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Criticality Safety Evaluation of a LLNL Training Assembly for Criticality Safety (TACS)

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Auspices Statement

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1.0 INTRODUCTION

Hands-on experimental training in the physical behavior of multiplying systems is one of ten key areas of training required for practitioners to become qualified in the discipline of criticality safety as identified in DOE-STD-1135-99, *Guidance for Nuclear Criticality Safety Engineer Training and Qualification*.

This document is a criticality safety evaluation of the training activities (or operations) associated with HS-3200, *Laboratory Class for Criticality Safety*. These activities utilize the Training Assembly for Criticality Safety (TACS).

The original intent of HS-3200 was to provide LLNL fissile material handlers with a practical hands-on experience as a supplement to the academic training they receive biennially in HS-3100, *Fundamentals of Criticality Safety*, as required by ANSI/ANS-8.20-1991, *Nuclear Criticality Safety Training*.

HS-3200 is to be enhanced to also address the training needs of nuclear criticality safety professionals under the auspices of the NNSA Nuclear Criticality Safety Program[1].

2.0 REQUIREMENTS

This document is provided in response to a Livermore Site Office[2] (previously a part of the DOE Oakland Operations Office) identified need for a new criticality safety evaluation to revise and supercede the preliminary study[3] by Koponen.

This document satisfies the format and content requirements of DOE-STD-3007-93, Change Notice No. 1, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Non-Reactor Nuclear Facilities*. The document also satisfies additional LLNL content requirements specified in CSG-P-004, Rev. 3, *Criticality Safety Evaluations*.

3.0 DESCRIPTION

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[1] David H. Crandall, letter to A. J. Eggenberger, February 8, 2006.

[2] Carol Sohn, letter to Alan Copeland, Subject: USQ 334-98-02, “Training Assembly for Criticality Safety (TACS) Use in B334”, June 17, 1999.

[3] CSM-279, *Preliminary Criticality Study for Criticality Training Assembly*, CSM-279, Brian Koponen, Lawrence Livermore National Laboratory, April 19, 1977.

Crites[4] and Barnett[5] have published descriptions of the TACS. Details of the assembly machine[6] and associated parts are available in drawings, COMATS[7], and a detailed inspection report[8]. Drawings of the D-38[9] and Oy[10] hemishells, chemical analysis results from samples of the Lucite and D-38 parts, and an engineering note on the Am-Li neutron source are also available. The relevant part details used in developing the COG model of the TACS assembly (see Section 6) are summarized in the tables below.

Table 3-1. TACS Fissile (Oy) Parts

COMATS	Part Weight (kilograms)			Minimum Inner
S/N	Oy-0.25Ni	Oy	U-235	Radius (inches)
18325	2.7271	2.7110	2.5250	2.3350
18326	2.7313	2.7270	2.5410	2.3330
500154	3.0703	3.0650	2.8560	2.5745
500155	3.0709	3.0700	2.8600	2.5730
500156	2.2959	2.2930	2.1360	2.7985
500157	2.2994	2.2960	2.1390	2.7975
23184	3.0978	3.0820	2.8770	2.9470
23181	3.1208	3.1130	2.8990	2.9450
Total	22.4135	22.3570	20.8330	--

Table 3-2. TACS Mock (D-38) Parts

Part	D-38 Parts		Minimum Inner
S/N	Weight (kilograms)	Density (g/cc)	Radius (inches)
003-3	2.7834	18.8998	2.3393
001-3	2.7851	18.8895	2.3393
003-2	3.1091	18.9002	2.5764
001-2	3.1136	18.8699	2.5763
003-1	2.3523	18.9102	2.7996
001-1	2.3617	18.8605	2.7996
004	3.2128	18.9089	2.9495
002	3.2136	18.9303	2.9495

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4 Preprint UCRl-82780, *A Training Facility for Criticality Safety*, T. R. Crites, T. J. Powell and G. E. Williams, August 30, 1979.

5 UCRL-53657, *An Experimental Study of Neutron Noise with Criticality Safety Applications in Mind*, Charles S. Barnett (Ph.D. thesis), November 1985.

6 Drawing No. AAA78-103783-00, *H.C. Criticality Assy. Fixture*.

7 Inventory Report for Owner 381872, Heinrichs, David P., 11/03/95.

8 Inspection Reports for Jerry Smith/Tom Anklam, *Neutron Multiplication Study*, MMED WO # M0004241/M0004986.

9 Drawing No. AAA82-108665-00, *Neutron Multiplication Study, Nesting Shells*

10 Drawing No. AAA00-113250-00, *Training Configuration Half Shells*

Total	22.9316	18.8971	--

One D-38 part has been assayed[11] at LLNL and confirmed to contain 0.2 wt-% ^{235}U.

The Lucite moderator parts are hemi-shells with a common outer radius so that only two parts will nest within the Oy (or D-38) cavity. The maximum authorized moderator mass is 694.8 grams corresponding to parts M3A and M3B.

Table 3-3. TACS Moderator (Lucite) Parts

Part	Lucite Parts		Minimum Inner
S/N	Weight (grams)	Density (g/cc)	Radius (inches)
M1A	156.0	1.1885	2.0469
M1B	156.9	1.1881	2.0466
M2A	265.7	1.1884	1.8115
M2B	264.8	1.1886	1.8074
M3A	347.8	1.1888	1.5796
M3B	347.0	1.1885	1.5757

The maximum (average) Lucite reflector thickness is 3.94 inches (or 10.0 cm) obtained by nesting R2A and R2B within R3A and R3B.

Table 3-4. TACS Reflector (Lucite and Cadmium) Parts

Part	Lucite and Cadmium Parts		Minimum Inner
S/N	Weight (kilograms)	Density (g/cc)	Radius (inches)
R1A	1.2027	1.1893	3.1372
R1B	1.2024	1.1881	3.1324
R2A	4.1481	1.1877	3.1368
R2B	4.1532	1.1878	3.1374
R3A	9.0204	1.1875	5.1062
R3B	9.0157	1.1876	5.1063
Cd-1	0.2412	8.5731	3.1537
Cd-2	0.2464	8.5748	3.1667
R4A	4.0066	1.1885	3.1987
R4B	3987.3	1.1884	3.1997

The measured thickness of the cadmium hemishells ranges from 22 – 31 mils for part Cd-1 and 19 – 32 mils for part Cd-2. These hemishells are designed to nest

[11] Philip Miller, email to Rich Evarts (November 10, 2000).

snuggly within Lucite reflector parts R4A and R4B, which in turn may be nested within R3A and R3B.

A diaphragm separates the two halves of the TACS assembly. It has been measured and determined to be a 0.010-inch thick Al-6061 sheet with a central 1-inch inner diameter hole that accommodate the source and an outer diameter of 17.468 inches. A new, stiffer, 0.030-inch thick Al-6061 diaphragm may be fabricated for future use. The Al-6061 neutron source holder has yet to be designed and fabricated.

4.0 METHODOLOGY

This criticality safety evaluation uses two principal methods for the determination of subcriticality; namely direct comparison to subcritical experiments and COG calculations of the effective neutron multiplication constant (k-eff).

4.1 SUBCRITICAL EXPERIMENTS

The TACS is a known configuration that has been assembled many times with a measured central source leakage multiplication of about 10 as published by Barnett [5] for the assembly in its highest reactivity configuration. This is an adequate margin of safety for manual operations (i.e., hand assembly).

4.2 COG CALCULATIONS

The LLNL-developed Monte-Carlo code COG[12] (version 10.19c) was used to make all calculations of the effective neutron multiplication constant (k-eff). The COG code developers installed, verified, and maintain this version on the GPS machines for criticality safety applications. All calculations utilized the ENDF/B-VI (Release 7) pointwise (continuous) cross-sections (except for copper and lead which utilize RED2002) and ENDF/B-VI (Release 2) S(α,β) data.

This methodology has been validated against critical experiments with highly enriched uranium (HEU) metal using the benchmark specifications from the ICSBEP Handbook[13]. The benchmark experiments include similar shapes (e.g., spheres, hemispheres, nested shells) and similar moderator and reflector materials (Lucite, water, polyethylene) from several US and foreign laboratories.

The details of the individual benchmark results are provided in Appendix B and presented graphically in the plot below. The ordinate is labeled bias, which is the difference in the COG (calculated) and ICSBEP (benchmark) k-eff values. The abscissa is labeled MFE, which is the median energy of those neutrons producing fission events.

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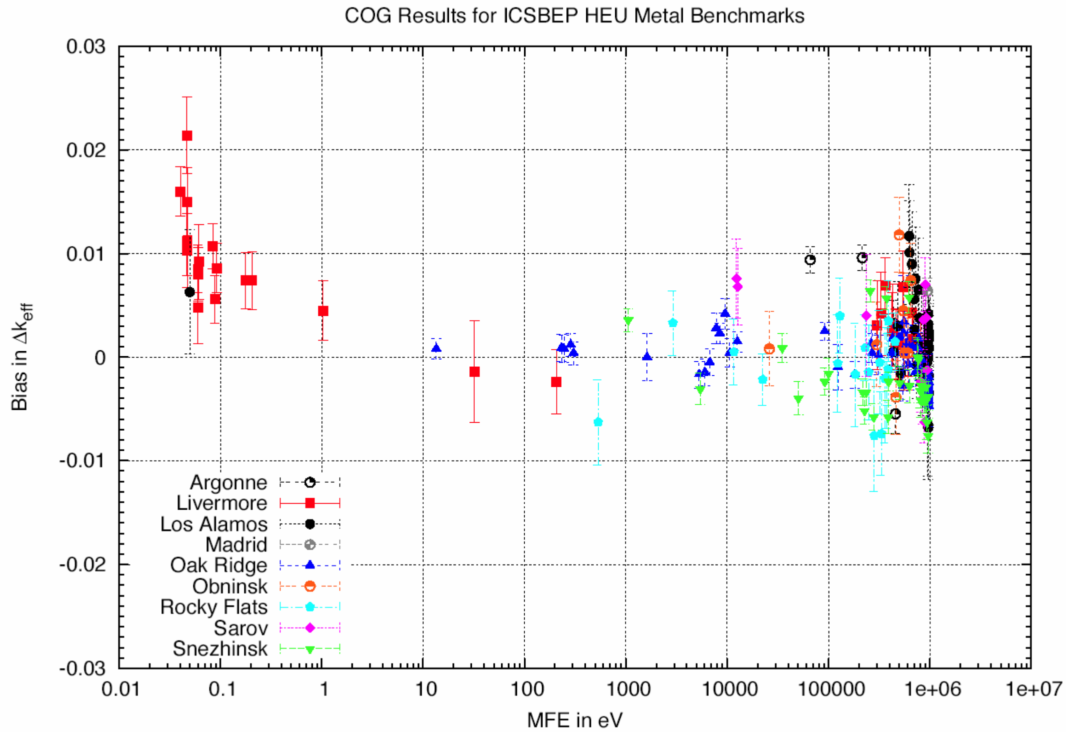
[12] UCRL-TM-202590, *COG: A Multiparticle Monte Carlo Transport Code User's Manual*, Fifth Edition, September 1, 2002.

[13] NEA/NSC/DOC(95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, September 2005 Edition, Nuclear Energy Agency, Organisation for Economic Cooperation and Development.



In examining the benchmark results given in the figure, we see that for a wide variety of 193 benchmark experiments, the COG calculational bias does not result in an under-prediction in excess of –1% Δk-eff.

The mean bias in the COG calculated critical k-eff value is estimated as 0.0010 ± 0.0047 (unweighted) or –0.0023 ± 0.0010 (weighted[14]). An adequate criterion for subcriticality is:

$$\text{k-eff} < 1 + B - 3U - M;$$

where, B is the weighted estimate of the mean bias (-0.0023); U is the total uncertainty (0.0047), which is estimated as the root-mean-square-sum of the unweighted bias uncertainty (0.0047) and Monte-Carlo calculational (statistical) uncertainty (0.0006); and M is the margin of safety (0.02). Consequently, k-eff ≤ 0.96 are subcritical with a conservative 2% safety margin.

[14] Weight factors are inversely proportional to the squares of the standard deviations.

5.0 DISCUSSION OF CONTINGENCIES

Table 5-1 lists the contingencies (or events) together with the physical (design features) or administrative controls that are sufficient to preclude any credible criticality accident risk. A synopsis of the technical basis is provided in the far-right column. The details are provided in Section 6.

