US DOT SPECIFICATION 6M RADIOACTIVE FISSILE MATERIAL PACKAGE NUCLEAR CRITICALITY SAFETY RE-EVALUATION

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Abstract

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A recent nuclear criticality safety analysis of the Department of Transportation (DOT) Specification 6M fissile material package is reported for a broad variety of fissile material loadings including ^{233}U, ^{235}U and ^{239}Pu as metal and the dioxide forms with varying degrees of homogeneous water moderation. The reported results satisfy appropriate criticality safety criteria and specifications of Titles 49 and 10 of the Code of Federal Regulations and the International Atomic Energy Agency Safety Series No. 6 on Regulations for the Safe Transport of Radioactive Material. The results of the nuclear criticality safety analysis form the bases for extending previous Fissile Class I (transport index = 0.0) package mass limits for specific package sizes. Each of the fissile isotopes (^{233}U, ^{235}U and ^{239}Pu) were evaluated with four different degrees of water moderation at variable material densities. Also, Fissile Class II ($0.1 <$ transport index < 10.0) package mass limits were determined for the same materials which are applicable to 30, 55 and 110 gallon (US) 6Ms. The re-evaluation (for specific sizes of US DOT Specification 6M packaging) demonstrates substantial safe increases of permitted fissile material loadings over generic mass limits previously applied to all sizes of 6M packages (10 to 110 gallon). Previous Fissile Class I (transport index of 0.0) load limits for all 6M package sizes were 1.6 kg ^{235}U, 0.5 kg ^{233}U and 0.9 kg ^{239}Pu for the single moderation limit of hydrogen to fissile material atom ratio of 3 (considering all sources of hydrogen within the 2R vessel). The re-evaluation justifies increasing the load limits for a 30 gallon 6M by factors of 4.3 for ^{235}U, 8.4 for ^{233}U and 6.2 for ^{239}Pu. These particular increases in package utility are the direct result of a specialized and detailed analysis which avoids excesses in safety conservatism.

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* Operated by Martin Marietta Energy Systems, Inc., for the US Department of Energy under Contract No. DE-AC05-840R21400.

INTRODUCTION

This nuclear criticality safety analysis of the Department of Transportation (DOT) 6M Specification fissile material package was performed to provide formal documentation of the package safety as used for an extended variety of fissile material forms and masses beyond those previously specified in Title 49 of the Code of the Federal Register (CFR). The considered fissile material forms included ^{233}U, ^{235}U, and ^{239}Pu metals and their dioxide forms with homogeneous water moderation with hydrogen to uranium or plutonium atomic ratios equal to or less than 1, 3, and 10. Specific evaluations were completed to determine Fissile Class I package mass loadings for various 6M container sizes. Also, evaluations were completed to determine the 30-gallon 6M Fissile Class II package mass loadings, which may be applied to the 55- and 110-gallon 6M packages.[1] The method of analysis and summarized results are presented.

The limiting fissile material masses and conditions of packaging, derived from the analysis, satisfy appropriate nuclear criticality safety criteria and specifications of Titles 10 & 49 CFR and IAEA Safety Series 6.

NUCLEAR CRITICALITY SAFETY ANALYSIS OF THE 6M SPECIFICATION PACKAGE

METHOD OF ANALYSIS

The nuclear criticality safety analyses of single packages and arrays under normal transport and hypothetical accident conditions were evaluated with the multidimensional, multigroup Monte Carlo criticality KENO IV program (CSAS2) module utilizing the 16 energy group Hansen-Roach cross sections provided within the SCALE [1] computer code.

The program and cross sections are considered well established on the basis of their success in calculating a large variety of critical experiments.[2-6]

The preparation of input data and the selection and processing of cross sections for use in the calculations were identical to the methods prescribed in the SCALE Manuals.

PACKAGE DESCRIPTION

The 10-, 15-, 30-, 55-, and 110-gallon 6Ms were considered in the safety analysis. Actual fabrication specification dimensions and materials were assumed and translated into geometry and material descriptions which were compatible with the computer code input requirements. Specific descriptions follow.

