Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Midterm Report:

Designing Flexibility into the Authorized Radioactive Contents of the 9982 Shipping Package

Chance Pittman, Augusta University

Dr. Edward Ketusky, Savannah River National Laboratory

Steven Nathan, Savannah River National Laboratory

Midterm Progress Toward Internship Goals

With regards to the planned contents for the 9982, three sets of radionuclides have been analyzed. A set of percentages by weight for plutonium from 3013 canisters, training sources sent in 9977's, and americium standards from 9978's were used as the bases for realistic contents that could be shipped in a 9982 package. Using the tables and limits located in G-BDR-A-00001 Rev. E, the calculations began by determining the mass limits for the radionuclides in each source. These mass limits were then used alongside the mass of the radionuclides in the sum-of-the-fractions methodology present in the content description. If this summation is less than or equal to one, the contents are allowed for shipment in the 9982. For the aforementioned sets, the listed radionuclides could be shipped as-is; however, the goal of the calculations is to determine the maximum content mass allowed. To do so, the percentages of weight were used to find where the summations would equal one rather than simply satisfy the inequality. By solving for the content mass when the inequality equals one, the maximum content mass is calculated, which can then be multiplied by each percent weight to get each radionuclide's mass.

The MCNP input files have also been compared to find differences between the oxide and metals forms of the radionuclides. While there are several differences present that make sense, such as oxides have more mass and a lower density due to the presence of oxygen in the oxide forms, there are other differences that are possibly unintentional. With the input files for the metals, both with and without a shielding pig, neutrons are being used in the photon models, seen by "imp:n" being present within the file instead of "imp:p", where "imp" stands for the importance of a region for either neutrons or photons. Effectively, this results in the dose due to photons being modelled with neutrons instead, potentially resulting in the calculated dose rates being incorrect. As MCNP is proprietary, I do not have access to it here and must consult with the person handling the shielding calculations to discuss what these differences may affect and how to change them. If he remains out of the office or if fixing these files takes longer than expected, the final report may focus more on the contents while discussing these differences; however, it could potentially lack discussion on finalizing the planned contents due to the mass limits still needing to be calculated.

Below is the midterm, or draft, report on the planned contents, as the shielding expert has not been present to discuss the MCNP issues.

Introduction

When designing a new radioactive material package, one must determine exactly what is to be shipped inside the packaging. This material is known as the content and is typically well defined so as to simplify any tests and analyses involving how the content acts inside the packaging. However, the 9982 package is being designed around a more flexible content definition as a way of letting the package be used in a wide variety of shipments. This flexibility has the side effect of requiring more in-depth analysis and potentially more restrictions in order to justify why any combination of the potential radionuclides would not become a situation where the package is likely to fail.

These analyses were done on each radionuclide individually to find the mass limits for thermal (decay heat), criticality, and dose rate under certain constraints. For decay heat, the content is limited to 60 watts. Criticality is limited by k_{safe}, here 0.936 based on a uranium solution benchmark[1]. Dose rate is limited to 200 mrem/hr at the surface of the 9982 package. By calculating the mass for each radionuclide that achieves the values, the mass limits are determined. This was done by criticality, thermal, and shielding professionals; as such, the documentation on the values is mostly on the end results rather than the calculations themselves.

To check if a known set of radionuclides can be shipped in the 9982, one follows a sum-of-the-fractions methodology where the radionuclide's mass and its corresponding mass limit are divided to determine if the ratio is less than one, indicating the radionuclide is below its limit.[2] In G-BDR-A-00001 Rev E section 1.2.2.1, a limit of 200 grams of fissile material is given.[2] Using either the four fissile nuclides from 10 CFR 71.4 or the four listed in Table 1-Section 1 of G-BDR-A-00001 Rev E, the sum of the fissile masses must be less than the given limit of 200 grams. Following this limit, the following four equations are given as a means of determining if criticality, thermal, or shielding issues would arise when including several radionuclides in the content:[2]

