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Criticality Safety Evaluation for the TACS at DAF

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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 and operations associated with HS-3201-P, *Nuclear Criticality 4-Day Training Course (Practical)*. This course was designed to also address the training needs of nuclear criticality safety professionals under the auspices of the NNSA Nuclear Criticality Safety Program[1].

The hands-on, or laboratory, portion of the course will utilize the Training Assembly for Criticality Safety (TACS) and will be conducted in the Device Assembly Facility (DAF) at the Nevada Nuclear Security Site (NNSS). The training activities will be conducted by Lawrence Livermore National Laboratory following the requirements of an Integrated Work Sheet (IWS) and associated Safety Plan. Students will be allowed to handle the fissile material under the supervision of an LLNL Certified Fissile Material Handler.

2.0 DESCRIPTION

2.1 TACS Fissile Parts

The TACS consists of four pairs of nesting highly enriched uranium (HEU- 93.15%) hemishells that were previously used in cross section and critical measurements as part of the "Nimbus" program. Fully assembled, they form a 6.24" diameter sphere with a central void of 4.68" diameter with a total ^{235}U weight of 20.833 kg. Each shell has a 0.6 cm diameter threaded hole at the pole, which historically allowed them to be handled with a threaded lifting fixture. The eight HEU shells are nickel plated for contamination control. Details of the shells are given in Table 2-1. The data in table 2-1 comes from a detailed inspection report[2] and drawings of the shells.[3,4]

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

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

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

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

Table 2-1. **TACS Fissile (HEU) Parts**

Part S/N	Part Weight (kilograms)			Minimum Inner Radius (inches)
	HEU-0.25Ni	HEU	U-235	
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	--

2.2 TACS Depleted Uranium Parts

To aid in obtaining multiplication data, a complimentary set of depleted uranium (D-38 or "Mock") shells are used in the laboratory. These shells closely match the dimensions of the enriched uranium shells. One D-38 part has been assayed[5] at LLNL and confirmed to contain 0.2 wt-% ^{235}U. Details for the D-38 shells are given in Table 2-2. The data in table 2-1 comes from a detailed inspection report[6] and drawings of the shells.[7] The D-38 and HEU shells are pictured in Figure 2.1.

Figure 2.1: HEU Shells (nickel clad, silvery colored) and D-38 Shells (unclad, black colored)

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

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

[7] Drawing No. AAA82-108665-00, *Neutron Multiplication Study, Nesting Shells.*

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

Part S/N	D-38 Parts		Minimum Inner Radius (inches)
	Weight (kilograms)	Density (g/cc)	
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
Total	22.9316	18.8971	--

2.3 TACS Moderator Parts

The inner cavity of the TACS assembly can be filled with Lucite moderator pieces. These 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 at one time. The maximum authorized moderator mass is 694.8 grams corresponding to parts M3A and M3B. Table 2-3 lists the dimensions of the Lucite moderator parts. The data in table 2-1 comes from a detailed inspection report[8].

Table 2-3. TACS Moderator (Lucite) Parts

Part S/N	Lucite Parts		Minimum Inner Radius (inches)
	Weight (grams)	Density (g/cc)	
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

2.4 TACS Reflector Parts

Various reflectors may be used around the TACS uranium parts, including pairs of lucite reflectors (RXA and RXB), steel reflectors (ST-Shell-XT and –XB), one pair of thin cadmium shells, and leaded gloves.

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

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

hemishells are designed to nest snuggly within Lucite reflector parts R4A and R4B, which in turn may be nested within R3A and R3B.

Table 2-4. TACS Reflector (Lucite and Cadmium) Parts

Part Number	Weight (kg)	Calculated Density (g/cc)	Minimum Inner 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
R4A†	4.0066	1.1885	3.1987
R4B†	3.9873	1.1884	3.1997
R5A*	0.2516	1.2188	3.2057
R5B*	0.2500	1.2031	3.2100
R6A*	0.5520	1.2617	3.1620
R6B*	0.5537	1.2678	3.1690
R7A*	2.0198	1.1898	3.1468
R7B*	2.0207	1.1886	3.1537
R8A*	2.9917	1.1908	3.1509
R8B*	2.9817	1.1798	3.1699
R9A*	2.9374	1.1879	5.1087
R9B*	2.9222	1.1818	5.1087
Cd-1†	0.2412	8.5731	3.1537
Cd-2†	0.2464	8.5748	3.1667

† Data taken from Inspection Reports for Jerry Smith/Tom Anklam, *Neutron Multiplication Study*, MMED WO # M0004241/M0004986

* Measurements made by C. Percher in May, 2008.

Two additional Lucite reflectors, LB1 and LB2, have been fabricated for use around the TACS. These reflectors are Lucite boxes designed to provide 1" of tangential reflection around TACS uranium hemishells (details of the boxes are provided in Appendix D).

Fourteen nesting 0.5" thick carbon steel shells can be used to create 3.5" (8.89 cm) of reflection around the assembly[9]. The steel reflector parts are described in Table 2-5. Shells labeled "B" (bottom) and "T" (top) with the same number are mated shells. Because the TACS outer radius is 3.12" and ST-Shell-04B and ST-Shell-04T radii are 3.5", there will be a small (0.38") gap between the TACS outer HEU shells and the steel. On the bottom half of the assembly, a small piece of cork or low density foam will be used to support the TACS shells and prevent a separation between the two halves of the assembly.

[9] Darrell Pugh, email to C. Percher (December 2009).

Table 2-5. TACS Carbon Steel Reflector Parts

Part Number	Weight (kg)	Calculated Density (g/cc)	Minimum Inner Radius (in)
ST-Shell-04B	4.9565	7.3500	3.5
ST-Shell-04T	4.7109	6.9858	3.5
ST-Shell-05B	6.6356	7.6556	4
ST-Shell-05T	6.4843	7.4810	4
ST-Shell-06B	8.1887	7.5589	4.5
ST-Shell-06T	8.2353	7.6019	4.5
ST-Shell-07B	10.112	7.6374	5
ST-Shell-07T	10.206	7.7083	5
ST-Shell-08B	11.614	7.3096	5.5
ST-Shell-08T	11.330	7.1309	5.5
ST-Shell-09B	14.100	7.5086	6
ST-Shell-09T	14.000	7.4553	6
ST-Shell-10B	16.200	6.9033	6.5
ST-Shell-10T	16.100	6.8607	6.5

Figure 2.2 shows a photograph of the carbon steel reflector shells nested together. There are smaller shells shown in the photograph, but the geometry of the TACS assembly will preclude the use of those shells. As shown in the photograph, all parts are inscribed and labeled in black (black lettering around the edge of each shell).

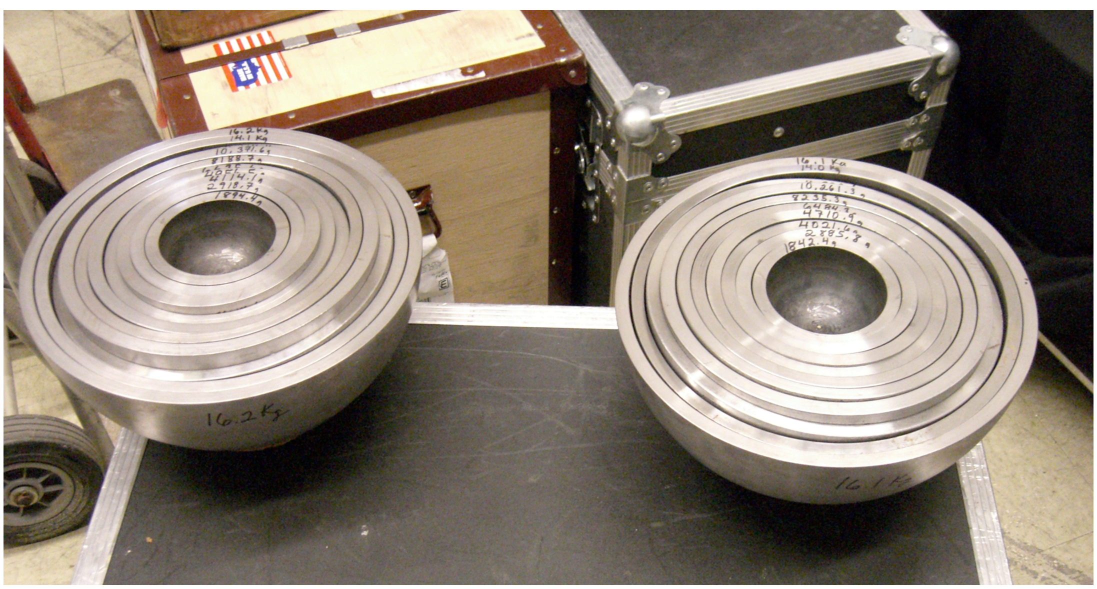

Figure 2.2: Full Set of Carbon Steel Shells
(Geometry will restrict the use of the innermost shells)

These shells can mate up with approved Lucite reflector shells for investigation of composite reflection, specifically Lucite shells R1A and R1B (IR: 3.12", OR: 3.94") backed by 6 sets of the carbon steel shells. This creates 0.82" (2 cm) of Lucite reflection followed by 3" of carbon steel reflection.

To augment a study of operator hand reflection worth, leaded gloves may be worn by students when handling the TACS shells. Standard leaded gloves come in 15 mil (0.381 mm) 30 mil (0.762 mm), 60 mil (1.524 mm), and 90 mil (2.286 mm) thicknesses. It is not expected that the leaded gloves will cause a large increase in the reactivity of the TACS.

2.5 Boraflex Sheets

Boraflex is a boron-impregnated silicone polymer that comes in thin, (approximately 1/4") flexible sheets and is used for neutron poison applications. Boraflex sheets may be used with the TACS as a reflector, moderator, or neutron poison during the class.

2.6 TACS Aluminum Shells

Aluminum surrogate shells are being fabricated to the same specifications as the HEU/D38 shells. These shells were made as non-fissile demonstration aids. Table 2-6 gives the design specification of the shells.