Actual

The dimensional and material specifications assumed for the five sizes of 6Ms were derived from Title 49 of the Code of Federal Regulations Part 178.104 and typical height to diameter ratios of steel DOT Specification 6C or 17C drums as prescribed in the American National Standards Institute, Inc., ANSI MH2.1-2.17-1979 or common vendor specifications.

[1] 1 gallon (US) = 3.785×10^{-3} m^3.

Since the specifications provide maximum and minimum values for various items, realistic extremes were assumed which would assure maximum reactivities for nuclear criticality safety evaluations. For instance, no credit was taken for excess end insulation on the 2R Specification container nor possible end play of the 2R for tolerances of fits. These interpretations of the specifications permits a longer 2R Specification container for fissile material than would practically exist. These interpretations provided adequate bases for the computational modeling since

- packaging volume reduction, resulting from normal and hypothetical accident conditions of transport testing [7,8], is local to limited surface regions of the outer drum and do not significantly alter the stacking densities of the packages, and
- thermal damage from the hypothetical accident fire test does not totally disassociate the hydrogen and oxygen from the cane fiberboard or plywood to depths greater than 5.08 cm (2 inches) [7, 8].

Computational

The computational models utilized for the array evaluations were based upon the typical dimensions and materials of actual packages. To equate the calculated square pitch arrays to possible close packed triangular pitch arrays of actual packages, the computational models replaced the outer drum hoop rings with straight walls having a 7 percent less outer radius. Table I provides typical computational dimensions for the various sized but thermally damaged packagings evaluated.

The container construction materials and package fissile material contents used in the computational model are presented in Table II.

The basic fissile materials considered in the evaluations were the metals and dioxides of isotopically pure ^{233}U, ^{235}U, and ^{239}Pu at theoretical and reduced densities with varying degrees of water moderation, depending upon the analysis being performed (e.g., single package versus array analyses).

The same fissile materials were considered in the single package analyses but at varying densities and degrees of moderation to account for maximum reactivities at optimum geometries and moderation.

Finite array calculations incorporated a 30.48 cm (12 inches) water reflector and packages were arranged to create a near cubic outer array boundary.

The maximum reactivity of damaged arrays was determined for water moderation between packages by introducing various densities of water within voids between packages and within the Celotex packaging.

Interstitial water moderation between packages was simulated by introducing variable density water into the voids of the packaging materials.

For the single package analysis, all materials outside the 2R vessel were assumed to be theoretical density water.

Table I. Computational Model Dimensions (cm)

Geometry	Material	10	15	30	55	110
		Package Size in Gallons				
Cylinder	Fiss Mat					
R		<6.6675	<6.6675	<6.6675	<6.6675	<6.6675
+H		<31.0696	<45.5286	<49.2125	<64.1350	<148.5900
-H		0.0	0.0	0.0	0.0	0.0
Cylinder	Void or					
R	H2O	6.6675	6.6675	6.6675	6.6675	6.6675
+H		31.0696	45.5286	49.2125	64.1350	148.5900
-H		0.0	0.0	0.0	0.0	0.0
Cylinder	Carbon					
R	Steel	7.3025	7.3025	7.3025	7.3025	7.3025
+H		31.7046	46.1636	49.8476	64.7700	149.2250
-H		-0.6350	-0.6350	-0.6350	-0.6350	-0.6350
Cylinder	Celotex*					
R		11.7568	12.8380	18.0975	23.4950	23.4950
+H		31.7046	46.1636	49.8476	64.7700	149.2250
-H		-0.6350	-0.6350	-0.6350	-0.6350	-0.6350
Cylinder	Plywood					
R	or	11.7568**	12.8380**	18.0975	23.4950	23.4950
+H	Charred**	34.2446**	48.7036**	52.3876	67.3100	151.7650
-H	Plywood	-3.1750**	-3.1750**	-3.1750	-3.1750	-3.1750
Cylinder	Celotex					
R		---	---	18.0975	23.4950	23.4950
+H		---	---	54.2926	69.2150	153.6700
-H		---	---	-5.0800	-5.0800	-5.0800
Cylinder	Charred					
R	Celotex	16.7361	17.8758	22.5523	27.5426	27.5426
+H		36.4798	50.9388	59.3726	74.2950	158.7500
-H		-5.4102	-5.4102	-10.1600	-10.1600	-10.1600
Cylinder	Carbon					
R	Steel	16.7361	17.8758	22.5523	27.5426	27.5426
+H		36.5710	51.0602	59.4940	74.4469	158.9019
-H		-5.5014	-5.5316	-10.2814	-10.3119	-10.3119
Cylinder	Void or					
R	var. dens	16.7361	17.8758	22.5523	27.5426	27.5426
+H	H2O	38.3848	52.8438	61.2776	76.2000	160.6550
-H		-7.3152	-7.3152	-12.0650	-12.0650	-12.0650
Cylinder	Carbon					
R	Steel	16.8279	17.9975	22.6771	27.7000	27.7000
+H		38.3848	52.8438	61.2776	76.2000	160.6550
-H		-7.3152	-7.3152	-12.0650	-12.0650	-12.0650
Cuboid	Void or					
+X,+Y	var. dens	16.8279	17.9975	22.6771	27.7000	27.7000
-X,-Y	H2O	-16.8279	-17.9975	-22.6771	-27.7000	-27.7000
+Z		38.3848	52.8438	61.2776	76.2000	160.6550
-Z		-7.3152	-7.3152	-12.0650	-12.0650	-12.0650