$$\sum \frac{M_i}{X_C} \leq 1 \tag{1}$$

$$\sum \frac{M_i}{X_T} \leq 1 \tag{2}$$

$$\sum \frac{M_i}{X_{NS}} \leq 1 \tag{3}$$

$$\sum \frac{M_i}{X_S} \leq 1 \tag{4}$$

Where, M_i is the mass, X_C is the mass limit for criticality, X_T is the mass limit for thermal heat, X_{NS} is the mass limit for dose without a shielding pig, and X_S is the mass limit for dose with a shielding pig for each individual radionuclide. In order to be allowed, the content must satisfy Equation 1, Equation 2, and either Equation 3 or Equation 4 depending on if a shielding pig is used or not. Since this report covers a theoretical content, both Equation 3 and Equation 4 were used as the presence of shielding was not considered.

WG Plutonium as Planned Contents[3]

REDESIGNATION CAMPAIGN ISOTOPIC MEASUREMENTS
Taken using calorimetry/gamma spetrometry at time of packaging.
Method uncertainty gives +/- of 0.2-0.4% Pu-239. Physical distribution
of radioisotopes in Rocky Flats process metals is likely narrower.

Measure Date	wt.% Pu-238*	wt.% Pu-239	wt.% Pu-240	wt.% Pu-241	wt.% Pu-242**	ppm Am/Pu	Sum Pu-239+241
Mean	0.0121	93.950	5.866	0.150	0.0207	1,526	94.101
Median	0.0109	93.935	5.880	0.162	0.0200	1,517	94.090
Min	0.0000	93.300	5.190	0.050	0.0100	582	93.490
Max	0.0203	94.730	6.470	0.230	0.0300	3,036	94.790

* Sometimes assigned 0.01 or 0.02
** By algorithm or assigned 0.02

Figure 1 The Percent Weight Values Used for the Planned 9982 Contents

When using the values for the percent weight from Figure 1 for Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242, one can expand Equations 1 through 4 to:

$$\left(\frac{P_{238}}{X_{C238}} + \frac{P_{239}}{X_{C239}} + \frac{P_{240}}{X_{C240}} + \frac{P_{241}}{X_{C241}} + \frac{P_{242}}{X_{C242}}\right) m \leq 1 \tag{5}$$

And so on, replacing X_C with X_T, X_{NS}, or X_S depending on the mass limit being used for the other three equations. Here, m is the total mass of the content inside the 9982 package, and P_N is the percent weight for the isotope N of plutonium. Since the maximum mass is desired here, the inequality in Equation 5 can be replaced by an equality as below:

$$\left(\frac{P_{238}}{X_{C238}} + \frac{P_{239}}{X_{C239}} + \frac{P_{240}}{X_{C240}} + \frac{P_{241}}{X_{C241}} + \frac{P_{242}}{X_{C242}}\right) m = 1 \tag{6}$$

From Equation 6, solving for m gives the maximum mass allowed for each type of mass limit. With this mixture of plutonium isotopes, the dose turns out to be the limiting factor due to its equation equaling one (1) at the lowest mass, as seen in Figure 2 below.

	Criticality	Thermal	Dose (no pig)	Dose (with pig)
Equation	Mi/Xc<=1	Mi/Xt<=1	Mi/Xns<=1	Mi/Xs<=1
Mean	9.998933525220850E-01	7.700754716471990E-03	1.000000000000000E+00	1.000000000000000E+00
Median	9.999039368563610E-01	7.681187275692490E-03	1.000000000000000E+00	1.000000000000000E+00
Min	1.000000000000000E+00	7.367195072407060E-03	1.000000000000000E+00	1.000000000000000E+00
Max	9.998237033538360E-01	7.939405239846030E-03	1.000000000000000E+00	1.000000000000000E+00

Figure 2 Dose as the Limiting Factor out of the Four Mass Limits

With the values of X_{NS} and X_S being equal for the five isotopes of plutonium, solving for m using X_{NS} instead of X_C in Equation 6 gave the maximum content mass. Since Figure 1 shows four sets of percent weights, each set is used to find a total mass as well as a set of masses for each isotope. Table 1 gives the values for each total mass for the mean, median, minimum, and maximum weight percentages.

