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Validation of COG 10 and ENDFB6R7 on the Surya Workstation for General Application to Highly Enriched Uranium Systems

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SUBJECT: **Validation of COG 10 and ENDFB6R7 on the *Surya* Workstation for General Application to Highly Enriched Uranium Systems**

1.0 Introduction

The COG 10 code package[1] on the *Surya* workstation is now validated with the ENBFB6R7 neutron cross section library for general application to highly enriched uranium (HEU) systems by comparison of the calculated $k_{effective}$ to the expected $k_{effective}$ of several relevant experimental benchmarks. This validation is supplemental to the installation and verification of COG 10 on the *Surya* workstation.[2]

2.0 Benchmark Experiments

Computational models for 348 experimental benchmarks are derived from the specifications of *Volume II, Highly Enriched Uranium Systems* of the International Handbook of Evaluated Criticality Safety Benchmark Experiments.[3] The basis for their selection is the availability of models in the proper code input format as developed and collected from previous efforts. Such a large number ensures the broadest possible Area-of-Applicability of the validation. The distribution of selected benchmarks by material form and characteristic fission energy as defined in the Handbook is shown below in Table 1. The number of experimental benchmark models from any given evaluation is indicated in Table 2.

Table 1. Selected HEU Benchmarks by Material Form and Characteristic Fission Energy from Volume II of the ICSBEP Handbook

Material Form and Characteristic Fission Energy	Number Selected
METAL Systems (Fast, Intermediate, Thermal, Mixed)	246 (207, 7, 28, 4)
COMPOUND Systems (Fast, Intermediate, Thermal, Mixed)	20 (0, 0, 0, 20)
SOLUTION Systems (Intermediate, Thermal, Mixed)	82 (0, 82, 0)
TOTAL (Fast, Intermediate, Thermal, Mixed)	**348 (207, 7, 110, 24)**

Table 2. Selected Benchmarks by Evaluation from Volume II of the ICSBEP Handbook

Evaluation ID	Title	Number Selected
HEU-MET-FAST-001	Bare, Highly Enriched Uranium Sphere (Godiva)	1
HEU-MET-FAST-002	Topsy 8-Inch-Tuballoy-Reflected Oralloy Assemblies	6
HEU-MET-FAST-003	Reflected Oralloy Spherical Assemblies	11
HEU-MET-FAST-004	Water-Reflected, Highly Enriched Uranium Sphere	1
HEU-MET-FAST-005	Beryllium- and Molybdenum-Reflected Cylinders of Highly Enriched Uranium	6
HEU-MET-FAST-007	Uranium Metal Slabs Moderated with Polyethylene, Plexiglas, and Teflon	43
HEU-MET-FAST-008	Bare Sphere of Highly Enriched Uranium	1
HEU-MET-FAST-009	Spheres of Highly Enriched Uranium Reflected by Beryllium or Beryllium Oxide	2
HEU-MET-FAST-010	Spheres of Highly Enriched Uranium Reflected by Boron+Beryllium or Boron+Beryllium Oxide	2
HEU-MET-FAST-011	Sphere of Highly Enriched Uranium Reflected by Polyethylene	1
HEU-MET-FAST-012	Sphere of Highly Enriched Uranium Reflected by Aluminum	1
HEU-MET-FAST-013	Sphere of Highly Enriched Uranium Reflected by Steel	1
HEU-MET-FAST-014	Sphere of Highly Enriched Uranium Reflected by Depleted Uranium	1
HEU-MET-FAST-015	Unreflected Cylinder of Highly Enriched Uranium	1
HEU-MET-FAST-016	Beryllium-Reflecetd and Beryllium Oxide-Reflected Cylinders of Highly Enriched Uranium	2
HEU-MET-FAST-017	Beryllium-Moderated and Reflected Cylinder of Highly Enriched Uranium	1
HEU-MET-FAST-018	Bare Spherical Assembly of ^{235}U(90%)	1
HEU-MET-FAST-019	Graphite-Reflected Spherical Assembly of ^{235}U(90%)	1
HEU-MET-FAST-020	Polyethylene-Reflected Spherical Assembly of ^{235}U(90%)	1
HEU-MET-FAST-021	Steel-Reflected Spherical Assembly of ^{235}U(90%)	1
HEU-MET-FAST-022	Duralumin-Reflected Spherical Assembly of ^{235}U(90%)	1
HEU-MET-FAST-024	Sphere of Highly Enriched Uranium Reflected by Steel and Polyethylene	1
HEU-MET-FAST-025	Five Vanadium-Reflected HEU Cylinders	5
HEU-MET-FAST-028	^{235}U Sphere Reflected by Normal Uranium using Flattop	1

Table 2. Selected Benchmarks by Evaluation from Volume II of the ICSBEP Handbook

Evaluation ID	Title	Number Selected
HEU-MET-FAST-029	Spherical Assembly of ^{235}U(90%) with 4.7-cm Depleted Uranium Reflector	1
HEU-MET-FAST-030	Heterogeneous Cylinder of Highly Enriched Uranium with Beryllium Moderator and Depleted-Uranium Reflector	1
HEU-MET-FAST-031	Spherical Assembly of ^{235}U(90%) with Central Area of Polyethylene and 17.45-cm Polyethylene Reflector	1
HEU-MET-FAST-032	^{235}U(94%) Spheres Surrounded by Natural-Uranium Reflectors	4
HEU-MET-FAST-033	Two Heterogeneous Cylinders of Highly Enriched Uranium with Polyethylene and Steel	2
HEU-MET-FAST-034	Three Heterogeneous Cylinders of Highly Enriched Uranium with Polyethylene and Titanium, Aluminum, or Steel	3
HEU-MET-FAST-036	Two Heterogeneous Cylinders of Highly Enriched Uranium with Polyethylene and Depleted Uranium	2
HEU-MET-FAST-037	Two Heterogeneous Cylinders of Highly Enriched Uranium, Polyethylene, and Depleted Uranium with Polyethylene Reflector	2
HEU-MET-FAST-038	Two Heterogeneous Cylinders of Highly Enriched Uranium with Beryllium and Beryllium Oxide Moderators and Depleted-Uranium Reflector	2
HEU-MET-FAST-041	^{235}U(94%) Spheres Surrounded by Beryllium or Graphite Reflectors	6
HEU-MET-FAST-048	Oil Reflected Spheres and Hemispheres of Highly Enriched Uranium (93.1% ^{235}U) Metal with Oil or Steel Moderator	17
HEU-MET-FAST-051	Uranium (93.2) Metal Cylinders (7-Inch, 9-Inch, 11-Inch, 13-Inch, and 15-Inch Diameter) and Two 11-Inch-Diameter Interacting Uranium (93.2) Metal Cylinders	18
HEU-MET-FAST-055	ZPR-3 Assembly 23: A Cylindrical Assembly of U Metal (93% ^{235}U) and Aluminum Reflected by Depleted-Uranium	1
HEU-MET-FAST-058	Highly Enriched Uranium Metal Spheres with Beryllium Reflectors	5
HEU-MET-FAST-061	ZPPR-21 Phase F: A Cylindrical Assembly of U Metal Reflected by Graphite	1
HEU-MET-FAST-062	First Criticality of Coral-I Reactor, a 90%-Enriched Uranium Cylinder Reflected by Natural Uranium, both Metal	1