* Celotex is a trade name for fiberboard insulation (cellulose).

** The depth of charring due to the hypothetical accident fire test has been demonstrated to be approximately 5.08 cm (2 inches) from the surface of the package for Celotex, ref. 7,8. The plywood was assumed to char to the same depth as Celotex.

Note: Undamaged packaging assumed normal density Celotex and plywood in the charred regions. Interstitial water moderation was simulated by introducing variable density water into the voids of the packaging materials.

Table II. Package Computational Model

---------Container Construction Materials--------		
Material	Element	Atom Density (atoms/barn-cm)
Carbon Steel @ 7.82 g/cc (487 lb/cu ft)	Carbon	3.921E-03
	Iron	8.349E-02
Plywood @ 0.45 g/cc (28 lb/cu ft)	Hydrogen	1.671E-02
	Carbon	1.003E-02
	Oxygen	8.357E-03
Charred Plywood @ 0.20 g/cc (12 lb/cu ft)	Carbon	1.003E-02
Celotex @ 0.24 g/cc (15 lb/cu ft)	Hydrogen	8.914E-03
	Carbon	5.348E-03
	Oxygen	4.457E-03
Charred Celotex @ 0.11 g/cc (6.6 lb/cu ft)	Carbon	5.348E-03

-----Fissile Material Contents and Forms------		
Material	Fissile Isotope Density (g/cc)*	H/U or Pu Atom Ratio
235-U	4.7 - 18.74	0
235-UO2 + 0.5 H2O	1.8 - 7.1	1
235-UO2 + 1.5 H2O	1.1 - 4.6	3
235-UO2 + 5.0 H2O	0.6 - 2.1	10
233-U	4.6 - 18.4	0
233-UO2 + 0.5 H2O	1.7 - 7.0	1
233-UO2 + 1.5 H2O	1.1 - 4.5	3
233-UO2 + 5.0 H2O	0.5 - 2.0	10
239-Pu	4.9 - 19.7	0
239-PuO2 + 0.5 H2O	1.8 - 7.4	1
239-PuO2 + 1.5 H2O	1.2 - 4.7	3
239-PuO2 + 5.0 H2O	0.5 - 2.1	10

* Maximum values are assumed theoretical densities.

SINGLE PACKAGE ANALYSIS

The single package analysis was based upon computational studies of full water reflection and flooding of the 2R vessel. The individually considered fissile materials were studied at various masses and densities within the water flooded and reflected 2R vessel to determine the maximum subcritical mass of each fissile isotope considered.