Table 1: Maximum Total Content Mass for Each Set of Percentages

	Analytical Maximum Mass (g)	Actual Maximum Mass (g)	Sum of the Percentages
For the Mean Percentages:	199.9810703	199.9786705	99.9988
For Median:	199.9649901	199.9807874	100.0079
For Min:	202.9426687	200	98.55
For Max:	197.0478415	199.9647407	101.4803

Each set of percent weights does not sum to 100 percent evenly; instead, as given in Table 1 under "Sum of the Percentages", each set falls within 1.5 percent or closer of 100 percent. This results in the sum of the masses of the isotopes being different from the value of m found when solving the equation. This difference can be seen by comparing the columns "Analytical Maximum Mass" and "Actual Maximum Mass" in Table 1, where the latter is the sum of the isotopes' masses and the former is the calculated value of m. These individual isotope masses are calculated by multiply the value of m by the percent weight for that isotope from Figure 1. Table 2 shows the values under "Actual Maximum Mass" from Table 1 split into the constituent isotope masses.

Table 2: Maximum Mass for Each Isotope for Each Set of Percentages				
Isotope	Mean Percentage Individual Mass (g)	Median Percentage Individual Mass (g)	Minimum Percentage Individual Mass (g)	Maximum Percentage Individual Mass (g)
Pu-238	0.02419771	0.021796184	0	0.040000712
Pu-239	187.8822155	187.8371135	189.3455099	186.6634202
Pu-240	11.73088958	11.75794142	10.53272451	12.74899534
Pu-241	0.299971605	0.323943284	0.101471334	0.453210035
Pu-242	0.041396082	0.039992998	0.020294267	0.059114352
Total Mass	199.9786705	199.9807874	200	199.9647407

These values from Table 2 serve as several planned content limits for the 9982 package. Each total mass is less than or equal to the 200-gram fissile material limit and they all satisfy the inequalities from Equations 1 through 4. While any of these groups of masses should be able to be shipped in the 9982, the mean and median groups likely represent the contents most similar to the materials in the redesignation campaign these calculations are based on. This is due to the minimum and maximum percentages likely coming from outliers or a single object with such measurements. The mean and median percentages are also the closest to summing to 100 percent, resulting in the value of m and the sum of the isotope masses being closer than with the minimum and maximum calculations.

Training Sources as Planned Contents[4]

Using several training sources shipped in the 9977 as planned contents for the 9982, as shown in Table 3, the isotopes' masses were already known; whereas, the previous situation involved indeterminant ones. As such, the listed isotopes were used in Equations 1 through 4 instead of solving Equation 6 again. With these sources, there is a difference between the mass limit for the materials in oxide form and in metal form; therefore, Equations 3 and 4 were done twice, once for the oxide value and once for the metal value, for each source.