Table 2. Selected Benchmarks by Evaluation from Volume II of the ICSBEP Handbook

Evaluation ID	Title	Number Selected
HEU-MET-FAST-063	Cylindrical Experiments using HEU Plates Reflected by Lithium Deuteride	2
HEU-MET-FAST-065	Unreflected Cylinder of Highly Enriched Uranium – Second Configuration	1
HEU-MET-FAST-066	Metal Spherical Shells of Highly Enriched Uranium Moderated and Reflected by Beryllium	9
HEU-MET-FAST-071	Uranium (93.14) Metal Annuli with One- and Two-Inch Graphite Reflectors	27
HEU-MET-FAST-076	Uranium (93.14 ^{235}U) Metal Annuli and Cylinders with Thick Polyethylene Reflectors and/or Internal Polyethylene Moderator	3
HEU-MET-FAST-079	Five Titanium-Reflected HEU Cylinders	5
HEU-MET-INTER-001	The Uranium/Iron Benchmark Assembly: A ^{235}U(93%)/Iron Cylinder Reflected by Stainless Steel	1
HEU-MET-INTER-006	The Initial Set of ZEUS Experiments: Intermediate-Spectrum Critical Assemblies with a Graphite-HEU Core Surrounded by a Copper Reflector	4
HEU-MET-INTER-009	'SPADE' Assemblies Part II: Highly Enriched Uranium Metal Foils Moderated by Beryllium Oxide	2
HEU-MET-THERM-001	Polyethylene Reflected and Moderated Highly Enriched Uranium System with Silicon	1
HEU-MET-THERM-003	Lattices of Oralloy Cubes in Water	7
HEU-MET-THERM-009	Polyethylene Reflected and Moderated Highly Enriched Uranium System with Magnesium Oxide	1
HEU-MET-THERM-010	Polyethylene Reflected and Moderated Highly Enriched Uranium System with Gadolinium	1
HEU-MET-THERM-025	Beryllium Moderated Critical Assemblies of Highly Enriched Uranium (ORNL CA-1 and CA-18)	2
HEU-MET-THERM-027	Highly Enriched Uranium Metal Moderated by Beryllium Oxide	15
HEU-MET-THERM-031	2 x 2 Array of Highly Enriched Uranium, Moderated and Reflected by Polyethylene	1
HEU-MET-MIXED-001	Heterogeneous Cylinder of Highly Enriched Uranium, Polyethylene, and Titanium with Polyethylene Reflector	1
HEU-MET-MIXED-002	Spherical Assembly of ^{235}U(90%) with Central Area of Polyethylene and 12.85-cm Polyethylene Reflector	1

Table 2. Selected Benchmarks by Evaluation from Volume II of the ICSBEP Handbook

Evaluation ID	Title	Number Selected
HEU-MET-MIXED-003	Spherical Assembly of ^{235}U(90%) with Central Area of Polyethylene and 15.85-cm Polyethylene Reflector	1
HEU-MET-MIXED-004	Heterogeneous Cylinder of Highly Enriched Uranium, Polyethylene, and Depleted Uranium with Reflector of Depleted Uranium	1
HEU-COMP-MIXED-001	Arrays of Cans of Highly Enriched Uranium Dioxide Reflected by Polyethylene	20
HEU-SOL-THERM-004	Reflected Uranyl-Fluoride Solutions in Heavy Water	6
HEU-SOL-THERM-009	Water-Reflected 6.4 Liter Spheres of Enriched Uranium Oxfluoride Solutions	4
HEU-SOL-THERM-010	Water-Reflected 9.7 Liter Spheres of Enriched Uranium Oxfluoride Solutions	4
HEU-SOL-THERM-011	Water-Reflected 17 Liter Spheres of Enriched Uranium Oxfluoride Solutions	2
HEU-SOL-THERM-012	Water-Reflected 91 Liter Sphere of Enriched Uranium Oxfluoride Solutions	1
HEU-SOL-THERM-013	Unreflected 174 Liter Spheres of Enriched Uranium Nitrate Solutions	4
HEU-SOL-THERM-020	Unreflected Cylinders of Uranyl-Fluoride Solutions in Heavy Water	5
HEU-SOL-THERM-038	WINCO Slab Tanks: Two Interacting Tanks of Highly Enriched Uranyl Nitrate Solution with Various Absorber-Reflector Plates	28
HEU-SOL-THERM-040	Intersecting Pipe Configurations Containing Highly Concentrated (453 gU/l) and Highly Enriched (93.17 wt.% ^{235}U) Uranyl Nitrate Solution	17
HEU-SOL-THERM-050	Unreflected Aluminum Cylinders containing Uranyl Fluoride Solutions	11
	TOTAL	**348**

3.0 Selected Code Options

Numerous code options are available to the user and default values are employed more often than not with a few notable exceptions that are relevant to validation and use. The total number of neutron histories simulated for each benchmark is specified in the basic data block as follows:

```
npart=5000
nbatch=1100
sdt=0.0001
nfirst=100
```

Also, the ENDFB6R7 neutron cross section library is employed for all benchmarks as is the available S(α,β) treatment for selected elements where appropriate. The only exception is the use of the RED2002 neutron cross section library for Zn and Pb. To this end, neutron cross section data is specified in the mix data block as follows:

```
nlib=ENDFB6R7
sablib=COGSAB (as necessary)
nlib2=RED2002 (as necessary)
```

4.0 Validation Methodology

Each benchmark result is normalized to the delayed critical condition ($k_{effective} = 1$) as follows:

$$k_{normalized} = (k_{calculated} - k_{expected}) + 1$$

The associated uncertainty ($\sigma_{combined}$) for each benchmark result becomes:

$$\sigma_{combined} = \sqrt{(\sigma_{calculated})^2 + (\sigma_{expected})^2}$$

The determination of an Upper Subcritical Limit (USL) to differentiate subcritical and critical conditions to a high probability by computation requires an assessment of the bias, the total uncertainty, and a margin of safety as follows:

$$\text{USL} = \{1 + \text{bias}\} - \{\text{total uncertainty}\} - \{\text{margin of safety}\}$$

Thus, a conservative criterion for general application is:

$$k_{calculated} + 3\sigma_{calculated} \leq \text{USL} = \{1 + \text{bias}\} - \{3\sigma_{total}\} - \{0.02\}$$

This criterion ensures better than 99.8% confidence that the USL lays below the selected benchmark results with an additional 0.02 margin of safety.

In practice, a simple estimate of {1+ bias} is the un-weighted average ($k_{average}$) of the calculated $k_{normalized}$ benchmark results:

$$k_{average} = \frac{\sum_{i=1}^{n} (k_{i,\ normalized})}{n}$$

The total uncertainty {$3\sigma_{total}$} is determined from the combination of the uncertainty of the bias estimate (σ_{bias}) and the average of the combined uncertainties of the individual benchmark results ($\sigma_{average}$) according to the following relations:

$$\sigma_{total} = \sqrt{(\sigma_{bias})^2 + (\sigma_{average})^2}$$

$$\sigma_{bias} = \sqrt{\frac{\sum_{i=1}^{n} (k_{i,\ normalized} - k_{average})^2}{n}}$$

$$\sigma_{average} = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{(\sigma_{i,\ combined})^2}}}$$

The 348 HEU benchmark results are provided in Table 3 and illustrated in Figure 1. From this data, $k_{average}$ = 0.9999 {1 + bias} where σ_{bias} = 0.0059 and $\sigma_{average}$ = 0.0015 are combined to yield $3\sigma_{total}$ = 0.0183 {total uncertainty}. Where a {margin of safety} of 0.02 is desired, the corresponding USL becomes 0.9616.

The additional results of Appendix A reveal the possibility of a significantly positive bias in the special case of calculated $k_{effective}$ for HEU systems with lead reflection. However, the potential to overestimate $k_{effective}$ with existing codes and neutron cross section data is well known and such a positive bias may be conservative with respect to many safety related applications. Thus, the results are supplemental to the Area-of-Applicability of this validation even though they are not employed in the statistical determinations described above.