Based upon the reliability of the computational method for water moderated and reflected single units and the assumed purity of fissile isotopes evaluated, it is concluded that the single package subcritical fissile material mass limits should not exceed

- 23.75 kg as a single mass of uranium metal enriched in ^{235}U,
- 148.59 kg as compounds of uranium enriched in ^{235}U,
- 5.26 kg as a single mass of plutonium metal,
- 10.41 kg as compounds of plutonium,
- 7.39 kg as a single mass of uranium metal possessing more than 1 weight percent ^{233}U, and
- 16.5 kg as compounds of uranium possessing more than 1 weight percent ^{233}U.

As ^{239}Pu generates radioactive decay heat, along with associated isotopes of plutonium, the total mass of plutonium is restricted to 4.5 kg to accommodate the maximum permissible heat load to less than 10 watts in a single 6M. Uranium having more than 1 weight percent ^{233}U requires a maximum 2R vessel inside diameter no greater than 10.16 cm (4.0 inches).

MULTIPLE PACKAGE ARRAY ANALYSIS

Computational studies were performed on the undamaged and thermally damaged 6Ms to determine Fissile Class I fissile material mass limits for each package size considered. Fissile Class II fissile material mass limits for 30-gallon (and larger) packages were determined in a like manner.

The following sections provide results of these studies.

Fissile Class I Nuclear Criticality Calculations

Fissile Class I evaluations were conducted by calculating spectrally reflected three-dimensional models.

Several observations were drawn from a close review of the results.

Firstly, the k-eff of an infinite array of a given 6M packaging size and condition, as loaded with a given fissile material and density, is approximately directly proportional to the cube root of the fissile material mass. For example, an infinite array of 30-gallon thermally damaged 6M packages loaded with 18.9 kg ^{235}U metal at 18.74g U/cc has a computed k-eff equal to about 1.00. Therefore, the same array with 15.86 kg ^{235}U metal will have a k-eff equal to about 0.94 (i.e., the cube root of 15.86 kg divided by 18.9 kg).

Secondly, all sizes of undamaged 6Ms exhibit excess interunit moderation due to the cane fiberboard insulation.

Thirdly, reducing the density of a given fissile material mass has positive reactivity effects on 10-, 15-, and 30-gallon 6M sizes, whereas material density reductions have negative reactivity effects on the 55- and 110-gallon 6M sizes.

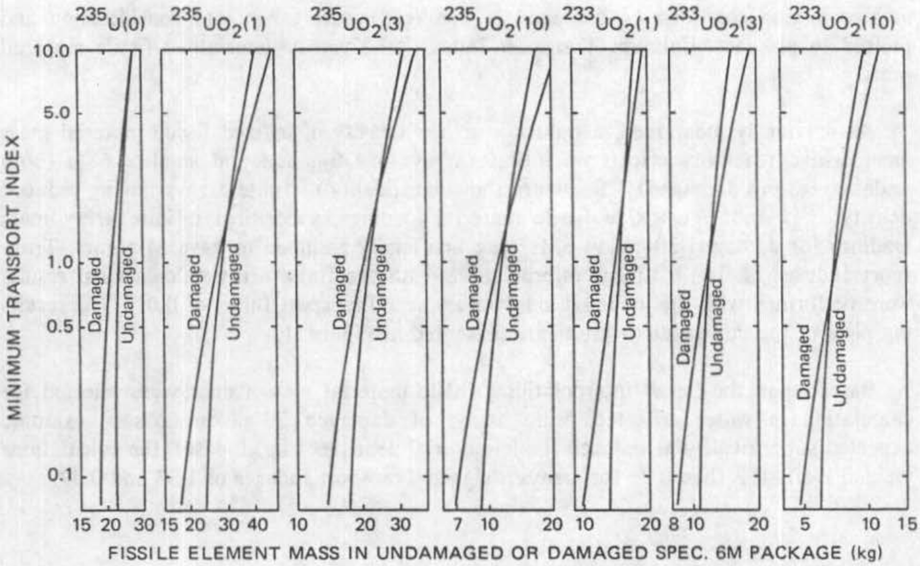

FIG. 1. Specification 6M minimum transport indexes versus uranium mass loadings at various H/μ atom ratios (0, 1, 3 and 10) for 30, 55 and 110 gallon packaging sizes.