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

Part S/N	D-38 Parts		Minimum Inner Radius (inches)
	Weight (kilograms)	Density (g/cc)	
A1A	383.1	2.7	2.3393
A1B	383.1	2.7	2.3393
A2A	435.1	2.7	2.5764
A2B	435.1	2.7	2.5764
A3A	325.6	2.7	2.7996
A3B	325.6	2.7	2.7996
A4A	436.5	2.7	2.9495
A4B	436.5	2.7	2.9495

2.7 TACS Assembly Table

The TACS assembly table is a vertical lift machine that is manually operated. A 0.030-inch thick Al-6061 diaphragm affixed to an aluminum ring supports the stationary top half of the assembly. Spherical aluminum neutron source holders (OD = 3") for an AmLi source or a 252Cf source may be affixed to the diaphram. The bottom, movable platform supports the lower half of the assembly and can be lowered and raised by means of a hand-crank. Various radiation detectors may be used near the detector, including He3 tubes embedded in large slabs of polyethylene. The experimental equipment has been described by Crites[10] and Barnett[11] and is pictured in Figure 2.3. Details of the assembly

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

machine[12] and associated parts are available in drawings and a detailed inspection report[13].

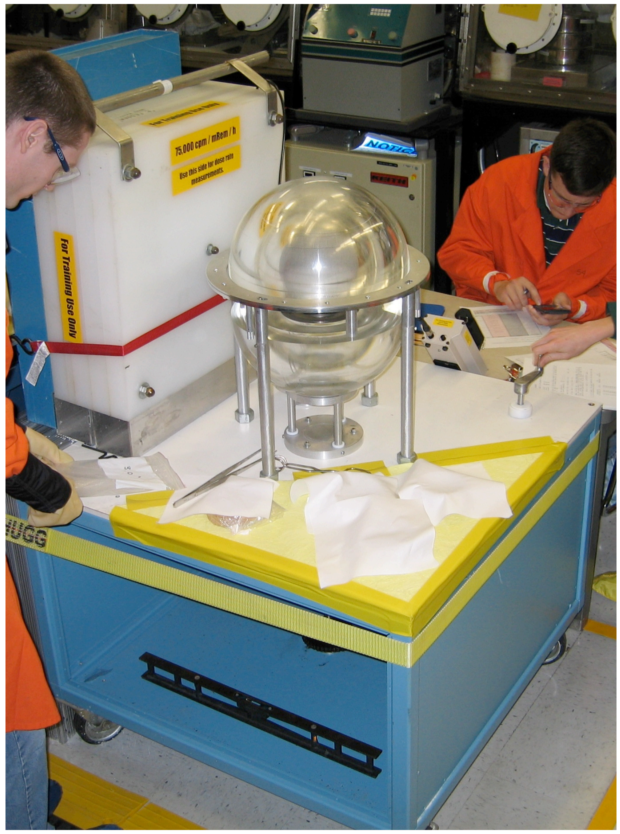

Figure 2.3: Vertical Lift Machine Table with the TACS

2.6 DAF Building Equipment and Workstations

A variety of buildings at DAF may potentially be used to conduct the TACS training. While the criticality course is being conducted, the TACS HEU shells will be the only material allowed in the building at DAF. The TACS workstation typically includes the TACS assembly table, a workbench to stage the depleted uranium and HEU hemishells, and a storage cabinet to store the moderators and reflectors when not in use.

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

[12] Drawing No. AAA78-103783-00, *H.C. Criticality Assy. Fixture*.

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

3.0 REQUIREMENTS

This document satisfies the format and content requirements of DOE-STD-3007-2007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Non-Reactor Nuclear Facilities*. The document also satisfies additional LLNL content requirements specified in CS-P-004, Rev. 6, *Criticality Safety Evaluations.* Additionally, this document satisfies the NSTec requirements given in CD-NOPS.001, Rev. 1, *Nuclear Criticality Safety Program*, and implements the JNPO requirements from JNPO-PRO-005.

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[7] for the assembly with 10 cm of Lucite reflection. 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[14] (version 10) was used to make all calculations of the effective neutron multiplication constant (k_{eff}). The COG10 code has been installed and verified[15] on the Nuclear Criticality Safety Division's *Auk* unclassified server for criticality safety applications. All calculations utilized the ENDF/B-VI (Release 7) pointwise (continuous) cross-sections and ENDF/B-VI (Release 2) $S(\alpha,\beta)$ data.

This methodology has been validated against critical experiments with highly enriched uranium (HEU) metal using the benchmark specifications from the ICSBEP Handbook[16]. The benchmark experiments include similar shapes (e.g., spheres, hemispheres, nested shells) and similar moderator and reflector materials (Lucite, water, polyethylene, steel) from several US and foreign laboratories.

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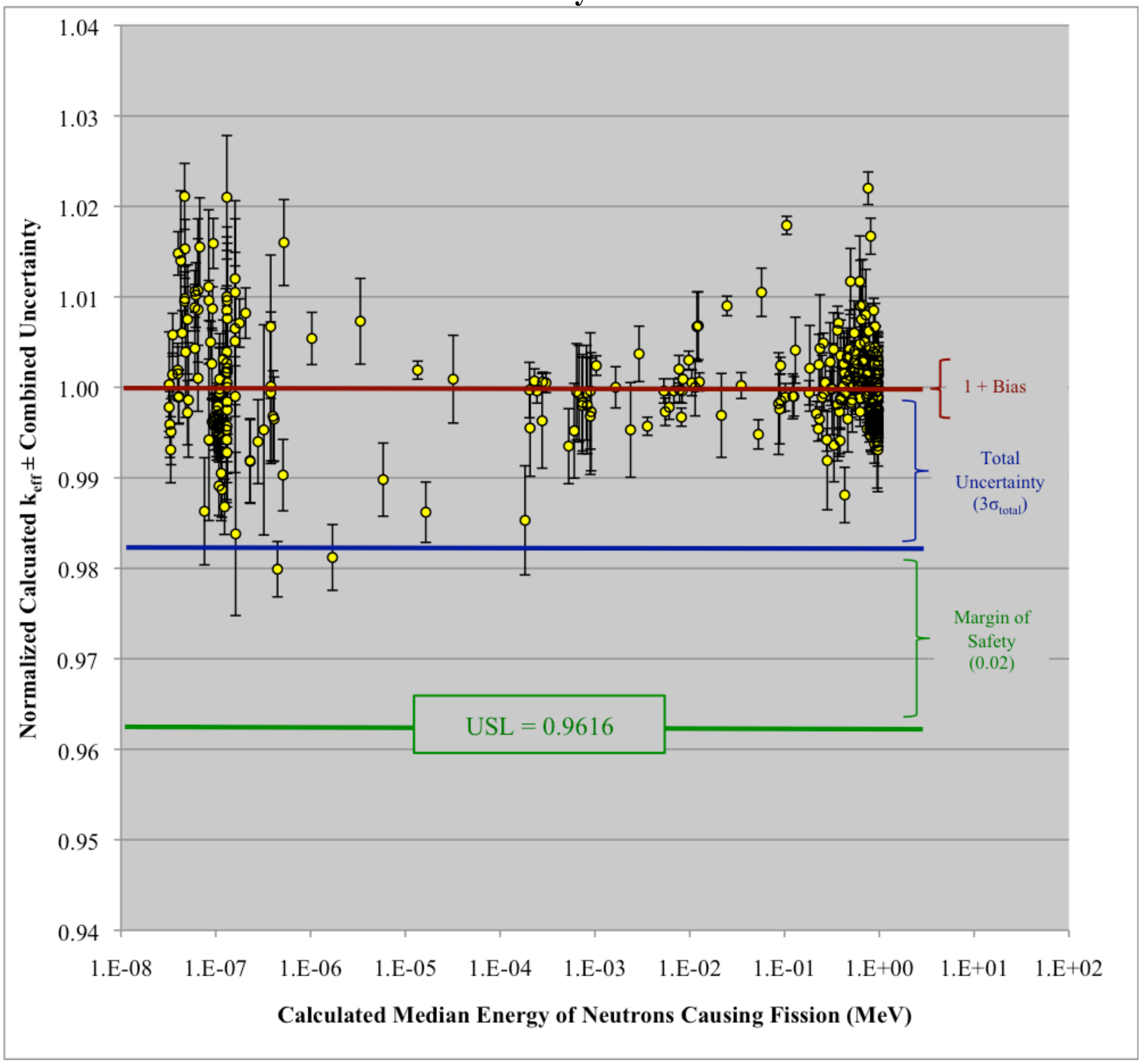
[14] *COG: A Multiparticle Monte Carlo Transport Code, Version 10*, **CCC-724**, contributed by the Lawrence Livermore National Laboratory to the Radiation Safety Information Computational Center at the Oak Ridge National Laboratory, released February 2006.

[15] C. Lee and P. Chou, *Verification of the Installation of COG10 on Auk,* CSAM10-144, Lawrence Livermore National Laboratory, November 18, 2010

[16] 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.

The details of the individual benchmark results are provided in CSM 1601[17] 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.

Figure 4.1: HEU Benchmark Results on the Auk Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library



In examining the benchmark results given in the figure, we see that for a wide variety of 348 benchmark experiments, the COG calculational bias does not result in an under-prediction in excess of –2% k_{eff}. As discussed in CSM 1601, an Upper Safety Limit of 0.9616 is considered subcritical with a conservative 2% safety margin.