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf001	1.000	0.001	0.9981	0.0006	9.5196E-01	0.9981	0.0012
hmf002-01	1.000	0.003	1.0019	0.0006	9.7939E-01	1.0019	0.0031
hmf002-02	1.000	0.003	1.0013	0.0006	9.7101E-01	1.0013	0.0031
hmf002-03	1.000	0.003	1.0012	0.0006	9.6513E-01	1.0012	0.0031
hmf002-04	1.000	0.003	0.9986	0.0006	9.5199E-01	0.9986	0.0031
hmf002-05	1.000	0.003	1.0004	0.0006	9.4979E-01	1.0004	0.0031
hmf002-06	1.000	0.003	1.0002	0.0006	9.5204E-01	1.0002	0.0031
hmf003-01	1.000	0.005	0.9936	0.0006	9.5363E-01	0.9936	0.0050
hmf003-02	1.000	0.005	0.9930	0.0006	9.6313E-01	0.9930	0.0050
hmf003-03	1.000	0.005	0.9983	0.0006	9.7168E-01	0.9983	0.0050
hmf003-04	1.000	0.003	0.9973	0.0006	9.8076E-01	0.9973	0.0031
hmf003-05	1.000	0.003	1.0011	0.0006	9.8120E-01	1.0011	0.0031
hmf003-07	1.000	0.003	1.0001	0.0006	9.7250E-01	1.0001	0.0031
hmf003-08	1.000	0.005	1.0086	0.0006	7.1963E-01	1.0086	0.0050
hmf003-09	1.000	0.005	1.0091	0.0006	6.6725E-01	1.0091	0.0050
hmf003-10	1.000	0.005	1.0097	0.0006	6.3202E-01	1.0097	0.0050
hmf003-11	1.000	0.005	1.0138	0.0006	6.2351E-01	1.0138	0.0050
hmf003-12	1.000	0.003	1.0055	0.0006	7.7610E-01	1.0055	0.0031
hmf004	1.0020	0.0035	1.0012	0.0006	5.1839E-01	0.9992	0.0036
hmf005-01	1.0000	0.0036	1.0072	0.0006	6.4957E-01	1.0072	0.0036
hmf005-02	1.0007	0.0036	1.0046	0.0006	5.4844E-01	1.0039	0.0036
hmf005-03	0.9996	0.0036	1.0125	0.0006	4.9550E-01	1.0129	0.0036
hmf005-04	0.9989	0.0036	0.9940	0.0006	4.6375E-01	0.9951	0.0036
hmf005-05	0.9980	0.0036	0.9991	0.0006	5.6246E-01	1.0011	0.0036
hmf005-06	0.9987	0.0036	0.9997	0.0006	6.0605E-01	1.0010	0.0036
hmf007-01	0.9950	0.0024	0.9899	0.0006	9.6913E-01	0.9949	0.0025
hmf007-02	0.9964	0.0014	0.9968	0.0006	7.8237E-01	1.0004	0.0015

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf007-03	0.9990	0.0013	0.9989	0.0006	7.2200E-01	0.9999	0.0014
hmf007-04	0.9948	0.0013	0.9964	0.0006	6.7382E-01	1.0016	0.0014
hmf007-05	0.9978	0.0018	0.9976	0.0006	5.9571E-01	0.9998	0.0019
hmf007-06	1.0006	0.0013	1.0027	0.0006	5.5688E-01	1.0021	0.0014
hmf007-07	0.9974	0.0014	0.9989	0.0006	5.4216E-01	1.0015	0.0015
hmf007-08	0.9973	0.0013	0.9974	0.0006	5.3936E-01	1.0001	0.0014
hmf007-09	0.9995	0.0056	1.0013	0.0006	5.5106E-01	1.0018	0.0056
hmf007-10	0.9981	0.0012	0.9969	0.0006	1.8311E-01	0.9988	0.0013
hmf007-11	0.9958	0.0013	0.9957	0.0006	1.0626E-02	0.9999	0.0014
hmf007-12	0.9932	0.0012	0.9920	0.0006	5.9426E-03	0.9988	0.0013
hmf007-13	0.9990	0.0012	0.9979	0.0006	6.9194E-03	0.9989	0.0013
hmf007-14	0.9964	0.0012	0.9953	0.0006	5.3476E-03	0.9989	0.0013
hmf007-15	0.9959	0.0012	0.9947	0.0006	8.2409E-03	0.9988	0.0013
hmf007-16	0.9969	0.0012	0.9964	0.0006	7.9469E-03	0.9995	0.0013
hmf007-17	0.9953	0.0012	0.9952	0.0006	2.4851E-04	0.9999	0.0013
hmf007-18	0.9972	0.0012	0.9983	0.0006	2.3068E-04	1.0011	0.0013
hmf007-19	0.9956	0.0015	0.9950	0.0006	9.5895E-01	0.9994	0.0016
hmf007-20	0.9950	0.0017	0.9967	0.0006	6.0300E-01	1.0017	0.0018
hmf007-21	0.9956	0.0018	0.9969	0.0006	5.8542E-01	1.0013	0.0019
hmf007-22	0.9963	0.0019	0.9975	0.0006	5.6798E-01	1.0012	0.0020
hmf007-23	0.9962	0.0017	0.9969	0.0006	4.2782E-01	1.0007	0.0018
hmf007-24	0.9970	0.0018	0.9979	0.0006	4.2038E-01	1.0009	0.0019
hmf007-25	0.9959	0.0018	0.9962	0.0006	2.6761E-01	1.0003	0.0019
hmf007-26	0.9966	0.0017	0.9969	0.0006	2.5828E-01	1.0003	0.0018
hmf007-27	0.9948	0.0014	0.9940	0.0006	7.5958E-01	0.9992	0.0015
hmf007-28	0.9970	0.0023	0.9973	0.0006	6.2519E-01	1.0003	0.0024
hmf007-29	0.9961	0.0014	0.9974	0.0006	4.9641E-01	1.0013	0.0015

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf007-30	0.9964	0.0021	0.9959	0.0006	1.2517E-01	0.9995	0.0022
hmf007-31	0.9996	0.0022	0.9999	0.0006	1.6433E-03	1.0003	0.0023
hmf007-32	0.9941	0.0012	1.0026	0.0006	8.6959E-01	1.0085	0.0013
hmf007-33	0.9977	0.0019	1.0144	0.0006	8.1143E-01	1.0167	0.0020
hmf007-34	0.9959	0.0017	1.0173	0.0006	7.5847E-01	1.0214	0.0018
hmf007-35	1.0003	0.0018	1.0007	0.0006	3.1077E-01	1.0004	0.0019
hmf007-36	0.9999	0.0007	1.0017	0.0006	9.1586E-02	1.0018	0.0009
hmf007-37	0.9988	0.0008	1.0003	0.0006	1.2358E-02	1.0015	0.0010
hmf007-38	1.0000	0.0008	1.0017	0.0006	8.5425E-03	1.0017	0.0010
hmf007-39	1.0018	0.0014	1.0040	0.0006	7.7317E-03	1.0022	0.0015
hmf007-40	1.0013	0.0008	1.0050	0.0006	9.4234E-03	1.0037	0.0010
hmf007-41	0.9994	0.0009	1.0003	0.0006	3.0613E-04	1.0009	0.0011
hmf007-42	1.0016	0.0009	1.0022	0.0006	2.8146E-04	1.0006	0.0011
hmf007-43	0.9998	0.0008	1.0002	0.0006	1.3336E-05	1.0004	0.0010
hmf008	0.9989	0.0016	0.9921	0.0006	9.3784E-01	0.9932	0.0017
hmf009-01	0.9992	0.0015	0.9953	0.0006	8.0773E-01	0.9961	0.0016
hmf009-02	0.9992	0.0015	0.9942	0.0006	8.1411E-01	0.9950	0.0016
hmf010-01	0.9992	0.0015	0.9967	0.0006	8.2332E-01	0.9975	0.0016
hmf010-02	0.9992	0.0015	0.9961	0.0006	8.2350E-01	0.9969	0.0016
hmf011	0.9989	0.0015	0.9975	0.0006	5.1018E-01	0.9986	0.0016
hmf012	0.9992	0.0018	0.9941	0.0006	9.0522E-01	0.9949	0.0019
hmf013	0.9990	0.0015	0.9940	0.0006	8.8380E-01	0.9950	0.0016
hmf014	0.9989	0.0017	0.9947	0.0006	9.1952E-01	0.9958	0.0018
hmf015	0.9996	0.0017	0.9931	0.0006	9.6576E-01	0.9935	0.0018
hmf016-01	0.9996	0.0018	0.9985	0.0006	7.5736E-01	0.9989	0.0019
hmf016-02	0.9996	0.0018	0.9995	0.0006	7.7561E-01	0.9999	0.0019
hmf017	0.9993	0.0014	1.0050	0.0006	6.2329E-01	1.0057	0.0015