Table 3: Training Sources' Isotopes						
Isotope	Source 1 Mass (g)	Source 2 Mass (g)	Source 3 Mass (g)	Source 4 Mass (g)	Source 5 Mass (g)	Source 6 Mass (g)
Beryllium*	19.125	19.125	19.125	19.125	19.125	19.125
Aluminum*	1.9125	1.9125	1.9125	1.9125	1.9125	1.9125
Magnesium*	6.375	6.375	6.375	6.375	6.375	6.375
Sodium*	3.825	3.825	3.825	3.825	3.825	3.825
Fluorine*	2.55	2.55	2.55	2.55	2.55	2.55
Pu-238	0.05	0.05	0.05	0.05	0.05	0.05
Pu-239	76.77	138.7	145.11	159.28	141.405	97.18
Pu-240	4.89	8.7	8.59	9.58	8.93	6.14
Pu-241	0.1	0.35	0.71	0.88	0.267	0.19
Pu-242	0.5	0.05	0.05	0.05	0.05	0.05
Am-241	0.5	0.05	0.05	0.05	0	0.05
Am-243	0.05	0.05	0.05	0.05	0	0.05
Cf-252	2.60E-07	2.60E-07	2.60E-07	2.60E-07	0	2.60E-07
Cm-248	5.70E-06	5.70E-06	5.70E-06	5.70E-06	0	5.70E-06
Np-237	0.05	0.05	0.05	0.05	0	0.05
Th-232	0.05	0.05	0.05	0.05	0	0.05
U-234	0.05	0.05	0.05	0.05	0	0.05
U-235	0.05	0.05	0.05	0.05	0	0.05
U-236	0.05	0.05	0.05	0.05	0	0.05
U-238	0.05	0.05	0.05	0.05	0	0.05
*Light elements to be evaluated at a later time. They are currently excluded from this analysis						

Table 4: Mass Limit Calculations								
	Criticality Summation	Thermal Summation	Dose with No Pig and in Metal Form Summation	Dose with No Pig and in Oxide Form Summation	Dose with a Pig and in Metal Form Summation	Dose with a Pig and in Oxide Form Summation	Total Fissile Mass (g)	Total Content Mass (g)
Source 1	0.416	0.00449	0.525	0.524	0.519	0.517	82.310	83.160
Source 2	0.741	0.00610	0.851	0.849	0.844	0.842	147.850	148.250
Source 3	0.775	0.00631	0.884	0.883	0.878	0.876	154.510	154.910
Source 4	0.851	0.00690	0.960	0.959	0.954	0.952	169.840	170.240
Source 5	0.754	0.00620	0.754	0.754	0.754	0.754	150.652	150.752
Source 6	0.520	0.00445	0.629	0.628	0.623	0.621	103.610	104.010

As shown in Table 4, each source falls under the limit of one (1) for each type of mass limit, indicating that each of these would meet the criteria for being shipped in the 9982. However, this is only true when the light elements beryllium, aluminum, magnesium, sodium, and fluorine are assumed to not be present. These light elements, marked with an asterisk in Table 3, are explicitly not permitted in G-BDR-A-00001 section 1.2.2.1.2. For the purpose of this calculation, the light elements were not considered as further analysis is required in order to allow them in a shipment.

In each of the above six sources, the mass limit for the dose would limit the total content mass the most, as the dose summations result in the highest values. Since the presence of a shielding pig and the form of the isotope is not known or considered here, four different maximum content masses were calculated for an average set of weight percentages. Each of these is shown in Table 5.

Table 5: Maximum Content Mass for an Average Source

	No Pig, Metal	No Pig, Oxide	Pig, Metal	Pig, Oxide
Avg Source:	174.1593329	174.4091091	175.4597784	175.876825

In order to have one set of isotopes fit inside the 9982 regardless of the form or the presence of a shielding pig, an average maximum mass of 174 grams was used, rounding down for the lowest value in Table 5. This value was then multiplied by the weight percentages to get another set of isotope mass that serve as planned contents for the 9982, shown in Table 6.

Table 6: Average Isotope Mass in a Training Source

Isotope	Mass (g)	Isotope	Mass (g)
Pu-238	0.069	Np-237	0.059
Pu-239	162.499	Th-232	0.059
Pu-240	10.077	U-234	0.059
Pu-241	0.490	U-235	0.059
Pu-242	0.226	U-236	0.059
Am-241	0.226	U-238	0.059
Am-243	0.059		
Cf-252	3.070E-07		
Cm-248	6.730E-06		

Americium Metals from S-SARA-G-00020[5]

A third, simpler, content is americium metal, either as a Am-241 or Am-243 standard or a mixture of both, as seen in Table 7.