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[17] C. Percher. *Validation of COG 10 and ENDFB6R7 on the Auk Workstation for General Application to Highly Enriched Uranium Systems. Lawrence Livermore National Laboratory. CSM 1601. December 23, 2010.*

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 (bounding reactivity). Operators under supervision of RI and CSE instructor	IWS approves all parts (as approved items) and configurations as part of an approved laboratory notebook	Known assembly with $M_o < 20$ (ok per 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).	IWS approves use of this diaphragm	Δk-eff < 0
Neutron source	Neutron sources (AmLi or ^{252}Cf) contain insignificant amounts of fissionable material. Other materials in the source do not increase k_{eff} significantly (due to added scattering).	IWS 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.	IWS includes this source holder as an approved item	Δk-eff ~ 0
Abnormal condition and controls that preclude any credible criticality accident risk			
Flooding	Full cavity flooding is considered incredible, defense-in-depth control for a 1.5-inch-radius Al-6061 source holder to provide additional safety under flooding conditons	IWS includes defense-in-depth control for Al-6061 source holder	k-eff < 0.96
Over-mass	Kilogram quantities of additional fissile materials are required to achieve criticality.	IWS strictly controls fissile materials	BEU
Unauthorized moderators	Moderator configurations are controlled by IWS and called out by part number. TACS cavity is uniquely shaped and would need specially-fit moderators.	IWS includes defense-in-depth control for Al-6061 source holder	k-eff < 0.96
Unauthorized reflectors	Reflector configurations are controlled by IWS and called out by part number. Other close-fitting reflectors not available.	IWS 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.	Automatic sprinklers. Hand extinguishers.	k-eff < 0.96

Beyond design basis events			
Moderate or large fires	Fires of such severity to impact the nickel cladding on the HEU are considered incredible.	Fire loading controls and building sprinklers/fire watch	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.	IWS includes defense-in-depth control for 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 IWS controls on approved parts and assemblies).	IWS prohibits offsetting the shells from one another using spacers, shims, or plastics	BEU

6.0 EVALUATION AND RESULTS

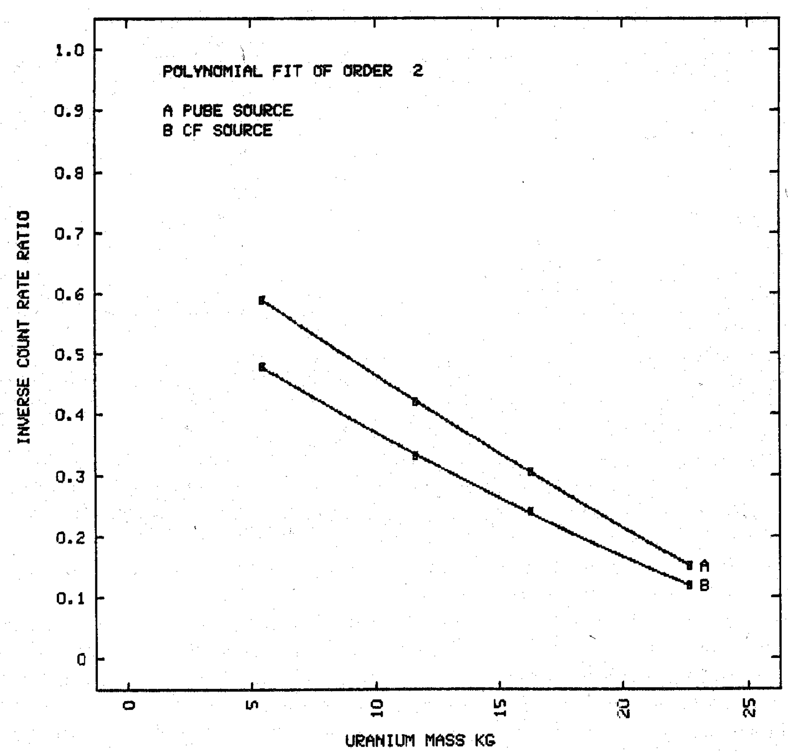
In order to calculate k_{eff} for various TACS configurations using COG, a model of the most significant parts (maximum authorized moderation with parts M3A, 18326, 500155, 500157, 23181, R2B and R3A in the lower assembly half and parts M3B, 18325, 500154, 500156, 23184, R2A and R3B in the upper assembly 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. A COG model of the ^{252}Cf (#300996) source was also developed, as shown in Figure 6-3.

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). This case, with no source or diaphragm modeled, will be the refernce case (CaseID: tacs1), which returned a k_{eff} of 0.9369(6).

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.



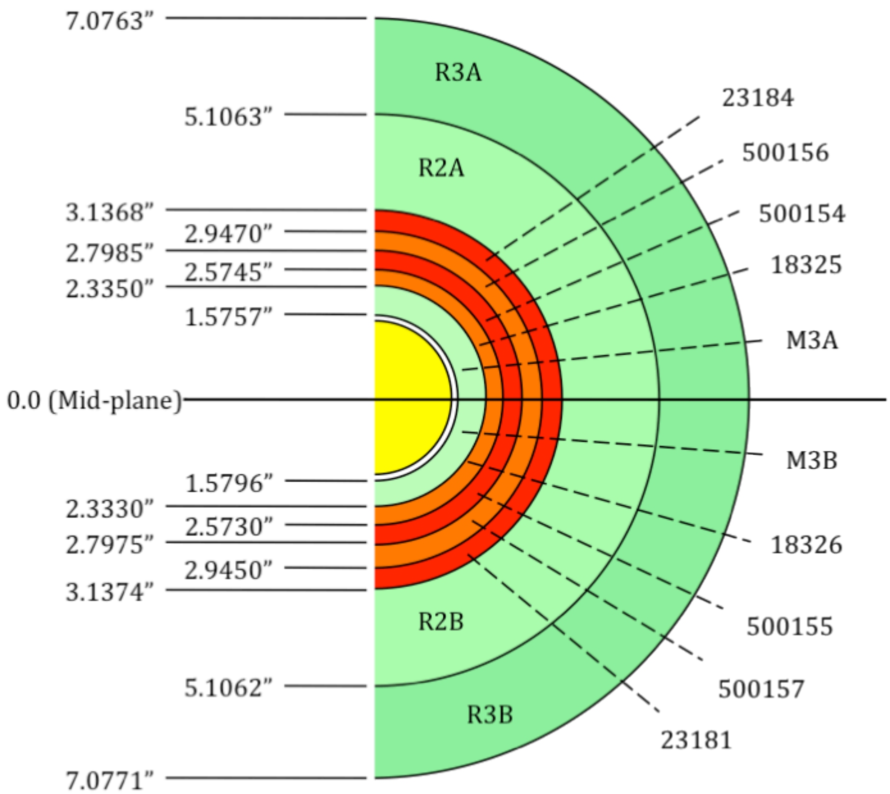


Table 6-1. COG Model of the TACS Assembly

Part	Material	Mass (kg)[c]	Density (g/cc)	IR (inch)	OR (inch)[b]
Upper assembly half					
M3A	$C_5H_8O_2$	0.3478	1.1888	1.5796	2.3186674
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
R3A	$C_5H_8O_2$	9.0204	1.1875	5.1062	7.0771158
Lower assembly half					
M3B	$C_5H_8O_2$	0.3470	1.1885	1.5757	2.3157756
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
R3B	$C_5H_8O_2$	9.0157	1.1876	5.1063	7.0762763

[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.

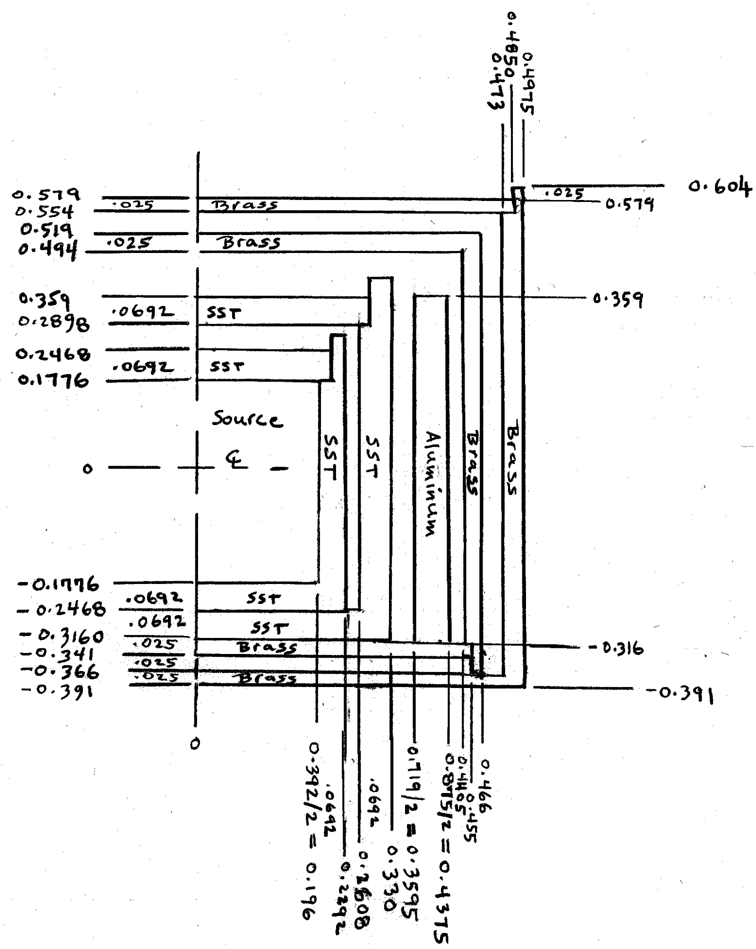


Table 6-2. COG Model of the Am-Li Neutron Source (S/N 401009)

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.

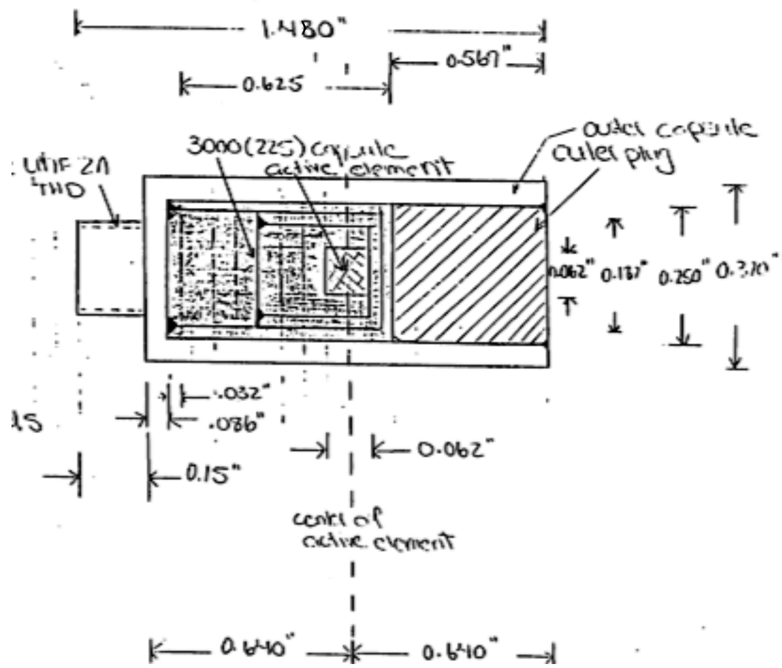


Table 6-3. COG Model of the 252Cf Neutron Source (S/N 300996)

Material	Mass (g)	Density (g/cc)	Volume (cc)
Active source region			
249Cf	0.0015	0.4746	0.0031
250Cf	0.0064	2.0536	
251Cf	0.0022	0.7133	
252Cf	0.0368	11.857	
Stainless Steel Encapsulation			
Fe	13.561	5.846	2.3197
Cr	3.2986	1.422	
Ni	1.4661	0.632	

Use of less Lucite moderator (M1A/B, M2A/B, or void instead of M3A/B), less fissile material (D-38 shells, aluminum 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.

