ by 2-3 std dev
***	(35) differ by >3 std dev

The *SB-CS Criticality Test Suite* has the following areas of applicability [NCS-TECH-07-002]:

Pu				
Spectrum	Fissile Form	Interstitials	Reflectors	Experiment
Fast	Metal	Aluminum	Aluminum	PU-MET-FAST-045
			Iron	PU-MET-FAST-045
			Nickel	PU-MET-FAST-045
			Tantalum	PU-MET-FAST-045
		Nickel	Aluminum	PU-MET-FAST-045
			Iron	PU-MET-FAST-045
			Nickel	PU-MET-FAST-045
			Tantalum	PU-MET-FAST-045
		None	Aluminum	PU-MET-FAST-009
			Beryllium	PU-MET-FAST-018
			Beryllium	PU-MET-FAST-019
			DU	PU-MET-FAST-020
			Graphite	PU-MET-FAST-023
			Graphite	PU-MET-FAST-030
			Lead	PU-MET-FAST-035
			Natural Uranium	PU-MET-FAST-006
			Natural Uranium	PU-MET-FAST-010
			None	PU-MET-FAST-001
			None	PU-MET-FAST-002
			None	PU-MET-FAST-029
			Polyethylene	PU-MET-FAST-024
			Polyethylene	PU-MET-FAST-027
			Polyethylene	PU-MET-FAST-031
			Steel	PU-MET-FAST-025
			Steel	PU-MET-FAST-026
			Steel	PU-MET-FAST-028
			Steel	PU-MET-FAST-032
			Thorium	PU-MET-FAST-008
			Tungsten	PU-MET-FAST-005
			Water	PU-MET-FAST-011
		Steel	Beryllium	PU-MET-FAST-021
			Beryllium-Oxide	PU-MET-FAST-021
			Copper	PU-MET-FAST-013
			Iron	PU-MET-FAST-015
			Natural Uranium	PU-MET-FAST-012
			Nickel	PU-MET-FAST-014

Pu				
Spectrum	Fissile Form	Interstitials	Reflectors	Experiment
		Tantalum	Aluminum	PU-MET-FAST-045
			Iron	PU-MET-FAST-045
			Nickel	PU-MET-FAST-045
			Tantalum	PU-MET-FAST-045
Thermal	Solution	Nitrate	Water	PU-SOL-THERM-001
				PU-SOL-THERM-002
				PU-SOL-THERM-003
				PU-SOL-THERM-004
				PU-SOL-THERM-005
				PU-SOL-THERM-006

HEU				
Spectrum	Fissile Form	Interstitials	Reflectors	Experiment
Fast	Metal	Beryllium	Beryllium	HEU-MET-FAST-017
			DU	HEU-MET-FAST-030
		Graphite	Aluminum	HEU-MET-FAST-067
		None	Beryllium	HEU-MET-FAST-041
			Graphite	HEU-MET-FAST-019
			Graphite	HEU-MET-FAST-041
			Natural Uranium	HEU-MET-FAST-028
			None	HEU-MET-FAST-001
			None	HEU-MET-FAST-008
			Oralloy	HEU-MET-FAST-003
			Tuballoy	HEU-MET-FAST-002
			Water	HEU-MET-FAST-004
		Plexiglas	None	HEU-MET-FAST-007
		Polyethylene	None	HEU-MET-FAST-007
			Polyethylene	HEU-MET-FAST-007
		Teflon	None	HEU-MET-FAST-007
		Tungsten	Aluminum	HEU-MET-FAST-067
Thermal	Compound	Aluminum	Water	HEU-COMP-THERM-002
		Graphite	Water	HEU-COMP-THERM-002
		Water	Water	HEU-COMP-THERM-002
	Solution	Nitrate	None	HEU-SOL-THERM-001

Mix Pu & HEU				
Spectrum	Fissile Form	Interstitials	Reflectors	Experiment
Fast	Metal	HEU	Natural Uranium	MIX-MET-FAST-002
		Plutonium	HEU	MIX-MET-FAST-001
		Plutonium	Natural Uranium	MIX-MET-FAST-002