Table 5-1. Contingency Table

Contingency	Design Features	Controls	Technical Basis
Normal conditions			
Normal operations	Fissile mass ≤ 22.4135 kg Oy(93.2)-0.25 Ni. Favorable fissile geometry of 8 hemis with IR ≥ 5.926 cm Substitution of Oy with D38 only reduces reactivity Moderator ≤ 694.8 g Lucite. Reflector ≤ 10 cm Lucite. Operators under supervision of RI and CSE instructor	OSP approves all parts (as approved items) and configurations (via lesson plan in the OSP appendix). COMATS.	Known assembly with Mo < 20 (ok per ANSI/ANS-1) k-eff ~ 0.93 (w/w/o a diaphragm or source holder)
Diaphragm	0.030" Al-6061 provides some separation between TACS halves, which slightly reduces k-eff (increases safety).	OSP approves use of this diaphragm	Δk-eff < 0
Neutron source	Am-Li source (S/N 401009) contains < 3 mg Am, which is insignificant. Other materials in the source do not increase k-eff significantly (due to added scattering).	OSP includes this source as an approved (or exempt) item.	Δk-eff ~ 0
Al-6061 source holder	Unlimited amounts of Al-6061 in the cavity do not increase k-eff significantly (due to added scattering). Consequently, use of an Al-6061 source holder for ALARA is recommended.	OSP includes this source holder as an approved item	Δk-eff ~ 0
Interaction with other SNM	Assembly machine tabletop provides ≥ 18" c-to-e spacing of the TACS from other SNM per AAA78-103777-00. LLNL policy requires establishment of a workstation (W/S) with a minimum 12" e-to-e spacing between W/S(s).	OSP requires use of assembly machine & establishing a W/S	Δk-eff ~ 0.002
Other reflectors (and poisons)	TACS is authorized for use with 10 cm Lucite reflection. Other approved reflectors such as unlimited (pure, borated, or lithium-doped) HDPE or LDPE, (detectors), H2O (people), MHE (used in Tech-1D) or Cd + Lucite (instead of 10 cm pure Lucite) will not increase k-eff more than 1%.	OSP provides the list of approved reflectors (consistent with this CSE)	Δk-eff < 0.01
Abnormal condition and controls that preclude any credible criticality accident risk			
Flooding	Increase in k-eff from total immersion of the TACS is offset by presence of a 1.5-inch-radius Al-6061 source holder.	OSP requires use of source holder.	k-eff < 0.96
Over-mass	Kilogram quantities of additional fissile materials are required to achieve criticality.	OSP/COMATS strictly controls fissile materials	BEU
Superior moderators	TACS cavity (IR = 5.926 cm) with source holder is a safe (limited volume) if filled with any moderator (e.g., H2O, HDPE, Lucite, Be, BeO, C, D2O).	OSP requires Al-6061 source holder be installed	k-eff < 0.96
Unauthorized reflectors	D, Be and C reflectors are special concerns subject to special controls. D38 and Nat-U are SNM controlled similar to fissile materials. Cu and ZrH2 are not credible hazards.	OSP strictly controls reflector parts and configurations	BEU
Small Fire	Credible fire is a small electrical fire of the smoke and stink type that does not involve fissile materials. TACS could be immersed due to sprinkler activation.	Automatic sprinklers. Hand extinguishers.	k-eff < 0.96
Beyond design basis events			
Moderate or large fires	Fires of such severity are considered incredible. However, such fires could disperse Oy in Lucite or water which is a criticality hazard.	Fire loading controls. Criticality hazard type 2.	BEU
Crushing	BDBE causes facility collapse crushing the TACS into a compact volume. However, presence of the Al-6061 source holder is sufficient to "safe" the TACS.	OSP requires use of the Al-6061 source holder	k-eff < 0.96
Latticing	Latticing of Oy shells in plastic or water (with shims) is not credible since it requires unauthorized assembly using (unavailable) unauthorized parts with the collusion of the RI and CSE Instructors (in violation of the OSP controls on approved parts and assemblies).	OSP controls plastics (used in RadCon) and prohibits shims or sheets that could be used to create a lattice.	BEU

6.0 EVALUATION AND RESULTS

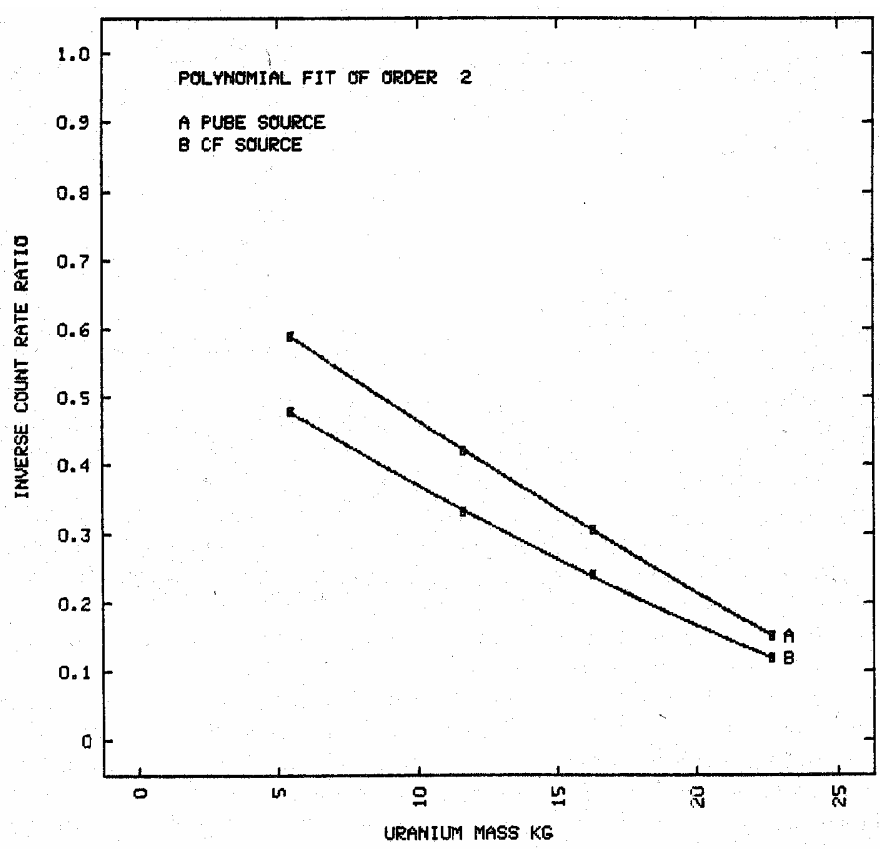
In order to calculate k-eff for various TACS configurations using COG, a model of the most significant parts (maximum authorized moderation with parts M3A, 18326, 500155, 500157, 23181, R2B and R3A in the lower assembly half and parts M3B, 18325, 500154, 500156, 23184, R2A and R3B in the upper assembly half) has been developed as shown in Table 6-1 and the dimensioned sketch above this table. A sample input listing is provided in Appendix A.

A COG model of the Am-Li neutron source (S/N 401009) has also been developed as shown in Table 6-2 and the dimensioned sketch above this table. The total mass of this source is modeled as 54.5 grams.

6.1 NORMAL CONDITIONS

The highest authorized reactivity TACS configuration corresponds to the TACS with 694.8 grams of Lucite moderator (parts M3A/M3B), 22.4135 kg U(93)-0.25Ni (parts 18325/18326, 500154/500155, 500156/500157, 23181, 23184) with 10 cm Lucite reflection (parts R2A/R2B and R3A/R3B).

The apparent central source leakage multiplication for this configuration is about 10 as measured by Barnett[5] using a 0.15-cm SST diaphragm with ^{252}Cf or Pu-Be sources with CH_2-embedded BF_3 tubes. Barnett's results are reproduced below.



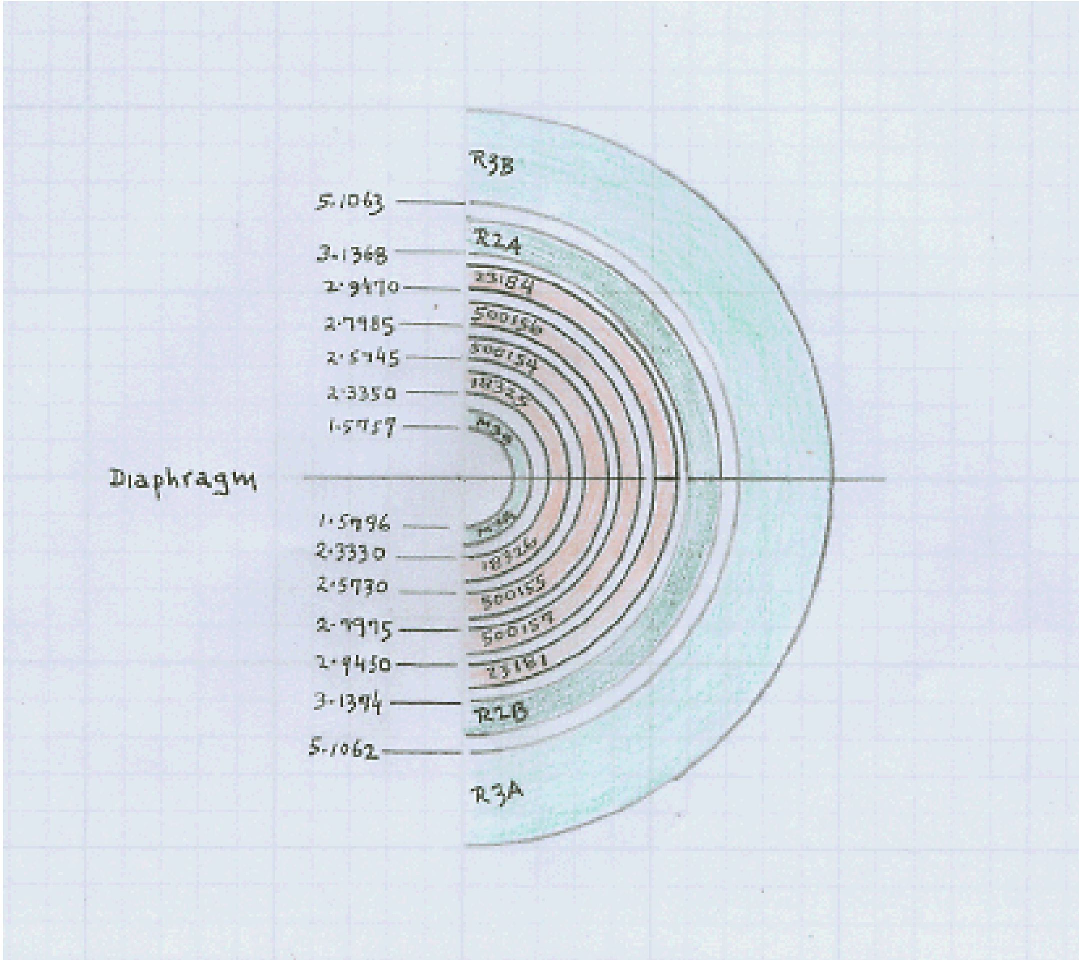


Table 6-1. COG Model of the TACS Assembly

Part	Material	Mass (kg)[c]	Density (g/cc)	IR (inch)	OR (inch)[b]
Upper assembly half					
M3B	$C_5H_8O_2$	0.3470	1.1885	1.5757	2.3157756
18325	U(93.1391)[a]	2.7271	18.9	2.3350	2.5680057
500154	U(93.1811)[a]	3.0703	18.9	2.5745	2.7934013
500156	U(93.1531)[a]	2.2959	18.9	2.7985	2.9416947
23184	U(93.3485)[a]	3.0978	18.9	2.9470	3.1199468
R2A	$C_5H_8O_2$	4.1481	1.1877	3.1368	5.0996783
R3B	$C_5H_8O_2$	9.0157	1.1876	5.1063	7.0762763
Lower assembly half					
M3A	$C_5H_8O_2$	0.3478	1.1888	1.5796	2.3186674
18326	U(93.1793)[a]	2.7313	18.9	2.3330	2.5666802
500155	U(93.1596)[a]	3.0709	18.9	2.5730	2.7921669
500157	U(93.1620)[a]	2.2994	18.9	2.7975	2.9409976
23181	U(93.1256)[a]	3.1208	18.9	2.9450	3.1193777
R2B	$C_5H_8O_2$	4.1532	1.1878	3.1374	5.1013984
R3A	$C_5H_8O_2$	9.0204	1.1875	5.1062	7.0771158

[a]U contains 1.1 wt-% ^{234}U. [b]OR = $[(3/4\pi)(\text{Mass/Density})+\text{IR}^3]^{1/3}$. [c]U replaces Ni.