Table 7: Americium Metal as Contents

Isotope	Mass (g)
Am-241	0.76923
Am-243	0.75924
Combined	1.52847

Here, the values of the metals on their own are below the limits declared in G-BDR-A-00001 Rev E Table 1 Section 1. As such, these two satisfy Equations 1 through 4. Together, the two masses are still below the limit of one (1) in each type of mass limit. Therefore, either together or separate, the Am-241 and Am-243 standards are suitable for shipping in the 9982.

Calculating A_2 values

For all the planned contents considered here, the use of a type B package had to be properly justified, as stated in LLNL's *Packaging Review Guide for Reviewing Safety Analysis Reports for Packaging* section 1.3.1.2. This is done by using the equation found in 10 CFR 71 Appendix A:

$$\sum_i \frac{B(i)}{A_2(i)} \leq 1 \qquad (7)$$

Where B(i) is the activity of radionuclide i in normal form, and $A_2(i)$ is the A_2 value for radionuclide i.

As 10 CFR 71 Appendix A gives the A_2 values for each isotope and the specific activity of each one, alongside already knowing the mass of each isotope, Equation 7 can be performed for each planned content to see if any came out below one (1), for which Type A packaging could be used instead. As seen in the attached spreadsheet, the summation from Equation 7 results in values that are not lower than 5, with the rest being 96.9 or greater, indicating that each of the planned contents require Type B packaging for shipment. These values are seen in Table 8.

Table 8: Activity/A_2 Ratios for each Content

Source	Source Set	Activity/A_2
WG Pu	Mean	565
	Median	565
	Min	531
	Max	591
Training Sources	Source 1	319
	Source 2	453
	Source 3	489
	Source 4	541
	Source 5	455
	Source 6	325
	Average Source	562
Americium Standards	Am-241	96.9
	Am-243	5.62
	Together	102

With Type B packages being split into Category I, II, and III packages, these planned contents' A_2 values and activity were used to find the A_2 value for the overall mixture, as done through an equation from 10 CFR Appendix A:

$$\sum_i \frac{1}{\frac{f(i)}{A_2(i)}} = A_2\ for\ mixture \quad (7)$$

Where *f(i)* is the fraction of activity for radionuclide *i* in the mixture and $A_2(i)$ is the appropriate A_2 value for radionuclide *i*.

Table 9: A2 Values for Mixtures		
Source	**Source Set**	**A_2 Value**
WG Pu	Mean	7.92E-02
	Median	8.33E-02
	Min	4.58E-02
	Max	1.02E-01
Training Sources	Source 1	Infinite
	Source 2	Infinite
	Source 3	Infinite
	Source 4	Infinite
	Source 5	Infinite
	Source 6	Infinite
	Average Source	Infinite
Americium Standards	Am-241	2.70E-02
	Am-243	2.70E-02
	Together	2.70E-02

As shown in Table 9, when the new A_2 values were calculated for the WG Pu contents, none were higher than $8.33*10^{-2}$ A_2, much lower than the 3000 A_2 value necessary for Category I packaging. Likewise, the americium metals remained at $2.7*10^{-2}$ for their A_2 values. However, since the Th-232, U-235, U-236, and U-238 have A_2 values of infinity, their corresponding A_2 values for the mixture are also infinity. This puts the package in the Category I portion of Type B packages. This is useful for showing that the 9982 is capable of handling all categories of Type B packages, allowing it to be used for any Type B contents.

Conclusions

By calculating the maximum content mass and each radionuclide's mass, the validity of the sum-of-the-fractions methodology was tested to a certain extent. If something was improperly designed, the maximum content mass would have resulted in fissile masses that exceeded the defined limit of 200 grams of fissile contents. Similarly, with the non-fissile radionuclides, significant errors in their calculated masses would arise if the equations had some inherent issue, such as having a calculated maximum mass above the defined mass limit. With each source's calculated radionuclide set being below their corresponding limits, the analyzed radionuclides are valid with the current methodology. While the other radionuclides remained unused due to the makeup of these three sources, these ones do produce more realistic or expected contents as they were used in other radioactive material packages. Their usage here in the calculations gives the 9982 a more stable foundation for approval since several contents that were already approved elsewhere are show to be compatible with this new package. Compared to trying to show that unfounded radionuclide sets, those created without reference to shipped packages, are what the 9982 could ship, these planned sets of radionuclides could all be future contents for the package instead of purely remaining on tables.