6.1.2 Effect of Neutron Sources 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), the 252Cf source (S/N 300996), or unlimited Al-6061 in the cavity results in no significant increase in k_{eff}. The geometry for these cases is shown in Figures 1-4. Consequently, these sources are acceptable for use with 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). Additionally, the presence of a 0.30" aluminum diaphragm slightly decreases k_{eff} (CaseID: tacs5) by separating the two halves of the assembly.

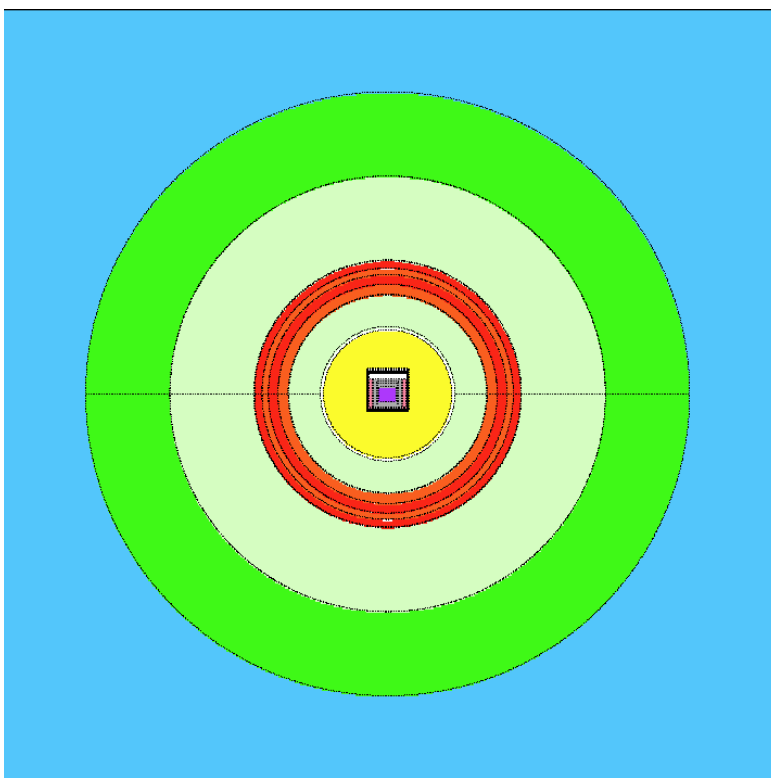


Figure 6.1: COG10 Model of TACS, CaseID: tacs2 (k_{eff} = 0.9369(6)).

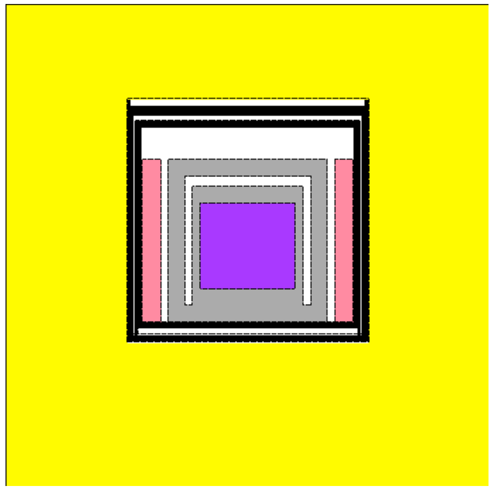


Figure 6.2: Close-up view of AmLi source from COG10 model shown in Fig 1.

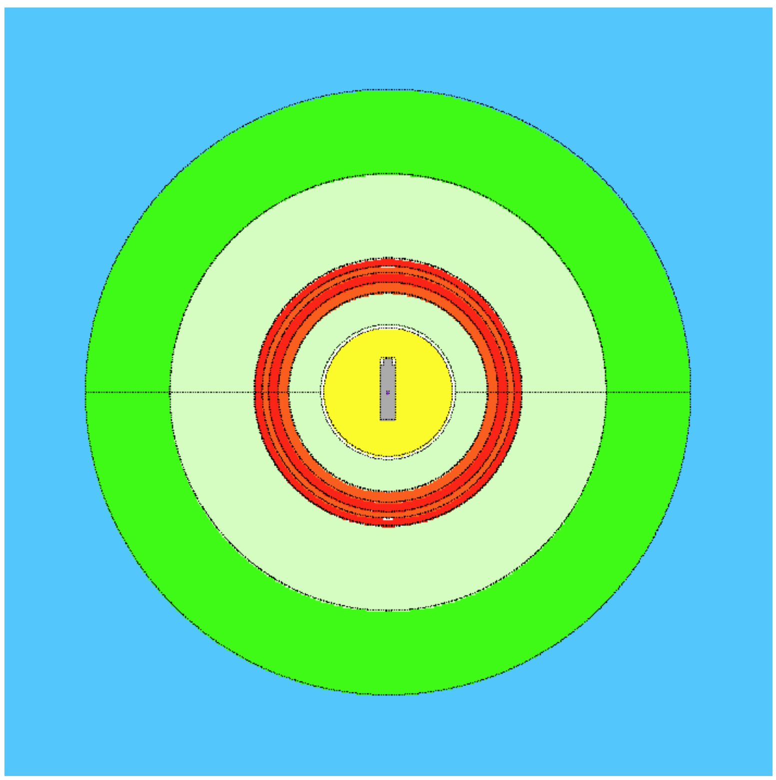


Figure 6.3: Modified COG10 Model of TACS, CaseID: tacs3
(k_{eff} = 0.9367(6)).

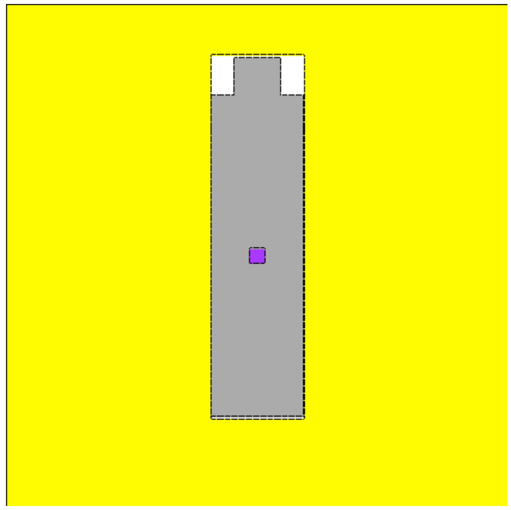


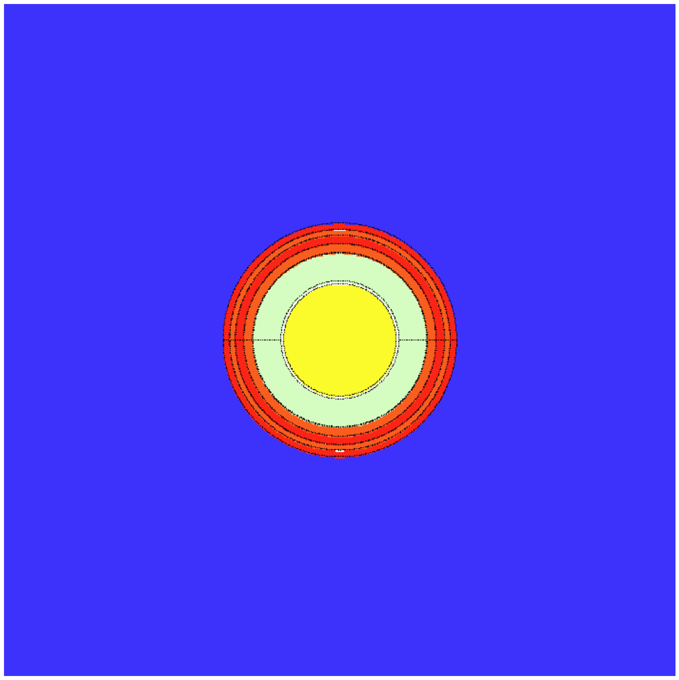
Figure 6.4: Close-up view of AmLi source from COG10 model shown in Fig 4.

Table 6-3. **Normal Conditions**

Case	k_{eff}	MFE	File	Remarks
Reference configuration (1.5-inch-IR Al-6061 source holder, no diaphragm)				
1	0.9369(6)	36.9 keV	tacs1	Reference configuration
Effect of a neutron source or unlimited aluminum in the cavity.				
2	0.9369(6)	37.8 keV	tacs2	tacs1 with Am-Li Source
3	0.9367(6)	36.6 keV	tacs3	tacs1 with Cf252 Source
4	0.9369(6)	36.0 keV	tacs4	tacs1 with (728g) Al-6061-filled cavity
Effect of a 0.030-inch Al-6061 diaphragm				
5	0.9354(6)	36.2 keV	tacs5	tacs1 with 0.30” diaphragm

6.1.3 Carbon Steel Reflection

Carbon steel reflection was investigated in place of the Lucite reflection around the TACS HEU shells. Figure 6.5 shows the TACS reflected by infinite carbon steel (modeled as iron at a density of 7.9 g/cm^3) reflection (shown in dark blue). This case returned a k_{eff} of 0.8729(6), indicating carbon steel is inferior to Lucite as a reflector.



k_{eff} = 0.8735(6)

Figure 6.5: COG10 geometry of TACS reflected by infinite carbon steel (CaseID: tacscs)

6.1.4 Composite Reflection with Lucite Backed by Carbon Steel

Lucite shells R1A and R1B have an outer diameter of 3.94". Therefore, they can mate up with carbon steel shells ST-Shell-05T and -05B, which have an inner radius of 4". An investigation of composite reflection was completed to examine the effect of 2 cm of Lucite (provided by R1A and R1B) backed by varying thicknesses of carbon steel. Infinite water was modeled on the outside of the carbon steel to additional reflection from operators, detectors, etc. Example geometry is shown in Figure 6.6 and the results are plotted in Figure 6.7.