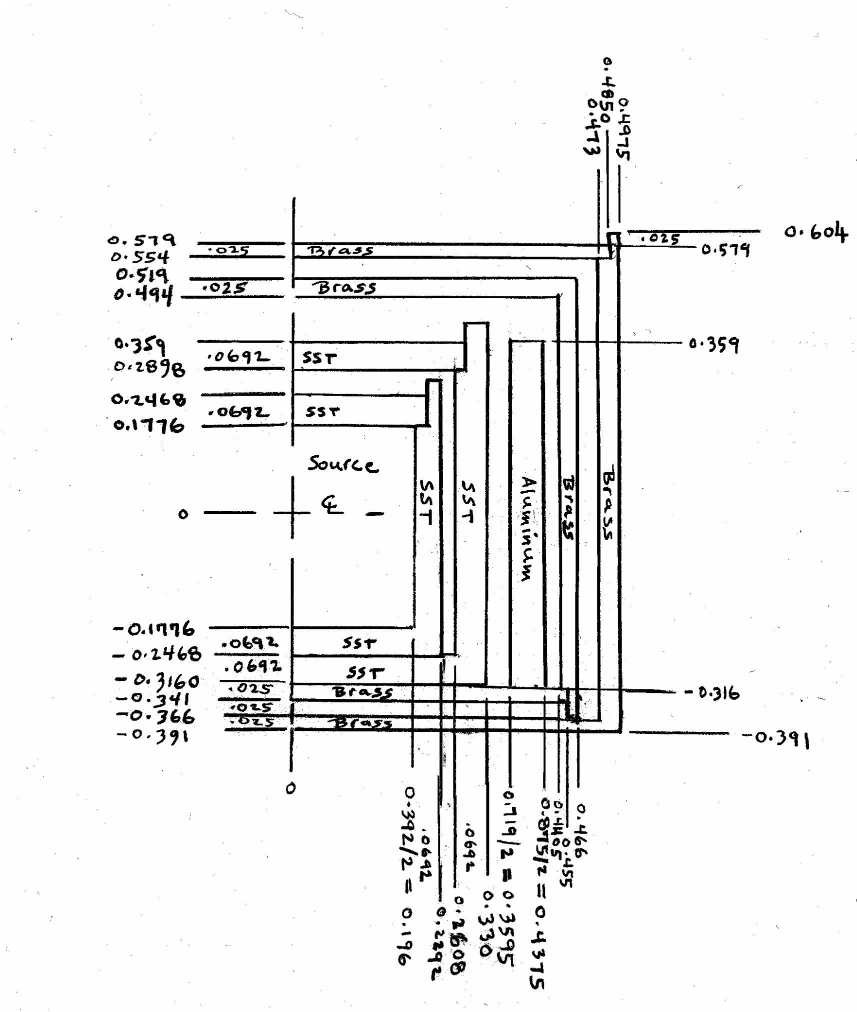


Table 6-2. COG Model of the Am-Li Neutron Source (S/N 401009)

Material	Mass (g)	Density (g/cc)	Volume (cc)
Active source region[a]			
Am (in AmO_2) O (in AmO_2) Li^7 (in Li^7H) H (in Li^7H)	0.0030 0.0004 0.4834 0.0695	4.270563-3 0.566891-3 0.6881 0.0989	0.7024835
First (innermost) layer of SST encapsulation			
Fe-18Cr-8Ni[b]	4.9963	7.9	0.6324370
Second layer of SST encapsulation			
Fe-18Cr-8Ni[b]	15.0520	7.9	1.9053178
Aluminum shim			
Al[b]	5.8327	2.7	2.1602684
Third layer of brass encapsulation			
Cu-35.8Zn-0.15Pb-0.05Fe[b]	13.0094	8.47	1.5359413
Fourth (outermost) layer of brass encapsulation			
Cu-35.8Zn-0.15Pb-0.05Fe[b]	15.0687	8.47	1.7790668

[a]Assumed substrate composition. [b]Assumed alloy composition.

Use of less Lucite moderator (M1A/B, M2A/B (or void) instead of M3A/B), less fissile material (D-38 shells (or void) substituted for any or all of the HEU shells), or less Lucite reflection (R1A/B, R4A/B (or void) in place of R2A/B plus R3A/B) will reduce k-eff. Therefore, any configuration using any combination of these parts is acceptable for use in the TACS.

6.1.1 Effect of the diaphragm

The COG calculated k-eff corresponding to the measured configuration by Barnett (with maximum authorized Lucite moderator, maximum fissile mass and 10 cm Lucite reflection) with a 0.059-inch SST diaphragm separating the two halves is k-eff = 0.9125 ± 0.0005 (file: tacs5 (in Table 6-3)). This result is in good agreement with the measured multiplication value of about ten.

Other results presented in Table 6-3, show that replacing this steel diaphragm with an Al-6061 diaphragm increases reactivity even if the diaphragm is significantly thicker. The highest (bounding) reactivity corresponds to a case with no diaphragm present in which the two halves of the TACS assembly in contact, where k-eff = 0.9293 ± 0.0005 (file: tacs1).

6.1.2 Effect of the Am-Li neutron source and Al-6061 parts

The COG calculational results given in Table 6-3 demonstrate that the presence of the Am-Li neutron source (S/N 401009) or unlimited Al-6061 in the cavity results no significant increase in k-eff. Consequently, this source is acceptable for use with or without an Al-6061 source holder. Aluminum spacers are also acceptable for use in separating the two halves of the TACS and clearly there is no safety significance if these or other small aluminum parts were to fall into the TACS central cavity (an anticipated event).

Table 6-3. Normal Conditions

Case	k-eff	MFE	File	Remarks
Effect of the diaphragm.				
1	0.9125(5)	52.3 keV	tacs5	tacs1 with 0.059-in. SST diaphragm
2	0.9213(6)	42.2 keV	tacs2	tacs1 with 0.059-in. Al-6061 diaphragm
3	0.9231(6)	43.8 keV	tacs6	tacs1 with 0.100-in. Al-6061 diaphragm
4	0.9293(6)	45.8 keV	tacs1	tacs1 as shown in Figure 6-1
Effect of the Am-Li source and unlimited aluminum in the cavity.				
5	0.9283(6)	46.3 keV	tacs3	tacs1 with Am-Li (S/N 401009)
6	0.9298(6)	43.7 keV	tacs4	tacs1 with (728g) Al-6061-filled cavity
Reference configuration (S/N 401009 Am-Li source within a 1.5-inch-IR Al-6061 source holder attached to a 0.030-inch Al-6061 diaphragm)				
7	0.9286(6)	43.5 keV	tacs50	Reference configuration

6.1.3 Effect of authorized reflector materials in close proximity to TACS

Several COG calculations were performed to assess the effects of people (H_2O) or neutron detectors (polyethylene or Lucite) in close proximity to the TACS. COG calculations were also performed to assess the effects of using the (available) Tech-1D assembly mock high explosives (RM-05-20H) shells in place of the Lucite. These results given in Table 6-4 confirm that Lucite is a superior reflector in comparison to polyethylene (LDPE or HDPE), RM-05-20H and water. The authorized Lucite reflector parts R2A/B and R3A/B provide 4 inches (10 cm) of Lucite reflection, which is demonstrated to be nearly effectively infinite since unlimited additional Lucite increases the reactivity only by Δk-eff ≤ 1%.

The COG calculational results in Table 6-4 further demonstrate that unlimited HDPE or RM-05-20H in lieu of Lucite is an equivalent (or slightly inferior) reflector than 10 cm Lucite. Consequently, HDPE, LDPE, or RM-05-20H (MHE) reflectors of any thickness are acceptable for use with the TACS.

Table 6-4. Normal Conditions (continued)

Case	k-eff	MFE	File	Reflector
Reference configuration with 10 cm Lucite in parts M2A/B and M3A/B (only)				
4	0.9293(6)	45.8 keV	tacs1	10 cm Lucite
Effect of other reflector materials (beyond 10 cm Lucite)				
8	0.9364(6)	39.2 keV	tacs21	10 cm Lucite + infinite water (people)
9	0.9372(6)	37.4 keV	tacs22	10 cm Lucite + infinite HPDE (detectors)
10	0.9384(6)	38.1 keV	tacs23	10 cm Lucite + infinite Lucite (detectors)
11	0.9400(6)	37.2 keV	tacs28	10 cm Lucite + infinite concrete (walls)
Effect of other reflector materials (instead of 10 cm Lucite)				
12	0.9033(5)	124.9 keV	tacs25a	Infinite mock HE (RM-05-20H)
13	0.9047(6)	43.2 keV	tacs24	Infinite water (people)
14	0.9291(6)	26.0 keV	tacs25	Infinite HDPE (detectors)
15	0.9378(6)	170.7 keV	tacs29	Infinite concrete (reference)
16	0.9417(6)	38.0 keV	tacs26	Infinite Lucite (detectors)

6.1.4 Effect of neutron poisons

Substituting borated or lithium-doped polyethylene (or Lucite) in place of the pure Lucite reflector parts will decrease k-eff significantly and consequently such reflector parts (when available) are acceptable for use with the TACS.

Placement of thin Cadmium metal shells (see Table 3-4) in the gap formed by the outermost HEU and innermost Lucite reflector surfaces will reduce k-eff significantly (due to neutron poisoning of the thermal neutron return) and consequently these parts are acceptable for use with the TACS.

Placement of a Cadmium sheet on top of the diaphragm separating the two halves of the TACS assembly also reduces k-eff and is therefore acceptable for use with the TACS. This effect has been observed experimentally to be small which indicates little poisoning but some reduction in interaction due to increased separation.

6.1.5 Effect of interaction with other fissionable materials

The TACS assembly machine provides 18-inches of spacing (center-to-edge) and the assembly machine will be located within a workstation (a defined area on the floor). The minimum separation between workstations is 12-inches per ES&H Manual, Document 20.6, *Criticality Safety*, Section 3.6, "Criticality Safety Mass Limit Guidelines for Workstations". Consequently, a hypothetical planar array of TACS assemblies located on a square 30-inch pitch were studied to simulate the effects of interaction with other fissionable materials. These cases also included effectively infinite concrete (axial) reflection to simulate the TACS located at 36-inches above the floor within a room with an 8-foot ceiling.

The COG results are provided in Table 6-5 which indicate a reactivity increase of only Δk-eff = 0.2% above that of a single TACS assembly with full Lucite reflection (see Section 6.1.3).

Table 6-5. Normal Conditions (continued)

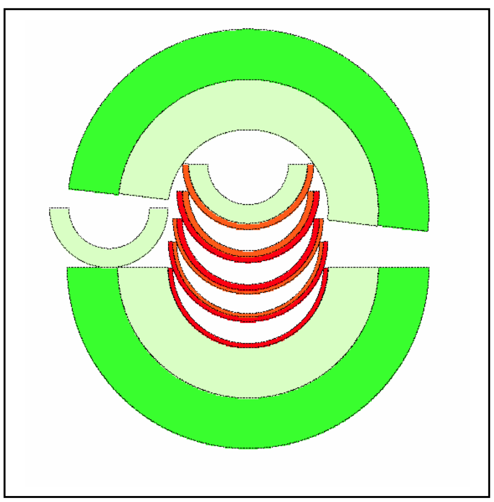
Case	k-eff	MFE	File	Reflection
Effect of interaction (infinite planar array with 30-inch square pitch)				
17	0.7673(6)	306.0 keV	tacs27a	0-in. Lucite
18	0.8573(6)	180.2 keV	tacs27b	1-in. Lucite
19	0.9231(6)	67.9 keV	tacs27f	2-in. Lucite
20	0.9420(5)	40.7 keV	tacs27c	3-in. Lucite
21	0.9436(5)	37.6 keV	tacs27d	5-in. Lucite
22	0.9417(6)	37.2 keV	tacs27e	7-in. Lucite
23	0.9417(6)	38.0 keV	tacs26	Infinite Lucite

6.1.6 Anticipated human errors during hand-stacking operations

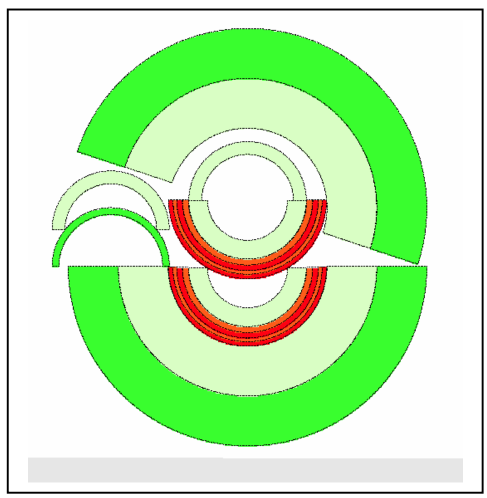
A few COG calculations were performed to calculate the reactivity of those configurations shown above Table 6-6 to convince the peer reviewer that these configurations are in fact much lower in reactivity than the (bounding) authorized configuration shown above Table 6-1.

Consequently, there is no need for strict criticality controls on the step-by-step assembly sequence since a stacking error only results in a less reactive assembly that increases the margin of safety.

Good Practice: A storage cabinet should be used for the storage of Lucite and D-38 shells when not in use. Only two Lucite moderator parts should be in use at any time.