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf018	1.0000	0.0016	0.9961	0.0006	9.3677E-01	0.9961	0.0017
hmf019	1.0000	0.0030	1.0030	0.0006	8.6377E-01	1.0030	0.0031
hmf020	1.0000	0.0042	0.9969	0.0006	8.1558E-01	0.9969	0.0042
hmf021	1.0000	0.0026	0.9948	0.0006	8.4523E-01	0.9948	0.0027
hmf022	1.0000	0.0021	0.9932	0.0006	8.8694E-01	0.9932	0.0022
hmf024	0.9990	0.0015	0.9962	0.0006	6.2837E-01	0.9972	0.0016
hmf025-01	0.9987	0.0014	0.9963	0.0006	9.4788E-01	0.9976	0.0015
hmf025-02	0.9990	0.0016	0.9977	0.0006	9.3347E-01	0.9987	0.0017
hmf025-03	0.9991	0.0016	0.9999	0.0006	9.1356E-01	1.0008	0.0017
hmf025-04	0.9995	0.0016	1.0012	0.0006	8.9829E-01	1.0017	0.0017
hmf025-05	0.9991	0.0016	1.0027	0.0006	8.9553E-01	1.0036	0.0017
hmf028	1.0000	0.0030	1.0026	0.0006	9.7850E-01	1.0026	0.0031
hmf029	1.0000	0.0030	1.0027	0.0006	9.1858E-01	1.0027	0.0031
hmf030	1.0000	0.0009	1.0064	0.0006	3.7165E-01	1.0064	0.0011
hmf031	1.0000	0.0059	1.0024	0.0006	2.3687E-01	1.0024	0.0059
hmf032-01	1.0000	0.0016	1.0031	0.0006	9.6687E-01	1.0031	0.0017
hmf032-02	1.0000	0.0027	1.0042	0.0006	9.6361E-01	1.0042	0.0028
hmf032-03	1.0000	0.0017	0.9986	0.0006	9.4863E-01	0.9986	0.0018
hmf032-04	1.0000	0.0017	0.9982	0.0006	9.4336E-01	0.9982	0.0018
hmf033-01	0.9991	0.0014	0.9978	0.0006	1.0135E-01	0.9987	0.0015
hmf033-02	0.9991	0.0014	0.9966	0.0006	5.5136E-03	0.9975	0.0015
hmf034-01	0.9990	0.0012	0.9942	0.0006	2.2703E-01	0.9952	0.0013
hmf034-02	0.9990	0.0012	0.9964	0.0006	2.1491E-01	0.9974	0.0013
hmf034-03	0.9990	0.0012	0.9973	0.0006	2.3278E-01	0.9983	0.0013
hmf036-01	0.9993	0.0015	0.9954	0.0006	5.2905E-02	0.9961	0.0016
hmf036-02	0.9993	0.0013	0.9940	0.0006	3.8207E-01	0.9947	0.0014
hmf037-01	0.9997	0.0011	0.9983	0.0006	9.2154E-02	0.9986	0.0013

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf037-02	0.9997	0.0011	0.9926	0.0006	2.7785E-01	0.9929	0.0013
hmf038-01	0.9999	0.0007	0.9977	0.0006	3.8965E-01	0.9978	0.0009
hmf038-02	0.9999	0.0009	1.0066	0.0006	2.5693E-01	1.0067	0.0011
hmf041-01	1.0013	0.0030	1.0066	0.0006	7.0047E-01	1.0053	0.0031
hmf041-02	1.0022	0.0043	1.0061	0.0006	4.8604E-01	1.0039	0.0043
hmf041-03	1.0006	0.0029	0.9994	0.0006	8.5102E-01	0.9988	0.0030
hmf041-04	1.0006	0.0025	1.0058	0.0006	7.8917E-01	1.0052	0.0026
hmf041-05	1.0006	0.0031	1.0004	0.0006	7.3817E-01	0.9998	0.0032
hmf041-06	1.0006	0.0045	1.0030	0.0006	7.0138E-01	1.0024	0.0045
hmf048-01	0.9998	0.0027	1.0024	0.0006	4.5290E-01	1.0026	0.0028
hmf048-02	1.0001	0.0033	1.0022	0.0006	2.2993E-01	1.0021	0.0034
hmf048-03	1.0002	0.0031	1.0019	0.0006	1.1706E-02	1.0017	0.0032
hmf048-04	0.9988	0.0030	1.0019	0.0006	2.8951E-03	1.0031	0.0031
hmf048-05	0.9996	0.0041	0.9937	0.0006	5.2743E-04	0.9941	0.0041
hmf048-06	1.0012	0.0034	1.0009	0.0006	3.8636E-01	0.9997	0.0035
hmf048-07	0.9998	0.0050	1.0010	0.0006	3.2077E-01	1.0012	0.0050
hmf048-08	0.9981	0.0047	0.9974	0.0006	1.8404E-01	0.9993	0.0047
hmf048-09	0.9983	0.0024	0.9963	0.0006	1.2259E-01	0.9980	0.0025
hmf048-10	0.9985	0.0046	0.9968	0.0006	2.1588E-02	0.9983	0.0046
hmf048-11	0.9997	0.0039	1.0025	0.0006	3.9165E-01	1.0028	0.0039
hmf048-12	1.0005	0.0046	1.0002	0.0006	2.4827E-01	0.9997	0.0046
hmf048-13	0.9989	0.0036	1.0036	0.0006	1.3038E-01	1.0047	0.0036
hmf048-14	1.0011	0.0049	0.9988	0.0006	3.7956E-01	0.9977	0.0049
hmf048-15	0.9981	0.0062	0.9974	0.0006	3.6507E-01	0.9993	0.0062
hmf048-16	0.9988	0.0040	0.9912	0.0006	3.3234E-01	0.9924	0.0040
hmf048-17	0.9978	0.0054	0.9888	0.0006	2.8347E-01	0.9910	0.0054
hmf051-01	0.9971	0.0005	0.9926	0.0006	9.6361E-01	0.9955	0.0008