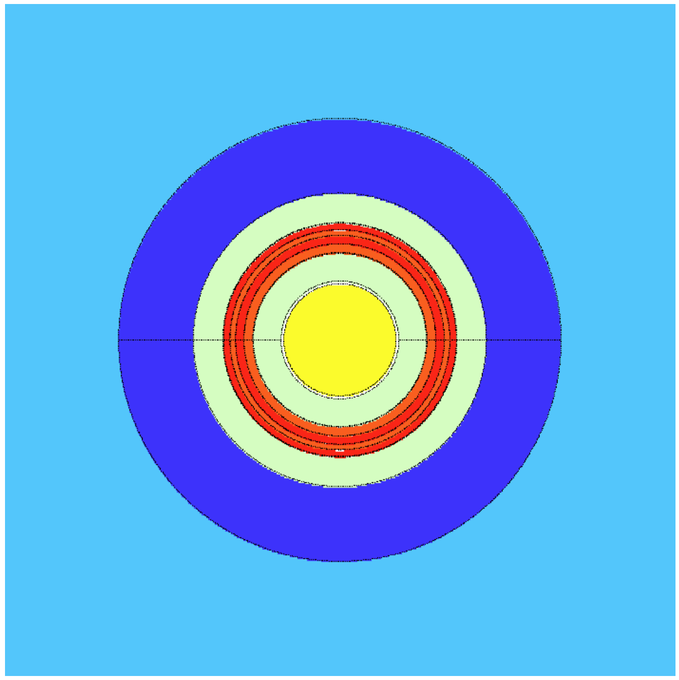
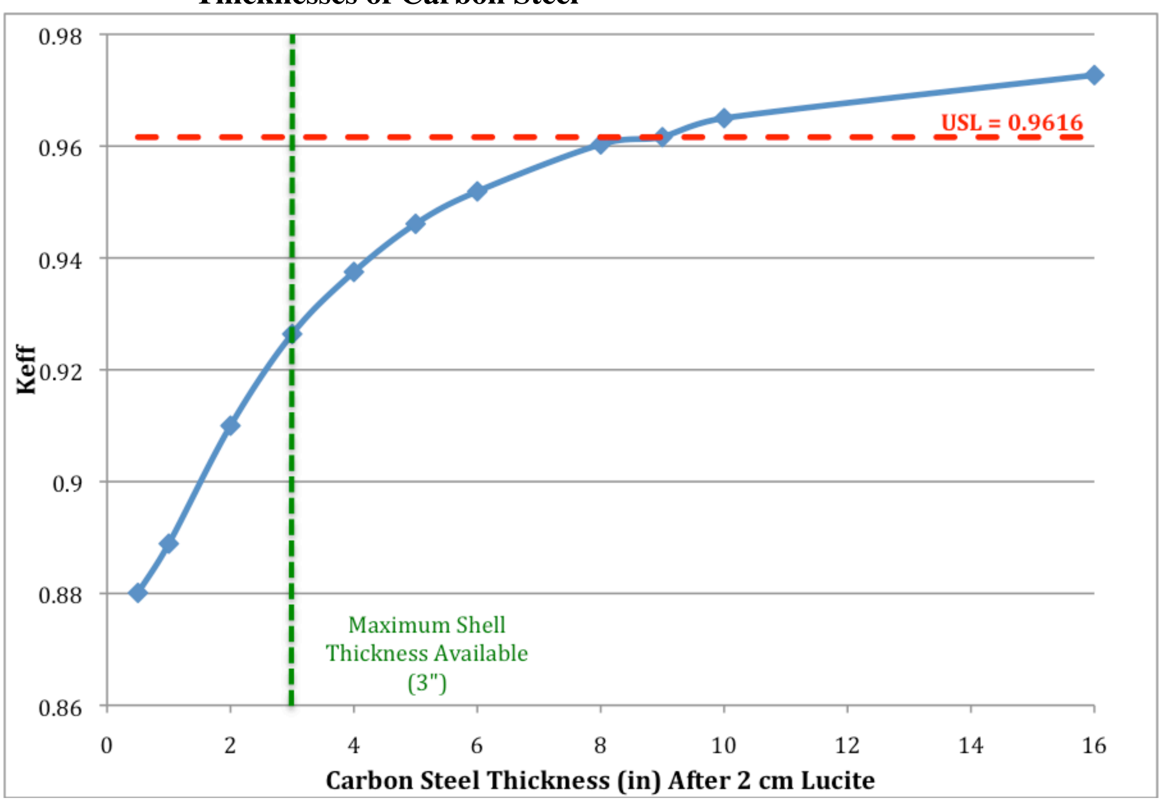


Figure 6.6: COG10 geometry of TACS reflected by 2 cm of Lucite (shown in light green) backed by 3" of carbon steel (dark blue). Infinite water reflection is outside the carbon steel. CaseID: 2lucs3, k_{eff} = 0.91006)

Figure 6.7: Effect of Composite Reflection from 2 cm of Lucite Backed by Varying Thicknesses of Carbon Steel

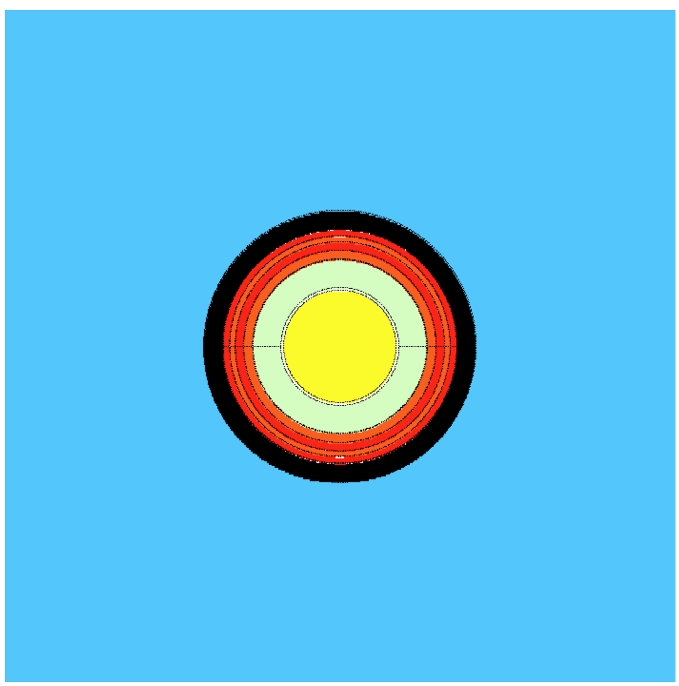


As shown from the above figure, adding more than 8 inches of carbon steel after the Lucite results in exceeding the USL of 0.9616. At infinite steel thickness, composite reflection from 2 cm of Lucite backed by carbon steel raises reactivity higher than either Lucite (infinite thickness k_{eff} = 0.9417(6)) or carbon steel (infinite thickness k_{eff} = 0.8729(6)) alone. However, we have only specific steel shells available, which add up to 3" of steel outside Lucite shells R1A and R1B. As shown in Figure 4.3, 3" of carbon steel thickness plus 2 cm of Lucite results in a safety subcritical 0.9264(6), CaseID: 2lucs4.

CONTROL: Composite reflection (hydrogenous reflector backed by a metal reflector) will be limited to 2 cm of Lucite reflection from R1A and R1B backed by 3" of carbon steel from shells ST-Shell-5T, -5B, -6T, -6B, -7T, -7B, -8T, -8B, -9T, -9B, -10T, and -10B.

6.1.5 Leaded Gloves

Additional COG10 calculations were completed to examine the effect of lead gloves on the assembly. Half an inch of close-fitting lead was modeled around the bare HEU shells of the TACS, as shown in Figure 6.8. This conservatively bounds the reflection presented from hands in leaded gloves, as the lead was modeled as covering the entire surface of the TACS (unrealistic for hands in gloves) and 90 mil gloves are only 2.286 mm thick.



k_{eff} = 0.9277(6)

Figure 6.8: COG10 Geometry of the TACS Reflected by 0.5" Lead (Black) and Infinite Water (blue)

The k_{eff} for this case was 0.9277(6), well below the USL of 0.9616. It is also less reactive than the reference case with Lucite reflection.

6.1.6 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.

Boraflex is a boron-impregnated silicone polymer that comes in thin flexible sheets. Typical Boraflex composition and density information provided by the manufacturer[18] is given in Table 6-4. The manufacturer describes Boraflex as a matrix of boron carbide (B_4C) within a silicone polymer. The density and composition of the binder is estimated as shown in Table 6-5 by assuming a simple mixture of boron carbide (ρ=2.52 g/cm^3) and unknown silicone polymer (ρ=1.43 g/cm^3) that results in the reported Boraflex density and composition.

Table 6-4. Typical Boraflex Compostion (ρ=1.8 g/cm^3)

Constituent	wt-%
Si	21.6
O	19.5
C	19.3
H	2.4
B	37.1

Table 6-5. Assumed Binder Composition (ρ=1.43 g/cm^3)

Constituent	wt-%
Si	41.1
O	37.2
C	17.1
H	4.6

Since the density of Boraflex (ρ = 1.43 g/cm^3 or greater) exceeds that of Lucite ($\rho \leq 1.2$ g/cm^3), a few cases were run to compare Boraflex (with or without boron carbide) to Lucite as a neutron reflector around the TACS (in its most reactive configuration with maximum moderation and fissile content) and as a moderator replacing the aluminum source holder. The results of COG calculations are provided in Table 6-6.

[18] Jeff K. Woolley, Vice President, Bisco Products, Inc., letter to Mr. S. E. Thomas, *Joseph Oat Spent Fuel Pool Racks, P.O. #14233, Bisco Boraflex Sales Order #1603*, September 16, 1988.

Table 6-6. **Boroflex Calculations**

File	k_{eff}	MFE	Remarks
tacs7	0.8460(6)	171.3 keV	TACS with Boraflex in source cavity (1.8 g/cm^3) instead of Lucite moderator
tacs8	0.7858(6)	417.2 keV	TACS with infinite Boraflex (1.8 g/cm^3)
tacs9	0.9173(6)	68.43 keV	TACS with Boraflex binder in cavity (1.43 g/cm^3, no boron) instead of Lucite moderator TACS with infinite Boraflex binder (1.43 g/cm^3, no boron)
tacs10	0.7412(6)		TACS with infinite Boraflex binder (1.43 g/cm^3, no boron)

CONTROL: Boroflex parts shall be labeled to avoid confusion with other materials.