Configuration 1



Configuration 2

Table 6-6. Anticipated Assembly Errors

Case	k-eff	MFE	File	Remarks
Bounding assemblies without assembly table, diaphragm and source holder.				
4	0.9293(6)	45.8 keV	tacs1	TACS as shown above Table 6-1*
24	0.8272(6)	174.2 keV	tacs72	Configuration 2*
25	0.7115(6)	309.2 keV	tacs71	Configuration 1*

*No diaphragm or source holder present.

6.2 ABNORMAL CONDITIONS

Abnormal conditions include unauthorized assembly configurations involving available (approved) parts, unauthorized configurations involving hypothetical (unapproved) parts, flooding, crushing and fire.

6.2.1 Immersion in water

Several COG calculations were performed to assess the TACS assembly under conditions of full immersion in water. The results provided in Table 6-7 demonstrate that Lucite is a superior reflector but inferior moderator in comparison to water.

Consequently, the most reactive (bounding) configuration is one with no Lucite moderator parts and the maximum Lucite reflector parts (R2A/B and R3A/B) with all eight HEU shells and the inner cavity and all void spaces (between shells and beyond the 4 inch (10 cm) Lucite reflector) filled with water. The k-eff corresponding to this configuration (with no diaphragm and no source holder) is greater than 0.96, which is unacceptable.

However, the results in Table 6-7 demonstrate that use of engineering design features (either a 0.059-inch SST diaphragm or 0.030-inch Al-6061 diaphragm with 1.5-inch-radius Al-6061 source holder) is sufficient to reduce the k-eff < 0.96, which is subcritical (safe) under full water immersion.

Table 6-7. Abnormal Conditions

Case	k-eff	MFE	File	Remarks
Hypothetical conditions of full immersion in water.				
26	0.9362(6)	8.4 keV	tacs9	Oy immersed in water (no Lucite)
27	0.9414(6)	14.9 keV	tacs14	tacs8 w/0.059-in. SST diaphragm
28	0.9583(6)	16.8 keV	tacs11	tacs8 w/1.5”-OR Al-6061 at center
29	0.9593(6)	17.4 keV	tacs12	tacs8 w/1.5”-OR void at center
30	0.9571(6)	16.5 keV	tacs16	tacs8 w/1.5”-OR-void+0.030”-Al6061-dia
31	0.9573(6)	16.1 keV	tacs17	tacs8 w/1.5”-OR-Al6061+0.030”-Al6061-dia
Full immersion without required engineering design features (incredible).				
32	0.9633(6)	11.6 keV	tacs7	tacs1 immersed in water
33	0.9660(6)	7.9 keV	tacs15	tacs8 w/0.030-in. Al-6061 diaphragm
34	0.9675(6)	8.3 keV	tacs10	tacs8 w/0.010-in. Al-6061 diaphragm
35	0.9676(6)	8.4 keV	tacs8	tacs1 (w/o M3A+B) immersed in water

Design Feature: A **source holder** at least 3-inches in diameter shall be fixed to the 0.030-inch Al-6061 diaphragm prior to use with fissile materials.

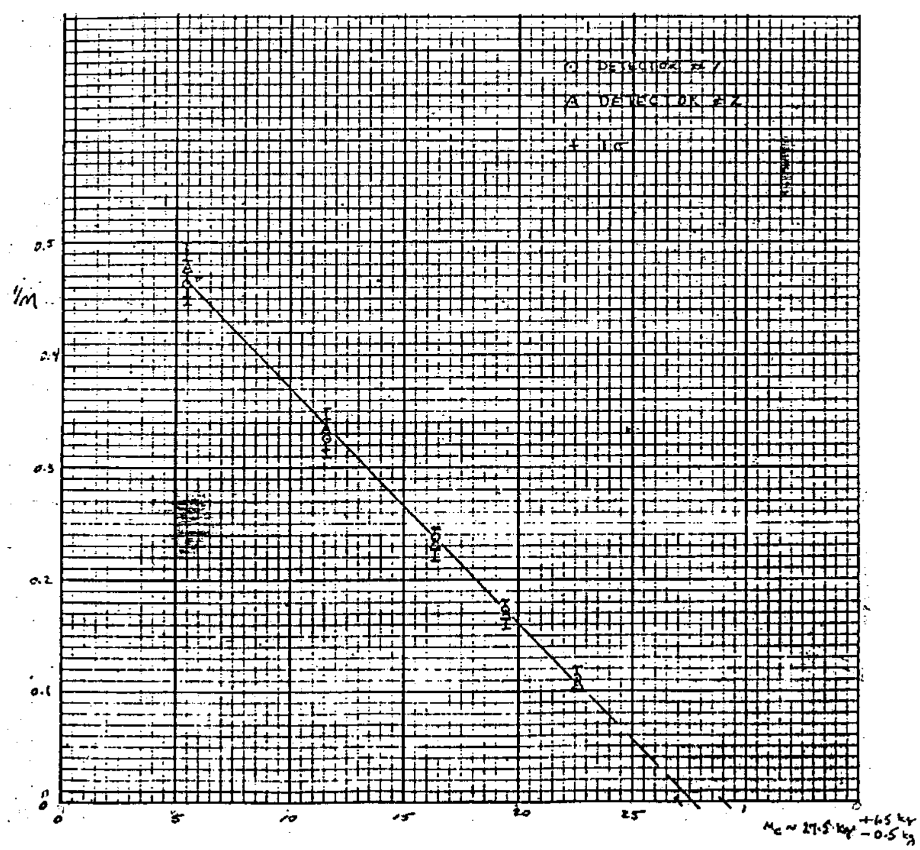
6.2.2 Unauthorized additions of fissionable material (over-mass)

Addition of sufficient mass of other fissionable materials will achieve criticality *in any system*. The results in Table 6-8 show that addition of about 1.0 kg Pu-239, 1.5 kg Pu-238, or 3.5 kg HEU to the TACS central cavity is necessary to achieve criticality.

Table 6-8. Abnormal Conditions (continued)

Case	k-eff	MFE	File	Remarks
Unauthorized assemblies with unapproved fissionable materials.				
36	0.9951(6)	104.9 keV	tacs41	3.5 kg Oy(94) at 18.90 g/cc
37	0.9946(6)	153.2 keV	tacs42	2.0 kg Pu-238 at 19.51 g/cc
38	1.0000(6)	108.7 keV	tacs43	1.5 kg Pu-239 at 19.84 g/cc

The COG estimated critical mass of about 26 kg Oy (filled cavity) is in remarkable agreement with the measured 1/M approach-to-critical estimate of 27 kg (empty cavity) as shown in the figure below.



CONTROL: Enriched uranium is limited to **20.9 kg ^{235}U**. Authorized enriched uranium parts are 18325, 18326, 500154, 500155, 500156, 500157, 23181 and 23184.

This administrative control will be implemented in an approved Operational Safety Plan (OSP) that assigns a Standardized Criticality Control Condition (SCCC) to a defined workstation for use by COMATS to ensure accountancy to the gram.

For a criticality accident to occur due to overmass, the following chain of events would have to occur:

(1) A significant quantity of SNM is transferred into the for use in another workstation;
(2) The fissile material handler approaches the TACS workstation with this (unauthorized) material by mistake; and,
(3) Two instructors allow placement of the unapproved item within (or near) the TACS (BEU) in a configuration not approved in the appendices to the OSP.

Consequently, this scenario is considered incredible (BEU). Note that the only other fissionable materials authorized are the negligible (non-accountable) quantity of ^{241}Am present in the sealed neutron source (S/N 401009) and the less than 50 grams of ^{235}U present in D-38 (which is addressed in the Section 6.2.4 as a reflector material).

It is acceptable to either establish a fissionable mass limit to accommodate the presence of the 3 mg of ^{241}Am present in S/N 401009 or consider this source as exempt from criticality control. The approach should be consistent with the practice of the facility.

6.2.3 Unauthorized moderators

Several COG calculations were performed where the limited (641 cm^3) volume cavity (between the 1.5-inch-radius Al-6061 source holder and inner-most HEU shell contour on both sides of the 0.030-inch-thick Al-6061 diaphragm) was completely filled with other moderator materials; namely, HDPE, ZrH_2, Lucite, UH_3, or Be fill the cavity in place of the M3A/B parts. As expected, the reactivity is greatest for HDPE, but in all cases k-eff < 0.96, which is safe (subcritical).

Table 6-9. Abnormal Conditions (continued)

Entry	k-eff	MFE	File	Remarks
Unauthorized moderators.				
39	0.9582(6)	10.0 keV	tacs51	0.620 kg HDPE at 0.967 g/cc
40	0.9510(6)	15.3 keV	tacs52	3.622 kg ZrH2 at 5.650 g/cc
41	0.9371(6)	31.8 keV	tacs53	1.046 kg Lucite at 1.200 g/cc
42	0.9273(6)	27.6 keV	tacs54	9.544 kg UH3 at 10.950 g/cc
43	0.8763(6)	171.7 keV	tacs55	1.612 kg Be at 1.85 g/cc

Consequently, this TACS configuration is considered geometry-favorable since there is no criticality accident risk due to placement of any moderator within the available volume of the cavity.

6.2.4 Unauthorized reflectors

The results provided in Table 6-10 indicate that the TACS can be made critical by the addition of a sufficient quantity of special reflector materials in place of the authorized Lucite reflector shells.

Table 6-10. Abnormal Conditions (continued)

Entry	k-eff	MFE	File	Remarks
Unauthorized reflectors.				
44	0.9952(6)	241.4 keV	tacs31	TACS with 2.5-in. BeO at 3.01 g/cc
45	0.9961(6)	195.4 keV	tacs32	TACS with 3.0-in. Be at 1.85 g/cc
46	0.9885(6)	104.1 keV	tacs33	TACS with 4.9-in. C5D8O2 at 1.345 g/cc
47	0.9918(6)	243.7 keV	tacs34	TACS with 5.1-in. Graphite at 2.25 g/cc
48	0.9928(6)	578.2 keV	tacs35	TACS with 5.9-in. Nat-U at 19.07 g/cc
49	0.9530(6)	191.0 keV	tacs38	TACS with 23 kg Nat-U in infinite Lucite
50	0.9994(6)	284.7 keV	tacs36	TACS with infinite Copper at 8.92 g/cc
51	1.0027(6)	16.4 keV	tacs37	TACS with infinite ZrH2 at 5.65 g/cc

6.2.4.1 Special concern reflectors (D, Be, C and their compounds)

The ES&H Manual, Document 20.6, *Criticality*, Section 3.4, "Special Concerns", identifies beryllium, graphite, deuterium or their compounds as materials with the potential for achieving a significantly reduced minimum critical mass. Consequently, in accordance with LLNL policy, operations with these materials in close proximity to fissionable materials require criticality safety review on a case-by-case basis.

This CSE has performed this review and these materials are deemed to constitute an unnecessary hazard and are therefore prohibited. These *special concern materials* are strictly controlled in accordance with laboratory policy and TACS activities are performed under the supervision of the Responsible Individual (RI) and qualified instructor familiar with this CSE and this potential hazard. Consequently, a criticality accident with these materials would require a scenario similar to that identified in Section 6.2.2, which has been determined to be incredible (BEU).

6.2.4.2 Heavy metal and other reflectors (U, Cu, ZrH_2)

COG calculations indicate that TACS can also be driven critical with approximately 5.9-inches of natural uranium (or D-38). However, this thickness corresponds to a mass in excess of 900 kilograms, which is not credible since less than 23 kg of D-38 is available (see Table 3-2). Therefore, an additional COG calculation has been performed to consider the effect of close-fitting reflection by 23 kg of natural uranium (or depleted uranium) in infinite Lucite in order to demonstrate that this configuration is subcritical (safe) with k-eff < 0.96.

The COG calculations with copper and ZrH_2 show that other heavy metals (or their compounds) may be a criticality hazard if present in huge quantities in close proximity to the TACS. However, this is not considered a credible hazard since no such parts are available. Nonetheless, these materials are prohibited as a good practice to ensure safety over the long run.

CONTROL: Depleted uranium mass is limited to **23.0 kg D-38**.

The D-38 shells listed in Table 3-2 are acceptable for use with the TACS as reflectors since their total mass is less than 23.0 kg D-38. Reflectors of natural-uranium, copper or other heavy metal (or their compounds) are not authorized.

Note that D-38 and or Nat-U are *special nuclear materials* that are controlled similar to fissile materials including a COMATS check. Consequently, the risk of a significant over-mass involving these materials is considered incredible.

6.2.5 Fire

The TACS itself (Al-6061, Lucite, D-38, HEU, Am-Li source) is not a credible fire risk. However, the neutron detectors and counting equipment are electrical equipment that could catch fire if sufficiently poorly maintained or abused.

This equipment is professionally maintained and checked out for proper performance prior to use with fissile materials. The combustible materials present in this equipment and the TACS itself correspond to an acceptable fire loading in order to ensure that a moderate or large fire is not credible.