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf051-02	0.9968	0.0005	0.9947	0.0006	9.6308E-01	0.9979	0.0008
hmf051-03	0.9974	0.0005	0.9929	0.0006	9.6482E-01	0.9955	0.0008
hmf051-04	0.9969	0.0005	0.9929	0.0006	9.6608E-01	0.9960	0.0008
hmf051-05	0.9975	0.0003	0.9934	0.0006	9.6630E-01	0.9959	0.0007
hmf051-06	0.9974	0.0004	0.9928	0.0006	9.6730E-01	0.9954	0.0007
hmf051-07	0.9975	0.0003	0.9934	0.0006	9.6567E-01	0.9959	0.0007
hmf051-08	0.9976	0.0003	0.9927	0.0006	9.6538E-01	0.9951	0.0007
hmf051-09	0.9982	0.0002	0.9928	0.0006	9.6396E-01	0.9946	0.0006
hmf051-10	0.9981	0.0002	0.9923	0.0006	9.6720E-01	0.9942	0.0006
hmf051-11	0.9973	0.0001	0.9919	0.0006	9.6738E-01	0.9946	0.0006
hmf051-12	0.9966	0.0002	0.9928	0.0006	9.6660E-01	0.9962	0.0006
hmf051-13	0.9979	0.0002	0.9943	0.0006	9.6573E-01	0.9964	0.0006
hmf051-14	0.9996	0.0002	0.9964	0.0006	9.5541E-01	0.9968	0.0006
hmf051-15	0.9998	0.0001	0.9962	0.0006	9.5877E-01	0.9964	0.0006
hmf051-16	0.9981	0.0001	0.9945	0.0006	9.6492E-01	0.9964	0.0006
hmf051-17	0.9969	0.0001	0.9931	0.0006	9.6904E-01	0.9962	0.0006
hmf051-18	0.9984	0.0002	0.9926	0.0006	9.7154E-01	0.9942	0.0006
hmf055	0.9955	0.0028	0.9975	0.0006	4.2007E-01	1.0020	0.0029
hmf058-01	1.0000	0.0026	1.0059	0.0006	3.6124E-01	1.0059	0.0027
hmf058-02	1.0000	0.0035	1.0053	0.0006	5.4459E-01	1.0053	0.0036
hmf058-03	1.0000	0.0027	1.0035	0.0006	6.7144E-01	1.0035	0.0028
hmf058-04	1.0000	0.0021	1.0006	0.0006	7.6452E-01	1.0006	0.0022
hmf058-05	1.0000	0.0033	0.9988	0.0006	8.1446E-01	0.9988	0.0034
hmf061	0.9998	0.0025	1.0037	0.0006	4.6030E-01	1.0039	0.0026
hmf062	0.9987	0.001	1.0040	0.0006	9.4033E-01	1.0053	0.0012
hmf063-01	0.9993	0.0040	0.9973	0.0006	8.5174E-01	0.9980	0.0040
hmf063-02	0.9988	0.0047	0.9986	0.0006	8.2432E-01	0.9998	0.0047

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf065	0.9995	0.0013	0.9950	0.0006	9.6589E-01	0.9955	0.0014
hmf066-01	1.0030	0.0033	1.0047	0.0006	4.8214E-01	1.0017	0.0034
hmf066-02	1.0023	0.0029	1.0024	0.0006	6.1315E-01	1.0001	0.0030
hmf066-03	1.0023	0.0026	1.0036	0.0006	6.8200E-01	1.0013	0.0027
hmf066-04	1.0043	0.0043	1.0077	0.0006	3.0300E-01	1.0034	0.0043
hmf066-05	1.0030	0.0033	1.0056	0.0006	4.6226E-01	1.0026	0.0034
hmf066-06	1.0028	0.0030	1.0044	0.0006	5.4809E-01	1.0016	0.0031
hmf066-07	1.0048	0.0039	1.0071	0.0006	4.3244E-01	1.0023	0.0039
hmf066-08	1.0039	0.0040	1.0069	0.0006	3.3050E-01	1.0030	0.0040
hmf066-09	1.0027	0.0036	1.0047	0.0006	4.2305E-01	1.0020	0.0036
hmf071-01	0.9991	0.0003	0.9972	0.0006	7.9292E-01	0.9981	0.0007
hmf071-02	1.0007	0.0002	0.9992	0.0006	7.3467E-01	0.9985	0.0006
hmf071-03	1.0021	0.0004	0.9996	0.0006	8.1252E-01	0.9975	0.0007
hmf071-04	1.0028	0.0005	0.9984	0.0006	8.4408E-01	0.9956	0.0008
hmf071-04a	1.0003	0.0004	0.9964	0.0006	8.4734E-01	0.9961	0.0007
hmf071-05	1.0014	0.0005	0.9975	0.0006	8.8633E-01	0.9961	0.0008
hmf071-05a	0.9997	0.0004	0.9962	0.0006	8.8544E-01	0.9965	0.0007
hmf071-06	1.0030	0.0005	1.0014	0.0006	7.7983E-01	0.9984	0.0008
hmf071-07	1.0033	0.0005	0.9995	0.0006	8.1517E-01	0.9962	0.0008
hmf071-08	0.9997	0.0004	0.9976	0.0006	8.6504E-01	0.9979	0.0007
hmf071-09	1.0018	0.0005	0.9965	0.0006	8.8395E-01	0.9947	0.0008
hmf071-10	1.0002	0.0005	0.9980	0.0006	7.8850E-01	0.9978	0.0008
hmf071-11	1.0010	0.0005	0.9989	0.0006	8.1007E-01	0.9979	0.0008
hmf071-12	0.9984	0.0004	0.9967	0.0006	7.9808E-01	0.9983	0.0007
hmf071-12a	0.9995	0.0003	0.9945	0.0006	7.9886E-01	0.9950	0.0007
hmf071-12b	1.0010	0.0003	0.9990	0.0006	7.9320E-01	0.9980	0.0007
hmf071-13	1.0005	0.0004	0.9956	0.0006	7.4556E-01	0.9951	0.0007

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf071-14	1.0008	0.0005	0.9982	0.0006	8.1292E-01	0.9974	0.0008
hmf071-15	1.0011	0.0005	0.9968	0.0006	8.4856E-01	0.9957	0.0008
hmf071-16	0.9994	0.0006	0.9957	0.0006	8.8374E-01	0.9963	0.0008
hmf071-16a	1.0003	0.0005	0.9967	0.0006	8.8543E-01	0.9964	0.0008
hmf071-17	1.0011	0.0005	0.9987	0.0006	7.8137E-01	0.9976	0.0008
hmf071-18	1.0010	0.0005	0.9988	0.0006	8.1704E-01	0.9978	0.0008
hmf071-19	0.9990	0.0004	0.9968	0.0006	8.0685E-01	0.9978	0.0007
hmf071-20	0.9987	0.0003	0.9952	0.0006	8.8296E-01	0.9965	0.0007
hmf071-21	1.0023	0.0005	0.9998	0.0006	7.4787E-01	0.9975	0.0008
hmf071-22	1.0028	0.0005	1.0002	0.0006	8.1461E-01	0.9974	0.0008
hmf076-01	0.9994	0.0006	0.9947	0.0006	8.6234E-01	0.9953	0.0008
hmf076-02	1.0008	0.0006	0.9966	0.0006	7.9009E-01	0.9958	0.0008
hmf076-03	1.0000	0.0005	0.9963	0.0006	7.9235E-01	0.9963	0.0008
hmf079-01	0.9996	0.0015	0.9979	0.0006	9.5675E-01	0.9983	0.0016
hmf079-02	0.9996	0.0014	0.9961	0.0006	9.5202E-01	0.9965	0.0015
hmf079-03	0.9996	0.0015	0.9974	0.0006	9.4280E-01	0.9978	0.0016
hmf079-04	0.9996	0.0014	0.9958	0.0006	9.3106E-01	0.9962	0.0015
hmf079-05	0.9996	0.0015	0.9957	0.0006	9.3255E-01	0.9961	0.0016
hmi001	0.9966	0.0026	1.0087	0.0006	5.7252E-02	1.0121	0.0027
hmi006-01	0.9977	0.0008	0.9934	0.0006	3.5906E-03	0.9957	0.0010
hmi006-02	1.0001	0.0008	0.9967	0.0006	8.1888E-03	0.9966	0.0010
hmi006-03	1.0015	0.0009	1.0104	0.0006	2.4694E-02	1.0089	0.0011
hmi006-04	1.0016	0.0008	1.0195	0.0006	1.0548E-01	1.0179	0.0010
hmi009-01	0.9975	0.0030	0.9964	0.0007	2.0396E-04	0.9989	0.0031
hmi009-02	0.9950	0.0048	0.9971	0.0006	3.1875E-05	1.0021	0.0048
hmt001	1.0010	0.0060	1.0081	0.0006	5.0367E-08	1.0071	0.0060
hmt003-01	1.0000	0.0010	0.9998	0.0006	4.3643E-01	0.9998	0.0012