To examine the impact of water moderation between packages, the thermally damaged 10-, 15-, and 30-gallon 6M packages were recalculated with varying densities of water introduced into void interstices of the cane fiberboard regions (charred and uncharred). The results demonstrated that the addition of water to the thermally damaged 6Ms has a negative effect on k-eff, and that this effect is most dramatic in the smaller packaging.

To examine the impact of introducing other elements with the considered fissile materials, carbon was introduced into the void interstices within reduced density ^{235}U metal as packaged within 15-gallon thermally damaged 6Ms. The results of this parameter study demonstrated that the addition of minimally neutron-moderating scattering centers within the fissile material have limited, if any, positive reactivity contribution to 6M packages. The packaging of ^{235}U, ^{233}U, or ^{239}Pu as compounds or alloys of other elements having no greater neutron moderating characteristics than carbon and greater nonfission neutron absorption characteristics will further reduce the reactivity of the materials evaluated.

Fissile Class II Nuclear Criticality Calculations

Fissile Class II evaluations were conducted by calculating selected three-dimensional arrays of undamaged and thermally damaged 30-gallon 6M packages.

To relate the calculational results to Minimum Transport Indexes, the number of packages evaluated for each mass loading (for k-effs = 0.93) at theoretical density and packaging condition (undamaged or damaged) were taken into consideration and plotted to provide Minimum Transport Index (T.I.) versus determined fissile material mass.

As previously mentioned, a reduction in the density of a fixed fissile material mass has positive reactivity effects on infinite arrays of 30-gallon and smaller 6Ms (both undamaged and damaged). To assure the subcriticality of finite arrays having reduced density ^{235}U and ^{233}U oxide fissile material loadings, subcritical infinite array mass loadings for damaged 30-gallon 6Ms were artificially assumed to have Minimum Transport Indexes of 0.01. Linear interpolations with the finite array calculational results were performed with the assumed mass values at a Transport Index of 0.01. The resulting plots of the interpolated results are presented in Figure 1.

Based upon the linear interpolations, fissile material mass values were selected for calculation in water reflected finite arrays of damaged 30-gallon 6Ms to examine expected subcriticality at reduced fissile material densities. In all cases, the calculations yielded k-effs less than 0.93 for arrays assigned Transport Indexes of 1.33 and 0.099.

ASSIGNMENT OF FISSILE MATERIAL MASS LIMITS FOR SPECIFIED TRANSPORT INDEXES

FISSILE CLASS I & II MASS LIMITS

It was concluded that Fissile Class I package fissile material mass limits may be defined from calculated mass values for thermally damaged packages which approximate array k-effs of 0.93. The derivation of mass limits from the thermally damaged package mass values assures an additional margin of subcriticality for infinite arrays of undamaged packages. The k-effs for the undamaged arrays will be on the order of 0.7 (for 10-gallon 6Ms) to 0.91 (for 110-gallon 6Ms).

It was concluded that Fissile Class II package fissile material mass limits could be derived from the relationship of Transport Index to package fissile material mass for the 30-gallon 6M package. Additionally, these mass limits may be applied to the 55- and 110-gallon 6M packages having the same Minimum Transport Index due to their increased size, which affords further excess neutron moderation between packages and increased neutron leakage from arrays of the same size.

Table III provides a summary of the derived Fissile Class I & II mass limits resulting from the computational results.

SUMMARY AND CONCLUSIONS

The evaluations performed on the Specification 6M package covered a broad range of fissile materials and forms for various packaging sizes. The analysis was performed

- to satisfy fissile material mass limit requirements for the single package safety analysis of the 10-, 15-, 30-, 55-, and 110-gallon 6Ms,