The worst credible scenario is for the electrical equipment to overheat and possibly deform (or melt) some electrical or plastic components resulting in a smoke and stink event that would be immediately terminated by automatic activation of the sprinklers. Hand-held fire extinguishers are available in LLNL facilities for use by the RI, instructors, or other qualified personnel for putting out these types of fires.

Good practice: Instructors and responsible individuals should be trained in the use of fire extinguishers by completing PU-3007, *Fire Extinguishers*, or HS1670-W, *Qualification for Fire Extinguishers Users – Web*.

6.3 BEYOND DESIGN BASIS EVENTS

Beyond design basis events considered in this evaluation include catastrophic fire, crushing and latticing.

6.3.1 Catastrophic fire involving fissile materials

The fire loading in all fissile material workstations, rooms, and buildings, is strictly controlled to preclude this type of event. Automatic fire (sprinkler) suppression systems with smoke or particulate detectors and hand extinguishers are provided to immediately put out any fire before it could propagate and involve fissile materials.

Nonetheless, were such a (BEU) catastrophic fire to occur, a criticality accident would only be possible in the following scenario:

(1) A large fire occurs in close proximity to the TACS;
(2) Fire melts nickel plating and HEU or exposes HEU to decomposition gases (hydrogen and oxygen) from Lucite or other plastics;
(3) Hydrogen or oxygen converts a large quantity of HEU into dispersible (including pyrophoric) forms (oxides, hydrides, hydroxides, etc.);
(4) Water (or Lucite) mixes with HEU in a slurry; and,
(5) A critical system is achieved in an unsafe shape and volume.

This scenario is considered incredible. The largest Lucite shell is at least 10-inches from the edge of the assembly table. Consequently, it is unlikely to be directly exposed to flame. However, the minimum auto-ignition temperature of Lucite is only 304 degrees Celsius (or 580 °F), whereas the melting point of nickel and uranium is 1455 and 1132 degrees Celsius. Therefore, the Lucite is expected to (completely) decompose into gaseous reaction products liberating hydrogen and oxygen leaving a carbonaceous char before the (insulated) uranium could begin to melt.

D-38 exposed to these gases could be converted to a pyrophoric powder. Granger[15] has reported a reaction rate of 100 grams per 30 minutes. Consequently, prompt activation of the fire suppression system or intervention by the instructors using hand extinguishers is sufficient to ensure safety (subcriticality).

Furthermore, the nickel-clad HEU parts are expected to resist attack from these gases and remain intact due to the non-reactive protective nickel coating. Minor hydriding could occur at the pole holes, but since this area is small and exposed

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[15] L. Grainger, Uranium and Thorium, George Newnes Limited, London, 1958, pages 66-67.

to the air, a protective layer of oxide is likely to form over the small surface of the pole holes. In this likely event, there would also be no criticality accident risk.

An important design feature of the TACS assembly machine is that it contains no cavities that can accumulate (dispersible) fissile and moderator materials into an unsafe geometry.

Consequently, the only potential critical geometry would be one involving a somewhat intact lower assembly that could contain a large quantity of dispersible HEU mixed in water or Lucite from a decomposed or melted upper assembly. This is considered incredible. Nonetheless, the following controls are considered good practice.

CONTROL: TACS is a **Criticality Hazard Type 2** [16].

6.3.2 Crushing

The TACS could only be crushed due to collapse of the facility due to a beyond design basis earthquake (BDBE). A simple model of the crushed TACS has been developed as described in Table 6-12.

This model collapses the source holder such that its radius at the waist equals the inner-most radius of the smallest Oy shell and the height is calculated as an ellipsoid that preserves the (assumed 200 cc) volume. The Oy shells are modeled in contact and the minimum thickness (as shown in the Figure above Table 6-12) preserved at the waist. The height of the ellipsoidal shape is calculated to preserve the actual Oy mass. The Lucite is modeled similarly based on parts R2A/B and R3A/B. The entire assembly is then immersed in infinite concrete. COG calculates k-eff < 0.96 for this hypothetical (bounding) configuration, which indicates that any degree of crushing will not result in a criticality accident.

Table 6-11. Abnormal Conditions (continued)

Entry	k-eff	MFE	File	Remarks
Hypothetical (BDBE) crushing.				
52	0.9448(6)	550.0 keV	bdbec	As above but concrete replaces Lucite.
53	0.9510(6)	395.3 keV	bdbe	As shown in Table 6-3.

[16] See ES&H Manual, Document 20.6, *Criticality Safety*, Section 5.2, "Fire-Fighting Guidelines".

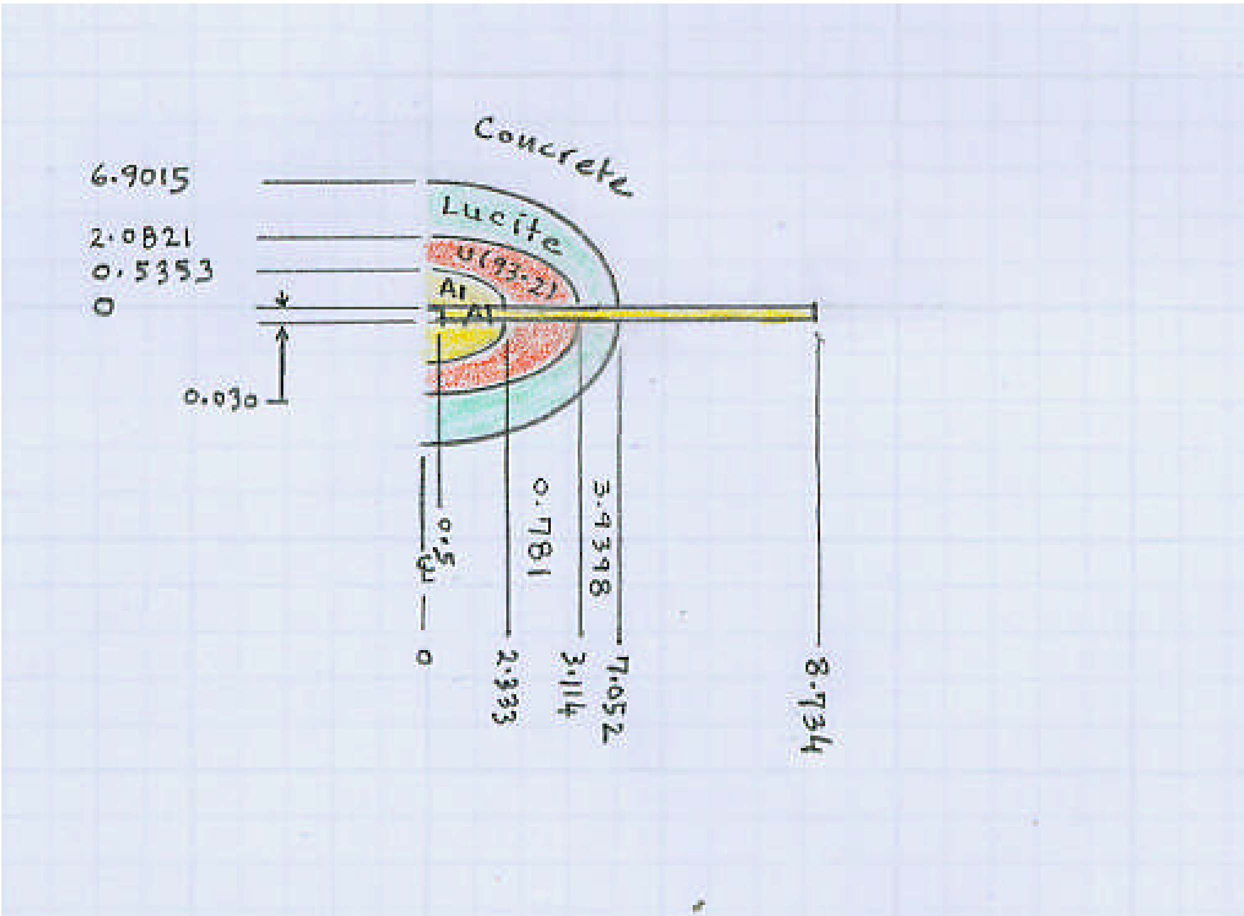

Table 6-12. COG Model of the Crushed TACS

Material	Mass (kg)	Density (g/cc)	Volume (cc)
Al-6061 Diaphragm	0.317	2.7	117.428
Al-6061 Source Holder	0.540	2.7	199.994
U(93.2)	22.413	18.9	1185.896
Lucite	26.337	1.1878	22173.165
Concrete	Infinite	2.3	Infinite

6.3.3 Latticing

The minimum thickness of a TACS HEU hemi-shell is 0.146-inch (or 0.37 cm). A few COG calculations were performed to study the effect of interstitial moderation by immersing the TACS in water and increasing the distance between each fissile shell as shown in the figure below. The results of these calculations demonstrate a significant increase in k-eff > 0.96 indicating a potential criticality hazard. However, the controls listed below are judged sufficient to preclude any credible hazard. These controls are supplemented by the good practices listed in Section 7.

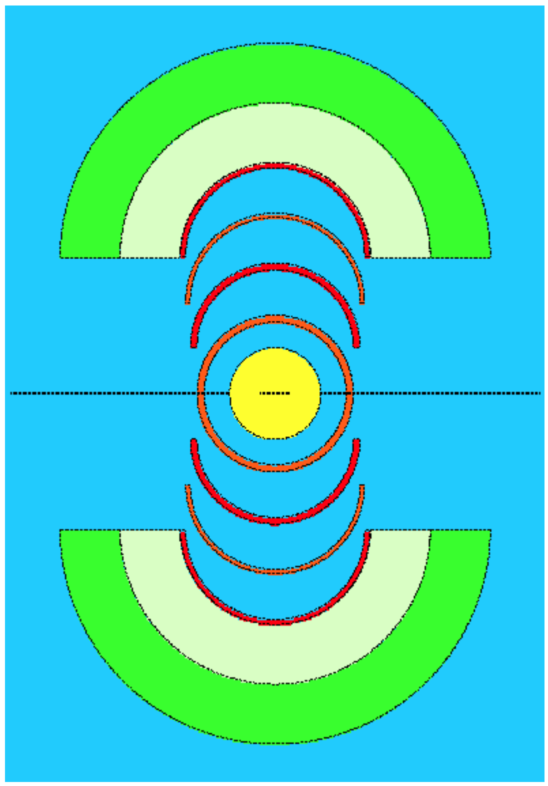

Table 6-13. COG Calculational Results (continued)

Entry	k-eff	MFE	File	Remarks
Latticing in water				
54	0.9573(6)	16.1 eV	tacs17	Immersed with 0.0-inch gaps
55	0.9747(6)	20.0 eV	tacs63	Immersed with 0.5-inch gaps
56	0.9868(6)	22.1 eV	tacs61	Immersed with 1.0-inch gaps
57	0.9813(6)	21.5 eV	tacs62	Immersed with 1.5-inch gaps

CONTROL: Spacers, shims, or plastics shall not be used to offset individual shells from one another.

7.0 DESIGN FEATURES AND ADMINISTRATIVE CONTROLS

Design features of the TACS that enhance criticality safety include:

(1) A neutron source holder that minimizes the cavity volume and enhances safety under flooding (see §6.2.1) and crushing (see Section 6.3.1) scenarios.

(2) An assembly machine (tabletop) that ensures that the neutron source holder is always present by fixing it to the diaphragm.

Administrative controls to ensure subcriticality (safety) are provided as Standard Criticality Control Condition I for implementation in the OSP as shown below. The OSP shall also identify that the TACS is a Criticality Hazard Type 2.

Condition I

Material and Form

A. Enriched uranium is limited to 20.9 kg ^{235}U.
B. Authorized enriched uranium parts are 18325, 18326, 500154, 500155, 500156, 500157, 23181, and 23184.

Moderation

A. Authorized Lucite moderator parts are M1A, M1B, M2A, M2B, M3A, and M3B.
B. Authorized Am-Li neutron source is 401009.
C. No liquids are allowed.

Reflection

A. Depleted uranium mass is limited to 23.0 kg D-38.
B. Authorized Lucite reflector parts are R1A, R1A, R2A, R2B, R3A, R3B, R4A, and R4B.
C. Authorized cadmium parts are Cd-1 and Cd-2.
D. Packaging, assembly table, staging tables, storage cabinet, personnel, detectors, etc., are allowed.

Shape

A. Spacers, shims, or plastics shall not be used to offset individual shells from one another.

8.0 SUMMARY AND CONCLUSIONS

This document satisfies the DOE O 420.1A, CSG-P-004, and DOE-STD-3007-93, Change Notice No. 1, requirements for a criticality safety evaluation. No credible criticality accident scenarios were identified. This satisfies the requirements for *Process Analysis* as well as the *Double Contingency Principal* as defined in ANSI/ANS-8.1, Sections 4.1.2 and 4.2.2, respectively.

9.0 REFERENCES

References are provided as footnotes.