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmt003-02	0.9910	0.0030	0.9805	0.0006	4.3223E-01	0.9895	0.0031
hmt003-03	0.9826	0.0060	0.9661	0.0005	1.8302E-04	0.9835	0.0060
hmt003-04	0.9876	0.0040	0.9770	0.0006	5.6177E-06	0.9894	0.0040
hmt003-05	0.9930	0.0030	0.9821	0.0006	1.1618E-07	0.9891	0.0031
hmt003-06	0.9889	0.0030	0.9679	0.0006	4.4820E-07	0.9790	0.0031
hmt003-07	0.9919	0.0030	0.9792	0.0006	1.2444E-07	0.9873	0.0031
hmt009	1.0009	0.0063	0.9990	0.0006	5.1447E-08	0.9981	0.0063
hmt010-02	1.0061	0.0072	1.0110	0.0006	4.8085E-08	1.0049	0.0072
hmt025-01	1.0037	0.0047	1.0205	0.0007	5.2434E-07	1.0168	0.0048
hmt025-02	1.0007	0.0054	1.0064	0.0007	6.7714E-08	1.0057	0.0054
hmt027-01	0.9947	0.0028	0.9992	0.0007	1.0383E-06	1.0045	0.0029
hmt027-02	0.9954	0.0027	1.0035	0.0007	2.0569E-07	1.0081	0.0028
hmt027-03	0.9946	0.0026	1.0045	0.0006	1.7730E-07	1.0099	0.0027
hmt027-04	0.9957	0.0023	1.0050	0.0006	9.2227E-08	1.0093	0.0024
hmt027-05	0.9965	0.0022	1.0024	0.0007	8.8296E-08	1.0059	0.0023
hmt027-06	0.9964	0.0021	1.0055	0.0007	8.4654E-08	1.0091	0.0022
hmt027-07	0.9964	0.0035	1.0053	0.0007	6.1553E-08	1.0089	0.0036
hmt027-08	0.9953	0.0034	1.0005	0.0007	6.0193E-08	1.0052	0.0035
hmt027-09	0.9950	0.0025	1.0047	0.0007	6.0212E-08	1.0097	0.0026
hmt027-10	0.9962	0.0022	1.0049	0.0007	6.0040E-08	1.0087	0.0023
hmt027-11	0.9956	0.0035	1.0056	0.0007	4.7246E-08	1.0100	0.0036
hmt027-12	0.9971	0.0032	1.0122	0.0007	4.7311E-08	1.0151	0.0033
hmt027-13	0.9945	0.0036	1.0165	0.0007	4.6936E-08	1.0220	0.0037
hmt027-14	0.9970	0.0032	1.0075	0.0007	4.6948E-08	1.0105	0.0033
hmt027-15	0.9962	0.0023	1.0122	0.0007	4.0237E-08	1.0160	0.0024
hmt031	1.0037	0.0024	1.0096	0.0006	4.4360E-08	1.0059	0.0025
hmm001	0.9995	0.0013	0.9999	0.0006	3.5041E-02	1.0004	0.0014

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmm002	1.0000	0.0037	1.0056	0.0006	1.2103E-02	1.0056	0.0037
hmm003	1.0000	0.0038	1.0072	0.0006	1.2489E-02	1.0072	0.0038
hmm004	0.9999	0.0009	1.0029	0.0006	1.0291E-03	1.0030	0.0011
hcm001-06	0.9953	0.0056	0.9934	0.0006	8.7228E-02	0.9981	0.0056
hcm001-07	0.9997	0.0038	0.9981	0.0006	8.7914E-02	0.9984	0.0038
hcm001-08	0.9984	0.0052	0.9916	0.0006	2.4529E-03	0.9932	0.0052
hcm001-10	0.9979	0.0052	0.9918	0.0006	5.8739E-04	0.9939	0.0052
hcm001-12	0.9972	0.0052	0.9945	0.0006	2.8572E-04	0.9973	0.0052
hcm001-13	1.0032	0.0053	0.9976	0.0006	2.1031E-04	0.9944	0.0053
hcm001-15	1.0083	0.0050	1.0061	0.0006	3.9984E-07	0.9978	0.0050
hcm001-16	1.0001	0.0046	0.9965	0.0006	4.1447E-07	0.9964	0.0046
hcm001-17	0.9997	0.0046	0.9924	0.0006	2.7973E-07	0.9927	0.0046
hcm001-18	1.0075	0.0046	0.9994	0.0006	2.2903E-07	0.9919	0.0046
hcm001-19	1.0039	0.0047	1.0104	0.0006	3.3725E-06	1.0065	0.0047
hcm001-20	1.0060	0.0065	1.0031	0.0006	8.9621E-04	0.9971	0.0065
hcm001-21	1.0026	0.0064	1.0024	0.0006	8.9423E-04	0.9998	0.0064
hcm001-22	1.0013	0.0064	0.9991	0.0006	8.8240E-04	0.9978	0.0064
hcm001-24	1.0020	0.0053	1.0003	0.0006	7.6395E-04	0.9983	0.0053
hcm001-25	0.9983	0.0053	0.9961	0.0006	7.2929E-04	0.9978	0.0053
hcm001-26	0.9998	0.0053	0.9991	0.0006	6.7210E-04	0.9993	0.0053
hcm001-27	0.9991	0.0053	0.9979	0.0006	6.3938E-04	0.9988	0.0053
hcm001-28	1.0037	0.0053	1.0018	0.0006	8.3129E-04	0.9981	0.0053
hcm001-29	0.9992	0.0052	0.9983	0.0006	8.1210E-04	0.9991	0.0052
hst004-01	1.0000	0.0033	0.9865	0.0006	1.6375E-05	0.9865	0.0034
hst004-02	1.0000	0.0036	0.9822	0.0005	1.7691E-06	0.9822	0.0036
hst004-03	1.0000	0.0039	0.9890	0.0006	5.0834E-07	0.9890	0.0039
hst004-04	1.0000	0.0046	0.9907	0.0005	2.3076E-07	0.9907	0.0046