Table III. Fissile Class I & II Mass Limits

Fissile Class I, Transport Index Equal to 0.0

Material Form	H/U or Pu	Uranium or Plutonium Dens(g/cc)	Uranium or Plutonium Mass Limits* (kg) 6M Package Size (gal) 10	15	30	55	110
235-U							
Metal or Alloys	0	4.7-18.7	0.91	1.69	15.08	20.75	23.5
Compounds	1	1.8-7.1	0.65	1.21	8.50	23.12**	34.54
	3	1.1-4.6	0.48	0.91	7.00	17.31**	30.38**
	10	0.5-2.1	0.27	0.51	4.23	10.51**	19.25**
233-U***							
Metal or Alloys	0	4.6-18.4	0.49	0.84	6.62	7.39	7.39
Compounds	1	1.7-7.0	0.42	0.76	5.99	12.54	16.50
	3	1.1-4.5	0.33	0.60	4.19	10.72**	15.63
	10	0.5-2.0	0.18	0.34	2.33	5.94**	9.96
239-Pu****							
Metal or Alloys	0	4.9-19.7	0.47	0.74	4.99	5.26	5.26
Compounds	1	1.8-7.4	0.46	0.81	7.84	10.41	10.41
	3	1.2-4.7	0.38	0.68	5.62	10.41	10.41
	10	0.5-2.1	0.24	0.44	3.42	7.65**	10.41

* Total uranium or plutonium in kilograms independent of isotopic composition. Uranium containing more than 1 weight percent 239-Pu or 233-U shall be considered as Pu or 233-U as appropriate.

** There is no minimum density restriction on this loading.

*** The 2R vessel maximum inside diameter is 10.16 cm (4.0 inches) for all 233-U loadings.

**** Plutonium content requires a mass restriction of 4.5 kg to accomodate a thermal heat load limitation of 10 watts.

Fissile Class II Mass Limits for 30-, 55-, and 110-gallon 6M Packages for Various Minimum Transport Indexes

Material Form	H/U	Uranium Dens(g/cc)	Total Uranium Mass Limits* (kgs) Minimum Transport Index 0.1	0.5	1.0	5.0	10.0
235-U**							
Metal or Alloys	0	4.7-18.7	18.00	20.20	21.60	-	-
Compounds	1	1.8-7.1	17.00	22.20	25.30	34.00	41.00
	3	1.1-4.6	14.00	18.00	20.70	27.60	31.50
	10	0.5-2.1	6.50	8.80	10.00	14.00	15.80
233-U***							
Compounds	1	1.7-7.0	8.60	11.00	12.00	15.00	16.50
	3	1.1-4.5	7.00	9.30	10.30	13.60	14.20
	10	0.5-2.0	3.60	5.60	6.30	8.30	9.30

* Total uranium in kilograms independent of isotopic composition.

** The Uranium shall contain no more than 1 weight percent 239-Pu or 233-U. Uranium containing more than 1 weight percent 233-U shall be considered as 233-U.

*** The 2R vessel maximum inside diameter is 10.16 cm (4.0 inches) for all 233-U loadings.

- to satisfy fissile material mass limit requirements for Fissile Class I packages (Minimum Transport Index = 0.0) of the 10-, 15-, 30-, 55-, and 110-gallon 6Ms as subcritical infinite arrays of undamaged and damaged packages, and
- to satisfy fissile material mass limit requirements for Fissile Class II packages (Minimum Transport Indexes = 0.1, 0.5, 1.0, 5.0, and 10.0) of 30-gallon 6Ms which may be applied to the 55- and 110-gallon 6M sizes.

The depth and breadth of the computational evaluations provide an adequate basis for the interpretation and application of subcritical results to the nuclear criticality safety analyses for the stated use of the Specification 6M package. Additional margins of subcriticality are introduced to the safety analysis by virtue of the evaluations considering 100 weight percent fissile isotopes. In the case of ^{233}U loadings, the array evaluations were performed for 2R vessel inside diameters of 13.335 cm (5.25 inches) instead of the 10.16 cm (4.0 inches) required by the single package analysis. These considerations plus "real world" circumstances of material containment prior to packaging, less than theoretical material densities, and less reactive material compositions and mixtures provide substantial margins of subcriticality to the single package evaluations and, to a lesser extent, to the array evaluations. It is concluded that the determined fissile material mass limits and conditions for use of the Specification 6M package meet specific Federal nuclear criticality safety regulations of 10 & 49 CFR and exceed regulatory intentions for margins of safety as the packaging is employed for practical use.

ACKNOWLEDGMENTS

Gratitude is expressed to Joe C. Turner and John R. Knight for the voluminous number of computational codings performed with a super degree of reliability and accuracy.

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