Appendix A

Sample COG Input Listing

```
TACS model of M3A/M3B, 8 Oy hemis, R2A/R2B, R3A/R3B
basic
 neutron delayedn INCHES
criticality
 npart=5000 nbatch=1020 sdt=0.0001 nfirst=21 norm=1.
 nsource=1  0 0 0
mix nlib=ENDFB6R7 sablib=COGSAB
$ -- Lower Assembly Materials ------------------------------------------------
 mat=1  a-f  1.1888 c 5 (h.ch2) 8 o16 2            $ Lucite M3A Moderator
 mat=2  w-p 18.9 u234 1.1 u235 93.1793 u238 5.7207 $ Oy  18326
 mat=3  w-p 18.9 u234 1.1 u235 93.1596 u238 5.7404 $ Oy 500155
 mat=4  w-p 18.9 u234 1.1 u235 93.1620 u238 5.7380 $ Oy 500157
 mat=5  w-p 18.9 u234 1.1 u235 93.1256 u238 5.7744 $ Oy  23181
 mat=6  a-f  1.1878 c 5 (h.ch2) 8 o16 2            $ Lucite R2B Reflector
 mat=7  a-f  1.1875 c 5 (h.ch2) 8 o16 2            $ Lucite R3A Reflector
$ -- Upper Assembly Materials ------------------------------------------------
 mat=11 a-f  1.1885 c 5 (h.ch2) 8 o16 2            $ Lucite M3B Moderator
 mat=12 w-p 18.9 u234 1.1 u235 93.1391 u238 5.7609 $ Oy  18325
 mat=13 w-p 18.9 u234 1.1 u235 93.1811 u238 5.7189 $ Oy 500154
 mat=14 w-p 18.9 u234 1.1 u235 93.1596 u238 5.7404 $ Oy 500155
 mat=15 w-p 18.9 u234 1.1 u235 93.3485 u238 5.5515 $ Oy  23184
 mat=16 a-f  1.1877 c 5 (h.ch2) 8 o16 2            $ Lucite R2A Reflector
 mat=17 a-f  1.1876 c 5 (h.ch2) 8 o16 2            $ Lucite R3B Reflector
assign-mc
  1 lime  2 orange  3 red  4 orange  5 red  6 lime  7 green
 11 lime 12 orange 13 red 14 orange 15 red 16 lime 17 green
geometry
$ -- Lower Assembly Geometry ---
 sector  1 M3A         1  -2 -15
 sector  2 Oy--18326   3  -4 -15
 sector  3 Oy-500155   5  -6 -15
 sector  4 Oy-500157   7  -8 -15
 sector  5 Oy--23181   9 -10 -15
 sector  6 R2B        11 -12 -15
 sector  7 R3A        13 -14 -15
$ -- Upper Assembly Geometry ---
 sector 11 M3B        21 -22  15
 sector 12 Oy--18325  23 -24  15
 sector 13 Oy-500154  25 -26  15
 sector 14 Oy-500156  27 -28  15
 sector 15 Oy--23184  29 -30  15
 sector 16 R2A        31 -32  15
 sector 17 R3B        33 -34  15
picture cs material color -9  0  9 -9  0 -9   9  0 -9
volume material           -8 -8 -8  8 -8 -8  -8  8 -8  16 16 16
surfaces $ Dimensions in INCHES
$ ---------------------------------------------------------------------------------------------
$ Lower assembly (moveable half) - heavy
$ ---------------------------------------------------------------------------------------------
   1 sphere  1.5796   2 sphere  2.3186674 $ Lucite/M3A (minimum inner with  347.8 g @  1.1888 g/cc)
   3 sphere  2.3330   4 sphere  2.5666802 $ Oy/18326   (minimum inner with 2731.3 g @ 18.9    g/cc)
   5 sphere  2.5730   6 sphere  2.7921669 $ Oy/500155  (minimum inner with 3070.9 g @ 18.9    g/cc)
   7 sphere  2.7975   8 sphere  2.9409976 $ Oy/500157  (minimum inner with 2299.4 g @ 18.9    g/cc)
   9 sphere  2.9450  10 sphere  3.1193777 $ Oy/23181   (minimum inner with 3120.8 g @ 18.9    g/cc)
  11 sphere  3.1374  12 sphere  5.1013984 $ Lucite/R2B (minimum inner with 4153.2 g @  1.1878 g/cc)
  13 sphere  5.1062  14 sphere  7.0771158 $ Lucite/R3A (minimum inner with 9020.4 g @  1.1875 g/cc)
$ ----------------------------------------------------------------------------------------------
$ Assembly midplane (no diaphragm)
$ ----------------------------------------------------------------------------------------------
  15 plane z 0.0                           $ Midplane
$ ----------------------------------------------------------------------------------------------
$ Upper assembly (fixed half) - light
$ ----------------------------------------------------------------------------------------------
  21 sphere  1.5757  22 sphere  2.3157756 $ Lucite/M3B (minimum inner with  347.0 g @  1.1885 g/cc)
  23 sphere  2.3350  24 sphere  2.5680057 $ Oy/18325   (minimum inner with 2727.1 g @ 18.9    g/cc)
  25 sphere  2.5745  26 sphere  2.7934013 $ Oy/500154  (minimum inner with 3070.3 g @ 18.9    g/cc)
  27 sphere  2.7985  28 sphere  2.9416947 $ Oy/500156  (minimum inner with 2295.9 g @ 18.9    g/cc)
  29 sphere  2.9470  30 sphere  3.1199468 $ Oy/23184   (minimum inner with 3097.8 g @ 18.9    g/cc)
  31 sphere  3.1368  32 sphere  5.0996783 $ Lucite/R2A (minimum inner with 4148.1 g @  1.1877 g/cc)
```

```
  33 sphere  5.1063  34 sphere  7.0762763 $ Lucite/R3B (minimum inner with 9015.7 g @  1.1876 g/cc)
end
```