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hst004-05	1.0000	0.0052	0.9896	0.0005	1.1461E-07	0.9896	0.0052
hst004-06	1.0000	0.0059	0.9878	0.0005	7.6065E-08	0.9878	0.0059
hst009-01	0.9990	0.0043	1.0018	0.0006	1.1970E-07	1.0028	0.0043
hst009-02	1.0000	0.0039	1.0020	0.0006	9.0902E-08	1.0020	0.0039
hst009-03	1.0000	0.0036	1.0014	0.0006	6.4772E-08	1.0014	0.0036
hst009-04	0.9986	0.0035	0.9965	0.0006	5.0394E-08	0.9979	0.0036
hst010-01	1.0000	0.0029	1.0019	0.0006	3.9737E-08	1.0019	0.0030
hst010-02	1.0000	0.0029	1.0009	0.0006	3.9857E-08	1.0009	0.0030
hst010-03	1.0000	0.0029	0.9999	0.0006	4.0550E-08	0.9999	0.0030
hst010-04	0.9992	0.0029	0.9963	0.0006	4.0886E-08	0.9971	0.0030
hst011-01	1.0000	0.0023	1.0054	0.0006	3.5149E-08	1.0054	0.0024
hst011-02	1.0000	0.0023	1.0023	0.0006	3.5097E-08	1.0023	0.0024
hst012	0.9999	0.0058	1.0016	0.0006	3.2287E-08	1.0017	0.0058
hst013-01	1.0012	0.0026	0.9983	0.0005	3.2284E-08	0.9971	0.0026
hst013-02	1.0007	0.0036	0.9977	0.0006	3.2896E-08	0.9970	0.0036
hst013-03	1.0009	0.0036	0.9937	0.0006	3.3449E-08	0.9928	0.0036
hst013-04	1.0003	0.0036	0.9946	0.0005	3.3750E-08	0.9943	0.0036
hst020-01	0.9966	0.0116	0.9915	0.0006	3.2234E-07	0.9949	0.0116
hst020-02	0.9956	0.0093	0.9965	0.0006	1.2702E-07	1.0009	0.0093
hst020-03	0.9957	0.0079	1.0069	0.0006	6.5026E-08	1.0112	0.0079
hst020-04	0.9955	0.0078	1.0035	0.0006	6.4863E-08	1.0080	0.0078
hst020-05	0.9959	0.0077	1.0102	0.0006	4.2825E-08	1.0143	0.0077
hst038-01	1.0000	0.0025	0.9957	0.0006	1.0797E-07	0.9957	0.0026
hst038-02	1.0000	0.0025	0.9956	0.0006	9.1894E-08	0.9956	0.0026
hst038-03	1.0000	0.0025	0.9962	0.0006	1.0238E-07	0.9962	0.0026
hst038-04	1.0000	0.0025	0.9966	0.0006	1.0799E-07	0.9966	0.0026
hst038-05	1.0000	0.0025	0.9958	0.0006	1.0805E-07	0.9958	0.0026

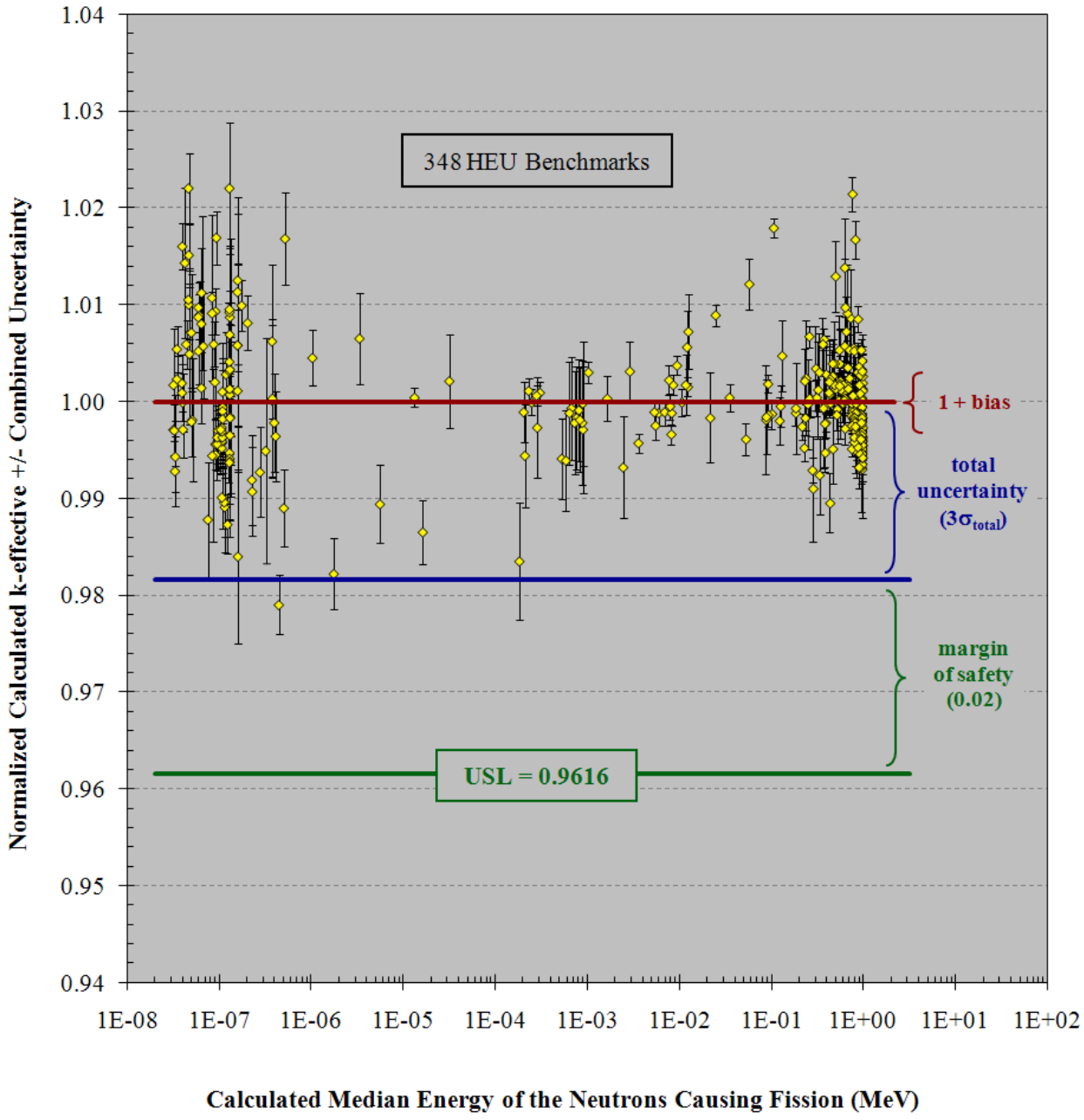
Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hst038-06	1.0000	0.0025	0.9945	0.0006	9.2748E-08	0.9945	0.0026
hst038-07	1.0000	0.0032	0.9959	0.0006	1.0260E-07	0.9959	0.0033
hst038-08	1.0000	0.0026	0.9962	0.0006	1.0214E-07	0.9962	0.0027
hst038-09	1.0000	0.0033	0.9959	0.0006	1.0184E-07	0.9959	0.0034
hst038-10	1.0000	0.0026	0.9959	0.0006	1.0340E-07	0.9959	0.0027
hst038-11	1.0000	0.0025	0.9973	0.0006	1.0797E-07	0.9973	0.0026
hst038-12	1.0000	0.0025	0.9952	0.0006	1.0787E-07	0.9952	0.0026
hst038-13	1.0000	0.0050	1.0010	0.0006	1.0963E-07	1.0010	0.0050
hst038-14	1.0000	0.0050	0.9994	0.0006	1.1026E-07	0.9994	0.0050
hst038-15	1.0000	0.0050	0.9990	0.0006	1.0988E-07	0.9990	0.0050
hst038-16	1.0000	0.0050	0.9982	0.0006	1.1015E-07	0.9982	0.0050
hst038-17	1.0000	0.0026	0.9962	0.0006	1.0766E-07	0.9962	0.0027
hst038-18	1.0000	0.0032	0.9963	0.0006	1.0785E-07	0.9963	0.0033
hst038-19	1.0000	0.0032	0.9959	0.0006	1.0823E-07	0.9959	0.0033
hst038-20	1.0000	0.0032	0.9963	0.0006	1.0791E-07	0.9963	0.0033
hst038-21	1.0000	0.0025	0.9970	0.0006	9.7752E-08	0.9970	0.0026
hst038-22	1.0000	0.0027	0.9956	0.0006	9.6082E-08	0.9956	0.0028
hst038-23	1.0000	0.0027	0.9963	0.0006	9.6221E-08	0.9963	0.0028
hst038-24	1.0000	0.0026	0.9963	0.0006	1.0980E-07	0.9963	0.0027
hst038-26	1.0000	0.0032	0.9969	0.0005	1.0803E-07	0.9969	0.0032
hst038-27	1.0000	0.0032	0.9901	0.0006	1.0824E-07	0.9901	0.0033
hst038-28	1.0000	0.0025	0.9971	0.0006	1.0525E-07	0.9971	0.0026
hst038-30	1.0000	0.0027	1.0169	0.0006	9.4216E-08	1.0169	0.0028
hst040-01	0.9957	0.0063	0.9988	0.0006	1.3066E-07	1.0031	0.0063
hst040-02	0.9920	0.0070	0.9885	0.0006	1.3195E-07	0.9965	0.0070
hst040-03	0.9929	0.0083	0.9998	0.0006	1.3170E-07	1.0069	0.0083
hst040-04	0.9911	0.0081	0.9998	0.0006	1.3213E-07	1.0087	0.0081