6.1.5 Anticipated Human Errors During Hand-Stacking Operations

A few COG calculations were performed to calculate the reactivity of those configurations shown in Figures 6.9 and 6.10. These configurations were run to demonstrate that the most reactive configuration is the reference configuration, and the results are given in Table 6-7.

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. Additionally, while there is a slight difference in the masses of matched moderators and reflectors (for instance, M3A versus M3B or R3A versus R3B), these parts are interchangeable.

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

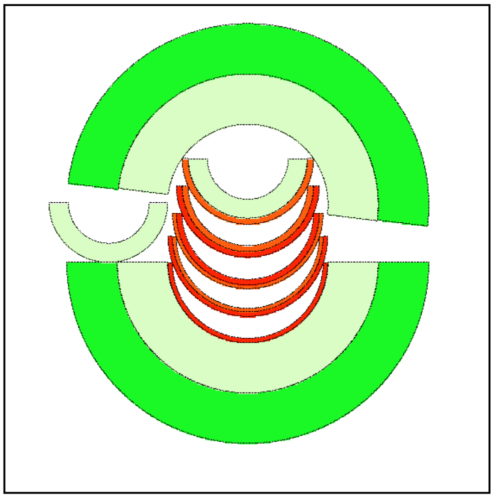


Figure 6.9: Configuration 1

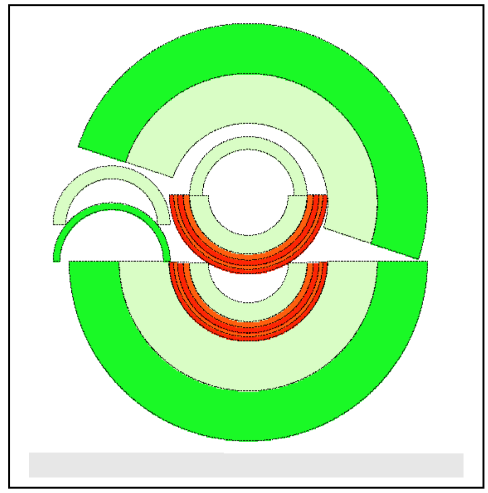


Figure 6.10: Configuration 2

Table 6-7. **Anticipated Assembly Errors**

File	k_{eff}	MFE	Remarks
tacs1	0.9293(6)	45.8 keV	TACS as shown above Table 6-1
tacs72	0.8273(6)	174.2 keV	Configuration 2*
tacs71	0.7138(6)	309.2 keV	Configuration 1*

*No source holder present.

6.1.6 Summary of Normal Conditions

The highest reactivity COG10 calculation for normal conditions was found to be the reference case (tacs1), 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), 10 cm Lucite reflection (parts R2A/R2B and R3A/R3B), backed by full water reflection. This case will be used during the abnormal condition calculations presented in the following sections.

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.

Full water flooding of the inner cavity of the TACS is not considered credible because the room would have to completely flood up to the level of the TACS (approximately 3-4 feet from the ground). Since the lower half of the TACS creates a bowl shape, it could be conceivable that the lower half of the TACS could flood and retain water, as shown in Figure 6.11. The keff for this case was also an acceptable 0.9559(6) (CaseID: halffl). Additionally, the nature of process for the class is that a 1.5-inch-radius Al-6061 source holder attached to an aluminum diaphragm is used. The results in Table 6-7 demonstrate that use of an this design feature (the 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 (CaseID tacswf). Therefore, this design feature will be credited as defense-in-depth for the TACS under immersion conditions.

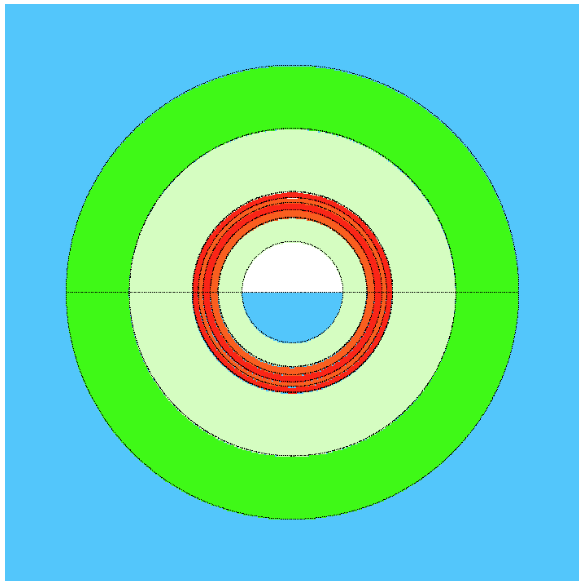


Figure 6.11: More Realistic Half-Filled TACS Cavity
k_{eff} = 0.9559(6), CaseID: halffl

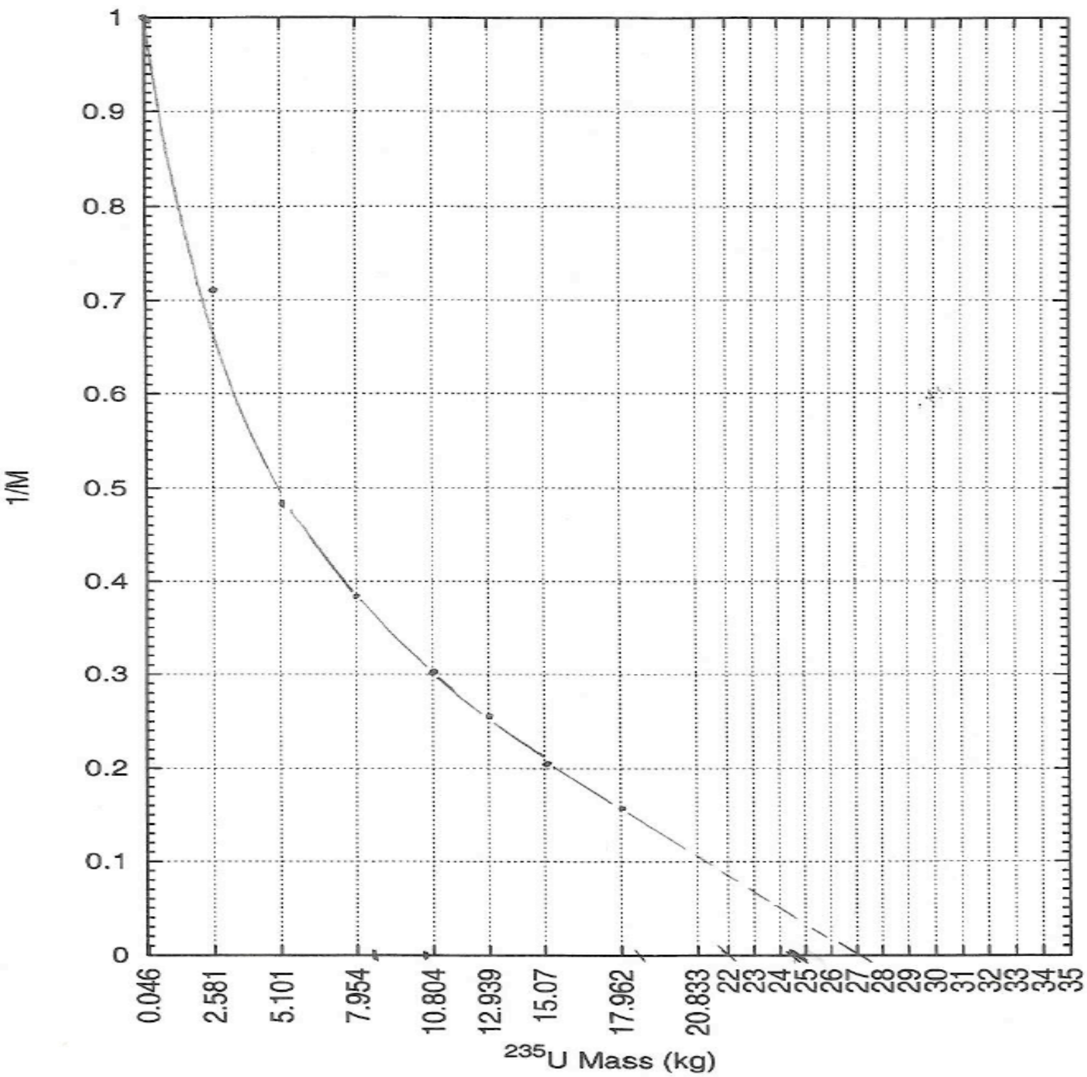
Table 6-7. Water Immersion Calculations

File	k_{eff}	MFE	Remarks
Hypothetical conditions of immersion in water.			
tacs9	0.9373(6)	8.76 keV	Oy immersed in water (no Lucite)
tacswa	0.9515(6)	24.0 keV	tacsw w/1.5"-OR Al-6061 at center
halffl	0.9559(6)	18.9 keV	tacs1 with a half-flooded cavity, full water reflection on the outside
Full immersion without required engineering design features (incredible).			
tacswf	0.9656(6)	11.6 keV	tacs1 immersed in water without Al source holder or M3A/B

DESIGN FEATURE: A 1.5" radius **source holder** will be affixed to the Al-6061 diaphragm during full assembly of the TACS as defense-in-depth against flooding.

6.2.2 Unauthorized Additions of Fissionable Material (Over-mass)

Addition of sufficient mass of other fissionable materials will achieve criticality *in any system*. With 10 cm of Lucite reflection, experiments with the TACS have consistently determined a critical mass of 27 kg of ^{235}U. An example of an experimental approach-to-critical by mass plot is shown in Figure 6.12 that demonstrates the extrapolation to a critical value of 27 kg.



Similarly, additions of kilogram quantities of other fissile materials (such as plutonium) in or near the TACS cavity could result in a criticality hazard. However, as stated in Section 2.0, during the criticality class, the TACS uranium shells, identified by serial number, will be the only fissile material allowed in the building at DAF outside of safes or closed shipping packages. Similar restrictions are already in place for Radiation Test Object (RTO) construction. For a criticality accident to occur due to overmass, the following chain of events would have to occur:

(1) A shipping package or a safe containing a significant quantity of SNM is opened in the building and material removed,
(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 by the Integrated Work Sheet (IWS).

Consequently, this scenario is considered incredible (BEU). Note that the only other fissionable materials authorized are the negligible (non-accountable) quantity of ^{241}Am and ^{252}Cf present in the sealed neutron sources 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).