Appendix B

COG ICSBEP Benchmark Results

MFE	Bias	d(BIAS)	# COG k-eff	ICSBEP k-eff	FILE	DESCRIPTION
439.0E+3	0.0033	0.0022	# 1.0049(6)	1.0016(21)	HEUMF055-1	ZPR-3/23 detailed "as-built" model
216.0E+3	0.0096	0.0012	# 1.0109(5)	1.0013(11)	HEUMF060-1	ZPR-9/4 detailed "as-built" model U/W
66.0E+3	0.0094	0.0013	# 1.0100(7)	1.0006(11)	HEUMI001-1	ZPR-9/34 detailed "as-built" model U/Fe
459.0E+3	-0.0055	0.0019	# 0.9951(5)	1.0006(18)	HEUMF061-1	ZPPR-21F detailed "as-built" model
6.5003E+5	0.0074	0.0036	# 1.0074(6)	1.0000(36)	HEUMF005-1	1(U6) 41(U11) 229(Mo)
5.4735E+5	0.0045	0.0036	# 1.0052(6)	1.0007(36)	HEUMF005-2	1(Em) 37(U11) 51(Be) 182(Mo)
4.9750E+5	0.0118	0.0036	# 1.0114(6)	0.9996(36)	HEUMF005-3	1(Em) 1(U8) 33(U11) 134(Be) 102(Mo)
4.6351E+5	-0.0039	0.0036	# 0.9950(6)	0.9989(36)	HEUMF005-4	1(U3) 30(U11) 1(Mo) 239(Be)
5.6391E+5	0.0004	0.0036	# 0.9984(6)	0.9980(36)	HEUMF005-5	1(Em) 36(U11) 24(Mo) 210(Be)
6.0722E+5	0.0004	0.0036	# 0.9991(6)	0.9987(36)	HEUMF005-6	1(Em) 39(U11) 51(Mo) 180(Be)
2.9953E+5	0.0012	0.0041	# 1.0013(6)	1.0001(41)	HEUMF068-1	KBR-22 (Used COG version 10.27d)
2.6091E+4	0.0008	0.0036	# 1.0016(6)	1.0008(36)	HEUMF068-2	KBR-23 (Used COG version 10.26d)
0.95311E+6	-0.0019	0.0010	# 0.9981(3)	1.0000(10)	HEUMF001-1	Godiva
0.98231E+6	0.0021	0.0031	# 1.0021(6)	1.0000(30)	HEUMF002-1	Popsy Sphere
0.96644E+6	0.0028	0.0031	# 1.0028(6)	1.0000(30)	HEUMF002-2	Popsy Cylnder
0.96409E+6	0.0000	0.0031	# 1.0000(6)	1.0000(30)	HEUMF002-3	Popsy //-piped
0.95480E+6	0.0001	0.0031	# 1.0001(6)	1.0000(30)	HEUMF002-4	Popsy //-piped
0.94697E+6	0.0000	0.0031	# 1.0000(6)	1.0000(30)	HEUMF002-5	Popsy //-piped
0.95532E+6	0.0014	0.0031	# 1.0014(6)	1.0000(30)	HEUMF002-6	Popsy //-piped
0.95117E+6	-0.0065	0.0050	# 0.9935(6)	1.0000(50)	HEUMF003-1	Oy 2.0"Tu
0.96357E+6	-0.0068	0.0050	# 0.9932(6)	1.0000(50)	HEUMF003-2	Oy 3.0"Tu
0.97262E+6	-0.0018	0.0050	# 0.9982(6)	1.0000(50)	HEUMF003-3	Oy 4.0"Tu
0.97945E+6	-0.0035	0.0031	# 0.9965(6)	1.0000(30)	HEUMF003-4	Oy 5.0"Tu
0.98192E+6	0.0018	0.0031	# 1.0018(6)	1.0000(30)	HEUMF003-5	Oy 7.0"Tu
0.98151E+6	0.0009	0.0031	# 1.0009(6)	1.0000(30)	HEUMF003-6	Oy 8.0"Tu
0.97075E+6	0.0018	0.0031	# 1.0018(7)	1.0000(30)	HEUMF003-7	Oy 11.0"Tu
0.71906E+6	0.0076	0.0050	# 1.0076(6)	1.0000(50)	HEUMF003-8	Oy 1.9"WC
0.66670E+6	0.0090	0.0050	# 1.0090(6)	1.0000(50)	HEUMF003-9	Oy 2.9"WC
0.63128E+6	0.0101	0.0050	# 1.0101(6)	1.0000(50)	HEUMF003-10	Oy 4.5"WC
0.62370E+6	0.0117	0.0050	# 1.0117(6)	1.0000(50)	HEUMF003-11	Oy 6.5"WC
0.77520E+6	0.0065	0.0050	# 1.0065(6)	1.0000(50)	HEUMF003-12	Oy 8.0"Ni
0.51727E+6	-0.0016	0.0006	# 1.0004(6)	1.0020(00)	HEUMF004-1	24.50 kg Oy Full Water
0.97812E+6	0.0024	0.0031	# 1.0024(6)	1.0000(30)	HEUMF028-1	17.84 kg Oy 7.09"Tu (Flattop)
0.96786E+6	0.0042	0.0017	# 1.0042(6)	1.0000(16)	HEUMF032-1	19.82 kg Oy 3.93"Tu (Comet)
0.96676E+6	0.0032	0.0028	# 1.0032(6)	1.0000(27)	HEUMF032-2	20.45 kg Oy 3.52"Tu (Comet)
0.94650E+6	-0.0014	0.0018	# 0.9986(6)	1.0000(17)	HEUMF032-3	26.56 kg Oy 1.74"Tu (Comet)
0.94137E+6	-0.0005	0.0018	# 0.9995(6)	1.0000(17)	HEUMF032-4	36.54 kg Oy 0.68"Tu (Comet)
0.70161E+6	0.0056	0.0031	# 1.0069(6)	1.0013(30)	HEUMF041-1	23.64 kg Oy 1.85"Be (Comet)
0.48479E+6	0.0030	0.0043	# 1.0052(6)	1.0022(43)	HEUMF041-2	14.00 kg Oy 4.64"Be (Comet)
0.85399E+6	0.0003	0.0030	# 1.0009(6)	1.0006(29)	HEUMF041-3	31.52 kg Oy 2.00"C (Comet)
0.78825E+6	0.0038	0.0026	# 1.0044(6)	1.0006(25)	HEUMF041-4	25.88 kg Oy 4.00"C (Comet)
0.73821E+6	-0.0008	0.0032	# 0.9998(6)	1.0006(31)	HEUMF041-5	22.90 kg Oy 6.00"C (Comet)
0.7022E+6	0.0027	0.0045	# 1.0033(6)	1.0006(45)	HEUMF041-6	20.77 kg Oy 8.00"C (Comet)
8.5055E+5	-0.0017	0.0040	# 0.9976(6)	0.9993(40)	HEUMF063-1	45.709 kg Oy 1" Li6D (Comet)
8.2713E+5	0.0014	0.0047	# 1.0002(6)	0.9988(47)	HEUMF063-2	40.564 kg Oy 1" LiD (Comet)
4.9908E-2	0.0063	0.0060	# 1.0073(6)	1.0010(60)	HEUMT001-1	Class Foils with CH2 and SiO2
4.3577E+5	0.0005	0.0012	# 1.0005(6)	1.0000(10)	HEUMT003-1	23.999 kg U(94) cube in H2O
0.36218E+6	0.0069	0.0027	# 1.0069(6)	1.0000(26)	HMF058-1	10.765 kg Oy in 7.980" Be (bench1)
0.54520E+6	0.0068	0.0035	# 1.0069(6)	1.0001(34)	HMF058-2	16.267 kg Oy in 3.650" Be (bench2)
0.67110E+6	0.0043	0.0028	# 1.0043(6)	1.0000(27)	HMF058-3	21.780 kg Oy in 2.140" Be (bench3)
0.76144E+6	0.0016	0.0021	# 1.0018(6)	1.0002(20)	HMF058-4	27.990 kg Oy in 1.285" Be (bench4)
0.81491E+6	0.0005	0.0033	# 1.0006(6)	1.0001(32)	HMF058-5	32.654 kg Oy in 0.875" Be (bench5)
0.48242E+6	0.0012	0.0034	# 1.0042(6)	1.0030(33)	HMF066-1	3.1460cm-Be/19.355kg-Oy/ 8.74cm-Be (bob1)
0.61315E+6	0.0011	0.0030	# 1.0034(6)	1.0023(29)	HMF066-2	3.1460cm-Be/25.566kg-Oy/ 5.28cm-Be (bob2)
0.68091E+6	0.0018	0.0027	# 1.0041(6)	1.0023(26)	HMF066-3	3.1460cm-Be/30.229kg-Oy/ 3.86cm-Be (bob3)
0.30320E+6	0.0031	0.0043	# 1.0074(6)	1.0043(43)	HMF066-4	4.0895cm-Be/16.498kg-Oy/13.2 cm-Be (bob4)
0.46190E+6	0.0013	0.0034	# 1.0043(6)	1.0030(33)	HMF066-5	4.0895cm-Be/22.709kg-Oy/ 7.85cm-Be (bob5)
0.54747E+6	0.0013	0.0031	# 1.0041(6)	1.0028(30)	HMF066-6	4.0895cm-Be/27.372kg-Oy/ 5.64cm-Be (bob6)
0.43221E+6	0.0031	0.0040	# 1.0079(6)	1.0048(39)	HMF066-7	4.6975cm-Be/24.643kg-Oy/ 7.67cm-Be (bob7)
0.32962E+6	0.0042	0.0040	# 1.0081(6)	1.0039(40)	HMF066-8	4.6975cm-Be/19.980kg-Oy/10.64cm-Be (bob8)
0.42236E+6	0.0025	0.0037	# 1.0052(6)	1.0027(36)	HMF066-9	6.5445cm-Be/37.234kg-Oy/ 5.49cm-Be (bob9)
2.0604E+2	-0.0024	0.0031	# 0.9951(7)	0.9975(30)	HMI009-1	69.90 kg Oy @ BeO/X= 62 (Spade-162 Pt 3)
3.2220E+1	-0.0014	0.0049	# 0.9936(7)	0.9950(48)	HMI009-2	42.16 kg Oy @ BeO/X= 124 (Spade-158)
1.0363E+0	0.0045	0.0029	# 0.9992(7)	0.9947(28)	HMT027-1	22.31 kg Oy @ BeO/X= 247 (Spade1-B)
2.0612E-1	0.0074	0.0028	# 1.0028(7)	0.9954(27)	HMT027-2	12.15 kg Oy @ BeO/X= 493 (Spade2)
1.7763E-1	0.0074	0.0027	# 1.0020(7)	0.9946(26)	HMT027-3	12.31 kg Oy @ BeO/X= 493 (Spade3-B)
9.2261E-2	0.0086	0.0024	# 1.0043(7)	0.9957(23)	HMT027-4	6.89 kg Oy @ BeO/X= 986 (Spade4)
8.8246E-2	0.0056	0.0023	# 1.0021(7)	0.9965(22)	HMT027-5	7.11 kg Oy @ BeO/X= 986 (Spade5-B)
8.4525E-2	0.0107	0.0022	# 1.0071(7)	0.9964(21)	HMT027-6	7.58 kg Oy @ BeO/X= 986 (Spade6c-B)
6.1559E-2	0.0092	0.0036	# 1.0056(7)	0.9964(35)	HMT027-7	4.68 kg Oy @ BeO/X=1920 (Spade7-E)
6.0246E-2	0.0048	0.0035	# 1.0001(7)	0.9953(34)	HMT027-8	4.79 kg Oy @ BeO/X=1920 (Spade8-D)
6.0256E-2	0.0080	0.0026	# 1.0030(7)	0.9950(25)	HMT027-9	4.61 kg Oy @ BeO/X=1920 (Spade9)
5.9953E-2	0.0085	0.0023	# 1.0047(6)	0.9962(22)	HMT027-10	4.84 kg Oy @ BeO/X=1920 (Spade10)
4.7247E-2	0.0103	0.0036	# 1.0059(6)	0.9956(35)	HMT027-11	3.66 kg Oy @ BeO/X=3830 (Spade11-D)
4.7376E-2	0.0150	0.0033	# 1.0121(7)	0.9971(32)	HMT027-12	3.87 kg Oy @ BeO/X=3830 (Spade12-E)
4.6876E-2	0.0214	0.0037	# 1.0159(7)	0.9945(36)	HMT027-13	3.63 kg Oy @ BeO/X=3830 (Spade13-D)
4.6896E-2	0.0112	0.0033	# 1.0082(7)	0.9970(32)	HMT027-14	3.87 kg Oy @ BeO/X=3830 (Spade14-A)
4.0302E-2	0.0160	0.0024	# 1.0122(7)	0.9962(23)	HMT027-15	2.90 kg Oy @ BeO/X=7660 (Spade15-B)
9.4298E+5	0.0064	0.0012	# 1.0051(6)	0.9987(10)	HEUMF062-1	Coral-I reactor
9.6629E+5	-0.0042	0.0025	# 0.9908(6)	0.9950(24)	HMF007-1	103.997 kg U(93.15) @ H/X=0.0 (bare)
7.7924E+5	0.0018	0.0015	# 0.9982(6)	0.9964(14)	HMF007-2	99.658 kg U(93.15) @ H/X=0.3 (bare)
7.2201E+5	-0.0015	0.0014	# 0.9975(6)	0.9990(13)	HMF007-3	97.756 kg U(93.15) @ H/X=0.3 (bare)
6.7251E+5	0.0010	0.0014	# 0.9958(6)	0.9948(13)	HMF007-4	95.929 kg U(93.15) @ H/X=0.4 (bare)
5.9557E+5	0.0007	0.0019	# 0.9985(6)	0.9978(18)	HMF007-5	93.974 kg U(93.15) @ H/X=0.5 (bare)
5.5810E+5	0.0034	0.0014	# 1.0040(6)	1.0006(13)	HMF007-6	92.089 kg U(93.15) @ H/X=0.6 (bare)
5.4556E+5	-0.0028	0.0015	# 1.0002(6)	0.9974(14)	HMF007-7	92.089 kg U(93.15) @ H/X=0.6 (bare)
5.3991E+5	0.0004	0.0014	# 0.9977(6)	0.9973(13)	HMF007-8	92.054 kg U(93.15) @ H/X=0.6 (bare)
5.4702E+5	0.0023	0.0056	# 1.0018(6)	0.9995(56)	HMF007-9	92.021 kg U(93.15) @ H/X=0.6 (bare)
1.8225E+5	-0.0017	0.0013	# 0.9964(6)	0.9981(12)	HMF007-10	76.687 kg U(93.15) @ H/X=1.5 (bare)
1.0598E+4	0.0004	0.0014	# 0.9962(6)	0.9958(13)	HMF007-11	64.299 kg U(93.15) @ H/X=2.5 (bare)

Appendix B

COG ICSBEP Benchmark Results

6.0365E+3	-0.0015	0.0013	# 0.9917(6)	0.9932(12)	HMF007-12	61.445 kg U(93.15) @ H/X=2.7 (bare)