Table 3. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hst040-05	0.9922	0.0082	0.9906	0.0006	1.3217E-07	0.9984	0.0082
hst040-06	0.9926	0.0072	0.9933	0.0006	1.3210E-07	1.0007	0.0072
hst040-07	0.9914	0.0069	0.9947	0.0006	1.3225E-07	1.0033	0.0069
hst040-08	0.9932	0.0078	0.9915	0.0006	1.3255E-07	0.9983	0.0078
hst040-09	0.9938	0.0067	0.9951	0.0006	1.3161E-07	1.0013	0.0067
hst040-10	0.9934	0.0066	1.0026	0.0006	1.3074E-07	1.0092	0.0066
hst040-11	0.9941	0.0066	1.0036	0.0006	1.3074E-07	1.0095	0.0066
hst040-12	0.9953	0.0073	0.9994	0.0006	1.3039E-07	1.0041	0.0073
hst040-13	0.9975	0.0069	0.9922	0.0006	1.3062E-07	0.9947	0.0069
hst040-14	0.9968	0.0068	1.0188	0.0006	1.3046E-07	1.0220	0.0068
hst040-15	0.9931	0.0062	0.9872	0.0006	1.3127E-07	0.9941	0.0062
hst040-16	0.9953	0.0060	0.9891	0.0006	1.3168E-07	0.9938	0.0060
hst040-17	0.9962	0.0077	0.9899	0.0006	1.3049E-07	0.9937	0.0077
hst050-01	0.9953	0.0086	1.0078	0.0006	1.6037E-07	1.0125	0.0086
hst050-02	0.9987	0.0083	1.0045	0.0006	1.6016E-07	1.0058	0.0083
hst050-03	0.9984	0.0079	1.0046	0.0006	3.7850E-07	1.0062	0.0079
hst050-04	0.9987	0.0084	1.0045	0.0006	1.5975E-07	1.0058	0.0084
hst050-05	0.9985	0.0085	1.0092	0.0006	8.4232E-08	1.0107	0.0085
hst050-06	0.9985	0.0081	1.0098	0.0006	1.5981E-07	1.0113	0.0081
hst050-07	0.9978	0.0078	0.9979	0.0006	3.8048E-07	1.0001	0.0078
hst050-08	0.9975	0.0084	0.9986	0.0006	1.6035E-07	1.0011	0.0084
hst050-09	0.9966	0.0082	0.9969	0.0006	3.8209E-07	1.0003	0.0082
hst050-10	0.9960	0.0090	0.9800	0.0006	1.6157E-07	0.9840	0.0090
hst050-11	0.9964	0.0089	0.9908	0.0006	8.4946E-08	0.9944	0.0089
348 total cases							

Figure 1. HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library



5.0 Recommended Upper Subcritical Limit

A conservative limit to differentiate subcritical from critical conditions by computation with the COG 10 code system and the ENDFB6R7 neutron cross section library on the *Surya* workstation for general application to HEU systems is:

$$k_{calculated} + 3\sigma_{calculated} \leq USL = 0.9616$$

which satisfies the criterion:

$$k_{calculated} + 3\sigma_{calculated} \leq USL = \{1 + bias\} - \{3\sigma_{total}\} - \{0.02\}$$

This criterion ensures better than 99.8% confidence that the USL lays below the 348 selected HEU benchmark results with an additional 0.02 margin of safety.

Some applications may warrant a lower limit if a higher confidence or a larger margin of safety is desired. Conversely, some applications may warrant a higher limit if a lower confidence or smaller margin of safety is justified. Results may also vary with the statistical methodology or the number and combination of selected HEU benchmarks.

6.0 References

1. *COG: A Multiparticle Monte Carlo Transport Code, Version 10*, **CCC-724**, contributed by the Lawrence Livermore National Laboratory to the Radiation Safety Information Computational Center at the Oak Ridge National Laboratory, released February 2006.

2. **CSAM 06-102**, *Installation and Verification of COG 10 Code on Unclassified Workstation Surya*, Shang-Chih Philip Chou, July 19, 2006.

3. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, **NEA/NSC/DOC(95)03**, Organization for Economic Cooperation and Development, Nuclear Energy Agency, Paris, France (September 2008 edition).

Appendix A. Supplemental HEU Benchmark Results on the *Surya* Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library (nlib2=RED2002 pb)

Evaluation ID	Title	Number Selected
HEU-MET-FAST-027	Spherical Assembly of ^{235}U(90%) with a 3.25-cm Lead Reflector	1
HEU-MET-FAST-057	Highly Enriched Uranium Metal Spheres and Cylinders Reflected by Lead	6
HEU-MET-FAST-064	Three Cylinders of Lead-Reflected Highly Enriched Uranium	1
HEU-SOL-THERM-038	WINCO Slab Tanks: Two Interacting Tanks of Highly Enriched Uranyl Nitrate Solution with Various Absorber-Reflector Plates	2

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hmf027	1.0000	0.0025	1.0069	0.0006	9.0257E-01	1.0069	0.0026
hmf057-01	1.0000	0.0020	1.0244	0.0006	8.1427E-01	1.0244	0.0021
hmf057-02	1.0000	0.0023	1.0256	0.0006	8.4624E-01	1.0256	0.0024
hmf057-03	1.0000	0.0032	1.0539	0.0006	8.0700E-01	1.0539	0.0033
hmf057-04	1.0000	0.0040	1.0124	0.0006	8.5798E-01	1.0124	0.0040
hmf057-05	1.0000	0.0019	1.0629	0.0006	7.9238E-01	1.0629	0.0020
hmf057-06	1.0000	0.0029	1.0313	0.0006	8.1707E-01	1.0313	0.0030
hmf064-01	0.9996	0.0008	1.0353	0.0006	8.0757E-01	1.0357	0.0010
hst038-25	1.0000	0.0032	0.9960	0.0006	1.0799E-07	0.9960	0.0033
hst038-29	1.0000	0.0025	1.0425	0.0006	1.0000E-07	1.0425	0.0026