CONTROL: Authorized enriched uranium parts are 18325, 18326, 500154, 500155, 500156, 500157, 23181, and 23184 (a total of 20.9 kg ^{235}U). All fissile materials other than those listed in Section 3.2.1 must be secured in closed shipping containers or safes or removed from the building. A surveillance of this condition must be performed prior to TACS assembly.

6.2.3 Unauthorized Moderators

Moderators authorized for use within the TACS cavity will be specifically allowed by serial number in the IWS. Because of the irregular shape of the TACS cavity (the space between the smallest HEU shell and the aluminum source holder), solid moderators would have to be specially fabricated to fill the cavity. Liquids will be expressly forbidden during the conduct of the criticality class. Other potential for loss of moderator control could occur due to sprinkler activation or fire-fighting, but this abnormal condition was already addressed in Section 6.2.1.

CONTROL: No liquids are allowed.

CONTROL: Authorized moderators are M1A/B, M2A/B, M3A/B, and Boroflex.

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. Unauthorized Reflector Calculations

Entry	k_{eff}	MFE	Remarks
tacsbeo	0.9949(6)	236.8 keV	TACS with 2.5-in. BeO at 3.01 g/cc
tacsbe	0.9941(6)	192.0 keV	TACS with 3.0-in. Be at 1.85 g/cc
tacsgr	1.0017(6)	170.4 keV	TACS with 5.1-in. Graphite at 2.25 g/cc
tacsdu	0.9927(6)	570.9 keV	TACS with 5.9-in. Nat-U at 19.07 g/cc
tacsdur	0.9272(6)	206.1 keV	TACS with 23 kg Nat-U in infinite Lucite
tacscu	0.9997(6)	281.3 keV	TACS with infinite Copper at 8.92 g/cc

As demonstrated by the calculations reported in Table 6-10, certain reflectors around the TACS, when used instead of the Lucite reflectors, could drive the assembly critical. Reflectors authorized for use with the TACS will be specifically allowed by serial number in the IWS. 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 the over-mass discussion in Section 6.2.2, which has been determined to be incredible (BEU).

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 2-2). 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 $k_{eff} < 0.96$ (CaseID: tacsdur). The D-38 shells listed in Table 2-2 are acceptable for use with the TACS as reflectors since their total mass is less than 23.0 kg D-38.

CONTROL: Approved reflectors are listed in Table 6-11. All lead bricks and reflector shells, other than those listed in Table 6-11, must be secured in cabinets or removed from the building. A surveillance of these conditions must be performed prior to TACS assembly.

Table 6-11: Approved Reflector Materials

Lucite Reflectors	Depleted Uranium Reflectors	Cadmium Reflectors	Steel Reflectors	Composite Reflectors	Other Reflectors
R1-A	001-1	Cd-1	ST-Shell-04B	R1A	Lead Gloves, up to 90 mil
R1-B	001-2	Cd-2	ST-Shell-04T	R1B	Boraflex sheets
R2-A	001-3		ST-Shell-05B	ST-Shell-05B	
R2-B	002		ST-Shell-05T	ST-Shell-05T	
R3-A	003-1		ST-Shell-06B	ST-Shell-06B	
R3-B	003-2		ST-Shell-06T	ST-Shell-06T	
R4-A	003-3		ST-Shell-07B	ST-Shell-07B	
R4-B	004		ST-Shell-07T	ST-Shell-07T	
R5-A			ST-Shell-08B	ST-Shell-08B	
R5-B	**Aluminum Reflectors**		ST-Shell-08T	ST-Shell-08T	
R6-A			ST-Shell-09B	ST-Shell-09B	
R6-B	A1A		ST-Shell-09T	ST-Shell-09T	
R7-A	A1B		ST-Shell-10B	ST-Shell-10B	
R7-B	A2A		ST-Shell-10T	ST-Shell-10T	
R8-A	A2B				
R8-B	A3A				
R9-A	A3B				

R9-B	A4A				
LB1	A4B				
LB2					

6.2.5 Fire

The TACS itself (Al-6061, Lucite, D-38, HEU, neutron source) is not a credible fire risk. However, the neutron detectors and counting equipment are electrical equipment that could catch fire if 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 terminated by either automatic activation of the sprinklers or hand fire extinguishers from the fire watch. Hand-held fire extinguishers are available in the DAF 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 fire extinguisher training.

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. Even with a very conservative combustible loading model and no sprinkler activation, the DAF DSA determined a maximum fire temperature of approximately 800ºF to occur in a high bay. The DAF is equipped with a fusible link sprinkler system that is designed to activate when they reach 165ºF. If the fire suppression system is not available, a dedicated fire watch with hand extinguishers is required 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 580 °F, whereas the melting point of nickel and uranium is 2647ºF and 2070ºC. 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.

The unclad D-38 exposed to these gases could be converted to a pyrophoric powder. Granger[19] 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 to the air, a protective

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

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 (e.g. steel reflector shells) that could contain a large quantity of dispersible HEU mixed in water or Lucite from a decomposed or melted full or partial assembly. This is considered incredible.

NOTE: TACS is a **Criticality Hazard Type 1** [20]. Water may be used as required to suppress a fire. Treat as any other radioactive material fire.

6.3.2 Crushing

As the DAF building and equipment are designed to PC-2 requirements, 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 $k_{eff} < 0.9616$ for this hypothetical (bounding) configuration, which indicates that any degree of crushing will not result in a criticality accident.

DESIGN FEATURE: A 1.5" radius **source holder** will be affixed to the Al-6061 diaphragm during full assembly of the TACS as defense-in-depth against crushing.

Table 6-11. Hypothetical (BDBE) Crushing

File	k_{eff}	MFE	Remarks
crush2	0.9269(6)	628.5 keV	As below but concrete replaces Lucite.
crush	0.9528(6)	396.3 keV	As shown in Table 6-12

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

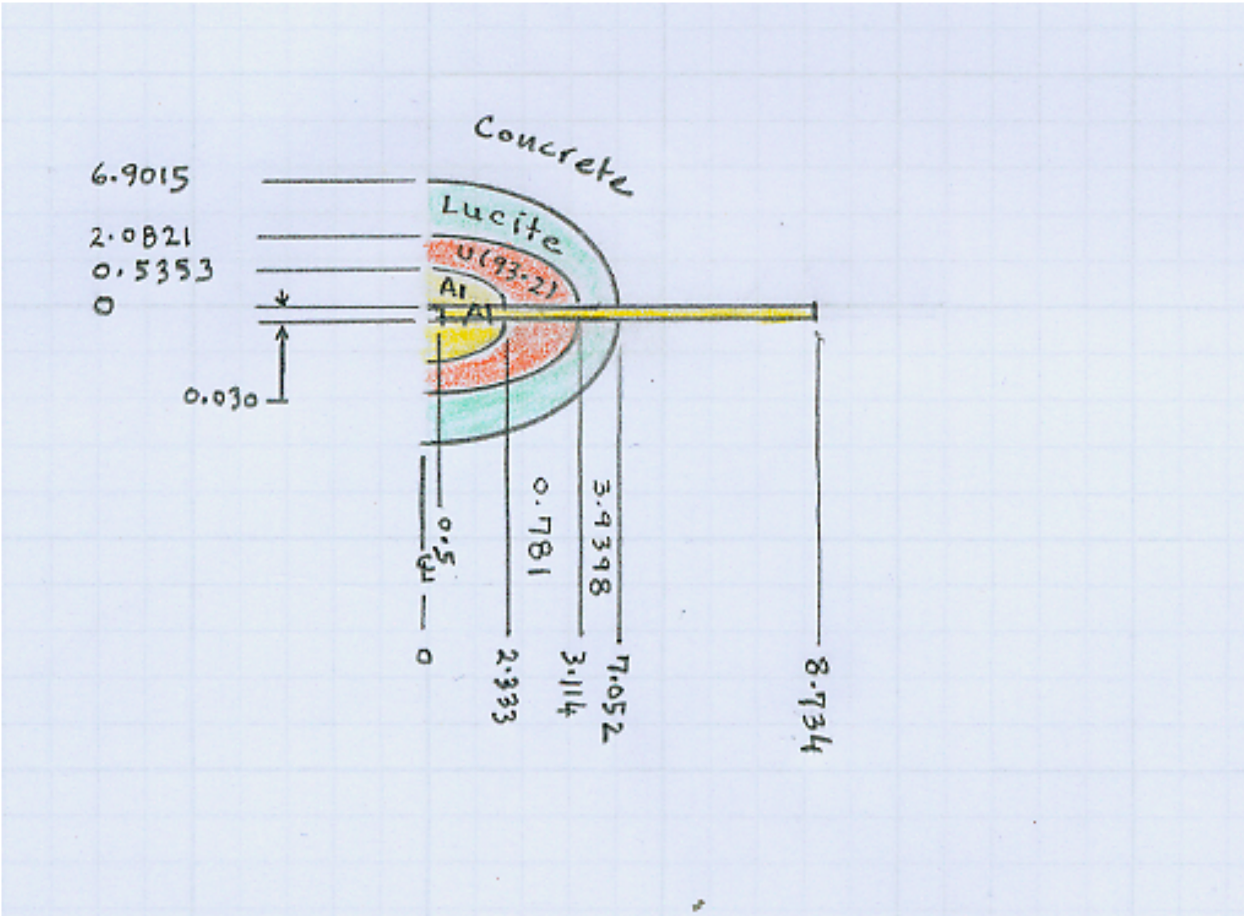


Table 6-12. COG Model of the Crushed TACS

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). Due to the fact the shells are thin, interstitial moderation (moderating materials between the shells) will likely increase reactivity by effective neutron thermalization. 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} > 0.9616 indicating a potential criticality hazard. However, the controls listed below are judged sufficient to preclude any credible hazard.