MFE	Bias	d(BIAS)	# COG k-eff	ICSBEP k-eff	FILE	DESCRIPTION
6.7391E+3	-0.0005	0.0013	# 0.9985(6)	0.9990(12)	HMF007-13	61.443 kg U(93.15) @ H/X=2.7 (bare)
5.2974E+3	-0.0017	0.0013	# 0.9947(6)	0.9964(12)	HMF007-14	61.444 kg U(93.15) @ H/X=2.7 (bare)
8.3858E+5	-0.0003	0.0013	# 0.9956(6)	0.9959(12)	HMF007-15	61.332 kg U(93.15) @ H/X=2.6 (bare)
7.8726E+5	-0.0010	0.0013	# 0.9959(6)	0.9969(12)	HMF007-16	61.333 kg U(93.15) @ H/X=2.6 (bare)
2.4607E+2	0.0008	0.0013	# 0.9961(6)	0.9953(12)	HMF007-17	46.058 kg U(93.15) @ H/X=4.8 (bare)
2.3241E+2	0.0009	0.0013	# 0.9981(6)	0.9972(12)	HMF007-18	46.057 kg U(93.15) @ H/X=4.8 (bare)
9.5996E+5	-0.0013	0.0016	# 0.9943(6)	0.9956(15)	HMF007-19	74.097 kg U(93.15) @ H/X=0.0 (bare)
6.0324E+5	0.0012	0.0018	# 0.9962(6)	0.9950(17)	HMF007-20	71.721 kg U(93.15) @ H/X=0.6 (bare)
5.8787E+5	0.0012	0.0019	# 0.9968(6)	0.9956(18)	HMF007-21	71.721 kg U(93.15) @ H/X=0.6 (bare)
5.7174E+5	0.0007	0.0020	# 0.9970(6)	0.9963(19)	HMF007-22	71.721 kg U(93.15) @ H/X=0.6 (bare)
4.2798E+5	0.0018	0.0018	# 0.9980(6)	0.9962(17)	HMF007-23	68.879 kg U(93.15) @ H/X=1.0 (bare)
4.2075E+5	0.0004	0.0019	# 0.9974(6)	0.9970(18)	HMF007-24	68.879 kg U(93.15) @ H/X=1.0 (bare)
2.7018E+5	0.0004	0.0019	# 0.9963(6)	0.9959(18)	HMF007-25	66.959 kg U(93.15) @ H/X=1.4 (bare)
2.6351E+5	0.0013	0.0018	# 0.9979(6)	0.9966(17)	HMF007-26	66.959 kg U(93.15) @ H/X=1.4 (bare)
7.5813E+5	0.0009	0.0015	# 0.9957(6)	0.9948(14)	HMF007-27	99.711 kg U(93.15) @ H/X=0.3 (bare)
6.2189E+5	-0.0008	0.0024	# 0.9962(6)	0.9970(23)	HMF007-28	95.205 kg U(93.15) @ H/X=0.5 (bare)
4.9498E+5	0.0019	0.0015	# 0.9980(6)	0.9961(14)	HMF007-29	92.063 kg U(93.15) @ H/X=0.7 (bare)
1.2374E+5	-0.0010	0.0022	# 0.9954(6)	0.9964(21)	HMF007-30	76.692 kg U(93.15) @ H/X=1.6 (bare)
1.6200E+3	0.0000	0.0023	# 0.9996(6)	0.9996(22)	HMF007-31	61.402 kg U(93.15) @ H/X=3.3 (bare)
3.1258E+5	0.0002	0.0019	# 1.0005(6)	1.0003(18)	HMF007-35	32.271 kg U(93.15) @ H/X=0.0 (6"CH2)
9.1940E+4	0.0025	0.0009	# 1.0024(6)	0.9999(07)	HMF007-36	30.664 kg U(93.15) @ H/X=0.4 (6"CH2)
1.2600E+4	0.0015	0.0010	# 1.0003(6)	0.9988(08)	HMF007-37	28.728 kg U(93.15) @ H/X=0.8 (6"CH2)
8.4686E+3	0.0023	0.0010	# 1.0023(6)	1.0000(08)	HMF007-38	28.646 kg U(93.15) @ H/X=0.9 (6"CH2)
7.8194E+3	0.0028	0.0015	# 1.0046(6)	1.0018(14)	HMF007-39	28.645 kg U(93.15) @ H/X=1.0 (6"CH2)
9.5561E+3	0.0042	0.0015	# 1.0055(6)	1.0013(14)	HMF007-40	28.641 kg U(93.15) @ H/X=0.9 (6"CH2)
3.0590E+2	0.0004	0.0011	# 0.9998(6)	0.9994(09)	HMF007-41	22.968 kg U(93.15) @ H/X=2.2 (6"CH2)
2.8569E+2	0.0012	0.0011	# 1.0028(6)	1.0016(09)	HMF007-42	22.968 kg U(93.15) @ H/X=2.3 (6"CH2)
1.3522E+1	0.0008	0.0010	# 1.0006(6)	0.9998(08)	HMF007-43	15.712 kg U(93.15) @ H/X=5.4 (6"CH2)
9.6437E+5	-0.0032	0.0006	# 0.9939(3)	0.9971(05)	HMF051-1	102.034 kg U(93.14) w/o impurities
9.6489E+5	-0.0019	0.0006	# 0.9949(3)	0.9968(05)	HMF051-2	109.386 kg U(93.14) w/o impurities
9.6455E+5	-0.0032	0.0006	# 0.9942(3)	0.9974(05)	HMF051-3	116.592 kg U(93.14) w/o impurities
9.6460E+5	-0.0019	0.0006	# 0.9950(3)	0.9969(05)	HMF051-4	123.937 kg U(93.14) w/o impurities
9.6574E+5	-0.0035	0.0004	# 0.9940(3)	0.9975(03)	HMF051-5	131.289 kg U(93.14) w/o impurities
9.6604E+5	-0.0037	0.0005	# 0.9937(3)	0.9974(04)	HMF051-6	138.539 kg U(93.14) w/o impurities
9.6580E+5	-0.0042	0.0004	# 0.9933(3)	0.9975(03)	HMF051-7	145.824 kg U(93.14) w/o impurities
9.6715E+5	-0.0040	0.0004	# 0.9936(3)	0.9976(02)	HMF051-8	153.120 kg U(93.14) w/o impurities
9.6774E+5	-0.0046	0.0004	# 0.9936(3)	0.9982(02)	HMF051-9	160.380 kg U(93.14) w/o impurities
9.6689E+5	-0.0043	0.0004	# 0.9938(3)	0.9981(03)	HMF051-10	167.732 kg U(93.14) w/o impurities
9.6552E+5	-0.0039	0.0003	# 0.9934(3)	0.9973(01)	HMF051-11	167.727 kg U(93.14) w/o impurities
9.6596E+5	-0.0032	0.0003	# 0.9934(3)	0.9966(01)	HMF051-12	174.988 kg U(93.14) w/o impurities
9.6613E+5	-0.0031	0.0003	# 0.9948(3)	0.9979(01)	HMF051-13	182.295 kg U(93.14) w/o impurities
9.5543E+5	-0.0028	0.0004	# 0.9968(3)	0.9996(02)	HMF051-14	58.701 kg U(93.14) w/o impurities
9.6024E+5	-0.0030	0.0003	# 0.9968(3)	0.9998(01)	HMF051-15	75.454 kg U(93.14) w/o impurities
9.6422E+5	-0.0025	0.0003	# 0.9956(3)	0.9981(01)	HMF051-16	99.474 kg U(93.14) w/o impurities
9.6848E+5	-0.0024	0.0003	# 0.9945(3)	0.9969(01)	HMF051-17	128.094 kg U(93.14) w/o impurities
9.7050E+5	-0.0047	0.0003	# 0.9937(3)	0.9984(01)	HMF051-18	164.879 kg U(93.14) w/o impurities
0.45382E+6	0.0015	0.0028	# 1.0013(6)	0.9998(27)	HEUMF048-1	(24.2 kg Oy shell(0.00 cm IR/oil) in oil)
0.22994E+6	0.0009	0.0032	# 1.0010(6)	1.0001(33)	HEUMF048-2	(25.8 kg Oy shell(4.02 cm IR/oil) in oil)
1.16690E+4	0.0005	0.0032	# 1.0007(6)	1.0002(31)	HEUMF048-3	(31.8 kg Oy shell(6.68 cm IR/oil) in oil)
2.92260E+3	0.0033	0.0031	# 1.0021(6)	0.9988(30)	HEUMF048-4	(38.2 kg Oy shell(8.01 cm IR/oil) in oil)
5.34180E+2	-0.0063	0.0041	# 0.9933(6)	0.9996(41)	HEUMF048-5	(66.5 kg Oy shell(12.01 cm IR/oil) in oil)
0.38734E+6	-0.0012	0.0035	# 1.0000(6)	1.0012(34)	HEUMF048-6	(25.8 kg Oy hemi (0.00 cm IR/oil) in oil)
0.31934E+6	-0.0005	0.0050	# 1.0003(6)	0.9998(50)	HEUMF048-7	(27.3 kg Oy hemi (4.02 cm IR/oil) in oil)
0.18446E+6	-0.0017	0.0050	# 0.9981(6)	0.9998(50)	HEUMF048-8	(32.0 kg Oy hemi (6.68 cm IR/oil) in oil)
0.12333E+6	-0.0006	0.0047	# 0.9975(6)	0.9981(47)	HEUMF048-9	(35.8 kg Oy hemi (8.01 cm IR/oil) in oil)
2.24900E+4	-0.0022	0.0025	# 0.9961(6)	0.9983(24)	HEUMF048-10	(52.8 kg Oy hemi (12.01 cm IR/oil) in oil)
0.39164E+6	0.0035	0.0039	# 1.0032(6)	0.9997(39)	HEUMF048-11	(31.6 kg Oy shell(4.02 cm IR/steel) in oil)
0.24814E+6	-0.0015	0.0046	# 0.9990(6)	1.0005(46)	HEUMF048-12	(51.8 kg Oy shell(8.01 cm IR/steel) in oil)
0.13006E+6	0.0040	0.0036	# 1.0029(6)	0.9989(36)	HEUMF048-13	(81.0 kg Oy shell(12.01 cm IR/steel) in oil)
0.37668E+6	-0.0020	0.0049	# 0.9991(6)	1.0011(49)	HEUMF048-14	(29.5 kg Oy hemi (4.02 cm IR/steel) in oil)
0.36131E+6	-0.0021	0.0062	# 0.9960(6)	0.9981(62)	HEUMF048-15	(35.6 kg Oy hemi (6.01 cm IR/steel) in oil)
0.33251E+6	-0.0074	0.0040	# 0.9914(6)	0.9988(40)	HEUMF048-16	(43.2 kg Oy hemi (8.01 cm IR/steel) in oil)
0.28378E+6	-0.0076	0.0054	# 0.9902(6)	0.9978(54)	HEUMF048-17	(58.0 kg Oy hemi (11.01 cm IR/steel) in oil)
0.93639E+6	-0.0013	0.0015	# 0.9987(6)	1.0000(14)	HEUMF018-1	59.259 kg U(90) unreflected
0.86277E+6	0.0036	0.0029	# 1.0035(6)	1.0000(28)	HEUMF019-1	54.272 kg U(90) 3.45 cm C
0.81735E+6	-0.0024	0.0029	# 0.9976(6)	1.0000(28)	HEUMF020-1	45.162 kg U(90) 1.45 cm CH2
0.84390E+6	-0.0040	0.0025	# 0.9960(6)	1.0000(24)	HEUMF021-1	33.162 kg U(90) 9.70 cm Steel
0.88564E+6	-0.0063	0.0020	# 0.9937(6)	1.0000(19)	HEUMF022-1	44.898 kg U(90) 3.90 cm Duralumin
0.90384E+6	0.0070	0.0026	# 1.0070(6)	1.0000(25)	HEUMF027-1	44.898 kg U(90) 3.25 cm Lead
0.92047E+6	0.0038	0.0021	# 1.0038(6)	1.0000(20)	HEUMF029-1	32.065 kg U(90) 4.70 cm D38
0.23651E+6	0.0040	0.0059	# 1.0040(6)	1.0000(59)	HEUMF031-1	27.787 kg U(90) 17.45 cm CH2
1.2719E+4	0.0068	0.0037	# 1.0068(6)	1.0000(37)	HEUMM002-1	35.238 kg U(90) 5.75cm-CH2/12.85cm-CH2
1.2311E+4	0.0076	0.0038	# 1.0076(6)	1.0000(38)	HEUMM003-1	35.237 kg U(90) 5.35cm-CH2/15.85cm-CH2
9.3813E+5	-0.0063	0.0017	# 0.9926(6)	0.9989(16)	HEUMF008-1	78 kg U(90) sphere (Be)
8.0777E+5	-0.0033	0.0016	# 0.9959(6)	0.9992(15)	HEUMF009-1	43.54 kg U(90) sphere (Be)
8.1500E+5	-0.0042	0.0016	# 0.9950(6)	0.9992(15)	HEUMF009-2	43.40 kg U(90) sphere (BeO)
8.2098E+5	-0.0033	0.0016	# 0.9959(6)	0.9992(15)	HEUMF010-1	43.802 kg U(90) sphere (B+Be)
8.2584E+5	-0.0028	0.0016	# 0.9964(6)	0.9992(15)	HEUMF010-2	43.802 kg U(90) sphere (B+BeO)
5.0600E+5	-0.0025	0.0016	# 0.9964(6)	0.9989(15)	HEUMF011-1	31.854 kg U(90) sphere (CH2)
9.0746E+5	-0.0043	0.0019	# 0.9949(6)	0.9992(18)	HEUMF012-1	57.65 kg U(90) sphere (Al)
8.7954E+5	-0.0038	0.0016	# 0.9952(6)	0.9990(15)	HEUMF013-1	42.89 kg U(90) sphere (Steel)
9.1843E+5	-0.0029	0.0018	# 0.9960(6)	0.9989(17)	HEUMF014-1	40.62 kg U(90) sphere (D-38)
0.96484E+6	-0.0076	0.0017	# 0.9920(6)	0.9996(17)	HEUMF015-1	64.060 kg U(96) cylinder (bare)
7.5945E+5	0.0000	0.0019	# 0.9996(6)	0.9996(18)	HEUMF016-1	40.424 kg U(96) cylinder (Be)
7.7423E+5	-0.0002	0.0019	# 0.9994(6)	0.9996(18)	HEUMF016-2	40.424 kg U(96) cylinder (BeO)
6.2463E+5	0.0058	0.0015	# 1.0051(6)	0.9993(14)	HEUMF017-1	81.206 kg U(96) cyl (Be/Mod+Ref)
6.2832E+5	-0.0028	0.0016	# 0.9962(6)	0.9990(15)	HEUMF024-1	32.437 kg U(96) sphere (STL/CH2)
3.7416E+5	0.0057	0.0011	# 1.0057(6)	1.0000(09)	HEUMF030-1	34.809 kg U(96) cyl (Be-mod/D38-ref)
1.0039E+5	-0.0016	0.0015	# 0.9975(6)	0.9991(14)	HEUMF033-1	75.287 kg U(96) @ H/X=1.7 w/Steel
5.4356E+3	-0.0031	0.0015	# 0.9960(6)	0.9991(14)	HEUMF033-2	63.677 kg U(96) @ H/X=3.4 w/Steel
2.2732E+5	-0.0052	0.0013	# 0.9938(6)	0.9990(12)	HEUMF034-1	92.877 kg U(96) @ H/X=1.7 w/Ti

Appendix B

COG ICSBEP Benchmark Results

2.1767E+5	-0.0034	0.0013	# 0.9956(6)	0.9990(12)	HEUMF034-2	92.877 kg U(96) @ H/X=1.7 w/Al
2.3588E+5	-0.0034	0.0013	# 0.9956(6)	0.9990(12)	HEUMF034-3	92.877 kg U(96) @ H/X=1.7 w/Steel
5.0449E+4	-0.0040	0.0016	# 0.9953(6)	0.9993(15)	HEUMF036-1	75.110 kg U(96) @ H/X=2.6 w/D38

MFE	Bias	d(BIAS)	# COG k-eff	ICSBEP k-eff	FILE	DESCRIPTION
3.8715E+5	-0.0058	0.0016	# 0.9935(6)	0.9993(15)	HEUMF036-2	110.291 kg U(96) @ H/X=1.4 w/D38
9.1987E+4	-0.0024	0.0013	# 0.9973(6)	0.9997(11)	HEUMF037-1	46.438 kg U(96) @ H/X=1.7 w/D38
2.7981E+5	-0.0058	0.0013	# 0.9939(6)	0.9997(11)	HEUMF037-2	69.658 kg U(96) @ H/X=1.7 w/D38+Cd
3.9116E+5	-0.0024	0.0009	# 0.9975(6)	0.9999(07)	HEUMF038-1	34.819 kg U(96) with Be/BeO
2.5831E+5	0.0064	0.0011	# 1.0063(6)	0.9999(09)	HEUMF038-2	52.223 kg U(96) with Be/BeO
9.6663E+5	-0.0038	0.0014	# 0.9957(6)	0.9995(13)	HEUMF065-1	63.646 kg U(96) cylinder (bare)
3.4998E+4	0.0009	0.0014	# 1.0004(6)	0.9995(13)	HEUMM001-1	69.658 kg U(96) @ H/X=1.7 w/Ti
1.0584E+3	0.0036	0.0011	# 1.0035(6)	0.9999(09)	HEUMM004-1	52.243 kg U(96) @ H/X=8.6 w/D38