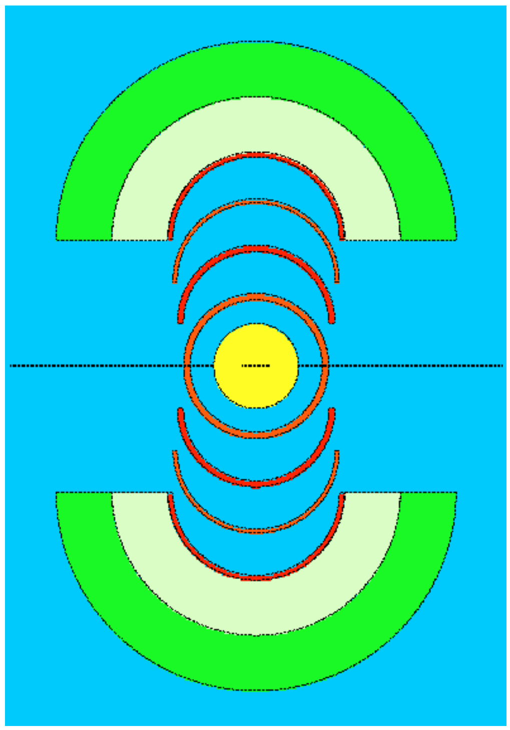


Table 6-13. Lattice in Water Calculations

File	k_{eff}	MFE	Remarks
tacswa	0.9515(6)	24.0 keV	Immersed with 0.0-inch gaps
gap05	0.9701(6)	217.7 eV	Immersed with 0.5-inch gaps
gap1	0.9839(6)	23.87 eV	Immersed with 1.0-inch gaps
gap15	0.9805(6)	2.313 eV	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

7.1 Defense-in-Depth Design Feature

(1) A 1.5" radius source holder that will be affixed to the Al-6061 diaphragm during full assembly of the TACS that enhances safety under flooding (see §6.2.1) and crushing (see §6.3.2) scenarios.

7.2 Administrative Controls

The following controls are provided for implementation in the Integrated Work Sheet Safety Plan as shown below. The SP shall also identify that the TACS is a Criticality Hazard Type 1.

7.2.1 Authorized TACS Fissile Materials

S/N	Part Weight (kilograms)			Minimum Inner Radius (inches)
	Oy-0.25Ni	Oy	U-235	
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	--

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

7.2.2 Authorized Moderators

Two of the six Lucite hemi-shells listed the following table are authorized to be placed within the central cavity of any TACS assembly configuration.

Lucite Moderators	Additional Moderators
M1A	Boraflex sheets, any amount
M1B	
M2A	
M2B	
M3A	
M3B	

7.2.3 Authorized Neutron Sources

Any one sealed neutron source listed in the following table is authorized to be placed within the central cavity of the TACS assembly.

AmLi Source	Californium Source
401009	300996

7.2.4 Authorized Reflector Materials

Any of the reflectors in the following table are allowed to be placed around the TACS assembly.

Lucite Reflectors	Depleted Uranium Reflectors	Cadmium Reflectors	Steel Reflectors	Composite Reflectors	Other Reflectors
R1-A	001-1	Cd-1	ST-Shell-04B	R1A	Lead Gloves, up to 90 mil
R1-B	001-2	Cd-2	ST-Shell-04T	R1B	Boraflex sheets
R2-A	001-3		ST-Shell-05B	ST-Shell-05B	
R2-B	002		ST-Shell-05T	ST-Shell-05T	
R3-A	003-1		ST-Shell-06B	ST-Shell-06B	
R3-B	003-2		ST-Shell-06T	ST-Shell-06T	
R4-A	003-3		ST-Shell-07B	ST-Shell-07B	
R4-B	004		ST-Shell-07T	ST-Shell-07T	
R5-A			ST-Shell-08B	ST-Shell-08B	
R5-B	**Aluminum Reflectors**		ST-Shell-08T	ST-Shell-08T	
R6-A			ST-Shell-09B	ST-Shell-09B	
R6-B	A1A		ST-Shell-09T	ST-Shell-09T	
R7-A	A1B		ST-Shell-10B	ST-Shell-10B	
R7-B	A2A		ST-Shell-10T	ST-Shell-10T	
R8-A	A2B				
R8-B	A3A				
R9-A	A3B				
R9-B	A4A				
LB1	A4B				
LB2					

7.3 Additional Criticality Controls

7.3.1 All fissile materials other than those listed in Section 7.2.1 must be secured in closed shipping containers or safes or removed from the building. All lead bricks and reflector shells, other than those listed in Section 7.2.4, must be secured in cabinets or removed from the building. A surveillance of these conditions must be performed prior to TACS assembly using form JNPO-F-095.

7.3.2 No liquids are allowed.

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

NOTE: Materials that are part of the workstation structure, approved equipment (See IWS) or packaging materials for fissionable material (i.e., shipping containers and approved contamination and cushioning materials), shall not be considered as controlled reflectors or moderators. Waste materials such as Kimwipes or tape shall also not be considered as controlled reflectors or moderators.

7.4 Criticality Hazard Type.

The Criticality Hazard Type is Type 1. Water may be used as required to suppress a fire. Treat as any other radioactive material fire.

8.0 SUMMARY AND CONCLUSIONS

This document satisfies the DOE O 420.1B, CS-P-004, CD-NOPS.001, JNPO-PRO-005, and DOE-STD-3007-2007 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, as required by DOE O 420.1B.

9.0 REFERENCES

References are provided as footnotes.

Appendix A
Sample COG Input Listing

```
tacs1: TACS model of 1.5"-IR Al-6061, M3A/B, 8 Oy hemis, R2A/R2B, R3A/R3B, 0.030-in. Al-6061 diaphragm
basic
 neutron delayedn INCHES
criticality
 npart=5000 nbatch=1020 sdt=0.0001 nfirst=21 norm=1.
 nsource=1  0 0 0
mix nlib=ENDFB6R7 nlib2=RED2002 zn pb sablib=COGSAB
$ -- Lower Assembly Materials --------------------------------------------
 mat=1  a-f  1.1885 c 5 (h.ch2) 8 o16 2           $ Lucite M3B Moderator
 mat=2  w-p 18.9 u234 1.1 u235 93.1793 u238 5.7207 $ HEU  18326
 mat=3  w-p 18.9 u234 1.1 u235 93.1596 u238 5.7404 $ HEU  500155
 mat=4  w-p 18.9 u234 1.1 u235 93.1620 u238 5.7380 $ HEU  500157
 mat=5  w-p 18.9 u234 1.1 u235 93.1256 u238 5.7744 $ HEU  23181
 mat=6  a-f  1.1878 c 5 (h.ch2) 8 o16 2           $ Lucite R2B Reflector
 mat=7  a-f  1.1876 c 5 (h.ch2) 8 o16 2           $ Lucite R3B Reflector
$ -- Upper Assembly Materials --------------------------------------------
 mat=11 a-f  1.1888 c 5 (h.ch2) 8 o16 2           $ Lucite M3A Moderator
 mat=12 w-p 18.9 u234 1.1 u235 93.1391 u238 5.7609 $ HEU  18325
 mat=13 w-p 18.9 u234 1.1 u235 93.1811 u238 5.7189 $ HEU 500154
 mat=14 w-p 18.9 u234 1.1 u235 93.1531 u238 5.7469 $ HEU 500156
 mat=15 w-p 18.9 u234 1.1 u235 93.3485 u238 5.5515 $ HEU  23184
 mat=16 a-f  1.1877 c 5 (h.ch2) 8 o16 2           $ Lucite R2A Reflector
 mat=17 a-f  1.1875 c 5 (h.ch2) 8 o16 2           $ Lucite R3A Reflector
$ -- Miscellaneous Materials ---------------------------------------------
 mat=20 w-p  2.7 al 98.0 mg 1.2 si 0.8            $ Al-6061 w/max. Mg+Si
 mat=99 a-f  1.0  (h.h2o) 2 o16 1
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 20 yellow
 99 sky
geometry
 $ -- Lower Assembly Geometry --------
 sector 20 Al6061     -62
 sector  1 M3B         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 R3B        13 -14 -15
 sector 99 water      14 -99 -15
$ -- Upper Assembly Geometry --------
 sector 11 M3A        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 R3A        33 -34  15
 sector 99 water      34 -99  15
picture cs material color -1  0  1 -1  0 -1   1  0 -1
picture cs material color -9  0  9 -9  0 -9   9  0 -9
picture cs material color  3  0  2  3  0 -1   6  0 -1
volume material           -8 -8 -8  8 -8 -8  -8  8 -8
                          16 16 16
surfaces $ Dimensions in INCHES
$ -----------------------------------------------------------------------------------------------------------------------
$ Lower assembly (moveable half)
$ -----------------------------------------------------------------------------------------------------------------------
   1 sphere  1.5757  2 sphere  2.3157756 $ Lucite/M3B (minimum inner with  347.8 g @  1.1888 g/cc)
   3 sphere  2.3330  4 sphere  2.5666802 $ HEU/18326  (minimum inner with 2731.3 g @ 18.9    g/cc)
   5 sphere  2.5730  6 sphere  2.7921669 $ HEU/500155 (minimum inner with 3070.9 g @ 18.9    g/cc)
   7 sphere  2.7975  8 sphere  2.9409976 $ HEU/500157 (minimum inner with 2299.4 g @ 18.9    g/cc)
   9 sphere  2.9450 10 sphere  3.1193777 $ HEU/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  5.1063 14 sphere  7.0762763 $ Lucite/R3B (minimum inner with 9020.4 g @  1.1875 g/cc)
$ -----------------------------------------------------------------------------------------------------------------------
$ Assembly midplane (no diaphragm)
```

Appendix A

Sample COG Input Listing

```
$ -------------------------------------------------------------------------------------------------------------------------
  15 plane    z  0.00  $ diaphragm/upper
$ -------------------------------------------------------------------------------------------------------------------------
$ Upper assembly (fixed half)
$ -------------------------------------------------------------------------------------------------------------------------
  21 sphere  1.5796  22 sphere  2.3186674 $ Lucite/M3A (minimum inner with  347.0 g @  1.1885 g/cc)
  23 sphere  2.3350  24 sphere  2.5680057 $ HEU/18325  (minimum inner with 2727.1 g @ 18.9    g/cc)
  25 sphere  2.5745  26 sphere  2.7934013 $ HEU/500154 (minimum inner with 3070.3 g @ 18.9    g/cc)
  27 sphere  2.7985  28 sphere  2.9416947 $ HEU/500156 (minimum inner with 2295.9 g @ 18.9    g/cc)
  29 sphere  2.9470  30 sphere  3.1199468 $ HEU/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  5.1062  34 sphere  7.0771158 $ Lucite/R3A (minimum inner with 9015.7 g @  1.1876 g/cc)
$ -------------------------------------------------------------------------------------------------------------------------
$  Source holder
$ -------------------------------------------------------------------------------------------------------------------------
  62 sphere  1.5
  99 sphere 20
end
```

Appendix B

Details of LB1 and LB2