References

[1] Harris, M. 2019. *Criticality Evaluation.* S-SARP-G-00001 Revision 2.

[2] Ketusky, E. 2019. *Content Definition for 9982 Radioactive Material Shipping Package.* G-BDR-A-00001 Revision E.

[3] Eberl, K. 2019. *"WG Pu" data, 9982 contents.*

[4] 2018. *Preparation, Loading and Shipment of a 9977 Shipping Container (Training Source).* ESO-RG-2018 300011.

[5] Ketusky, E. 2016. *New Brunswick Laboratory Pu/Am Standards Content Letter Amendment for Model 9978 Packaging Type B(M)F-96.* S-SARA-G-00020 Revision 2.

Appendix A Mass Limits for the 9982 Radionuclides [2]

Table A-1 Mass Limits

Section 1 - Fissionable Radionuclides (1 of 2) [a]			
Group	Radionuclide	Mass Limit Criteria[a] (gram)	
		Criticality	Thermal [d]
	Column	[I]	[II]
Fissile	U-233	200 [b,c]	2.10E+05
	U-235		9.80E+08
	Pu-239		3.10E+04
	Pu-241		1.90E+04
Non Fissile	Am-241	200 [b,c]	527
	Am-243		9.30E+03
	Cm-248		2.06E+03
	Np-237		2.90E+06
	U-234		3.40E+05
	U-236		3.40E+07
	U-238		7.00E+09
	Th-232		2.30E+10
	Pu-236		**3.3**[f]
	Pu-238		**106.3**[f]
	Pu-240		8.40E+03
	Pu-242		5.20E+05
	Cm-244		**21.2**[f]
	U-232		**85.0**[f]
	Cf-252		**3.1**[f]
Special Actinide Radionuclides (Ref. 2)	Am-242m	0.2 [b,c]	1.40E+04
	Cm-243		31.6
	Cm-245		1.10E+04
	Cm-247		2.00E+07
	Cf-249		392
	Cf-251		1.00E+03

a. Mass limits for combinations of radionuclides are to be determined using the provided Sum-of-the-Fractions Methodology, which immediately precedes this table.

b. NCSE N-NCS-A-00046, Nuclear Criticality Safety Evaluation: 9982 Shipping Package Analysis for Small Gram Quantity Content, 2019 (Ref. 1).

c. Mass limit specified is for each fissionable radionuclide and for the total mass of all fissionable radionuclides.

d. Decay heat of all radionuclides is limited to 60-watts (Section 1.2.2.8).

e. Reserved

f. Thermal mass limit less than criticality mass limit

g. Placeholder

Section 1 - Fissionable Radionuclides (2 of 2)					
Group	Radionuclide	Mass Limit Criteria (gram) [a,b]			
		Dose (without Shielding Pig)		Dose (with Shielding Pig)	
		Metal	Oxide	Metal	Oxide
	Column	[IIIa]	[IIIb]	[IVa]	[IVb]
Fissile	U-233	>200	>200	>200	>200
	U-235	>200	>200	>200	>200
	Pu-239	>200	>200	>200	>200
	Pu-241	>200	>200	>200	>200
Non-Fissile	Am-241	>200	>200	>200	>200
	Am-243	10.27	8.75	>200	>200
	Cm-248	0.16	0.17	0.17	0.17
	Np-237	>200	>200	>200	>200
	U-234	>200	>200	>200	>200
	U-236	>200	>200	>200	>200
	U-238	>200	>200	>200	>200
	Th-232	>200	>200	>200	>200
	Pu-236	1.19E-03	6.93E-04	3.51E-02	2.10E-02
	Pu-238	106.3	106.3	106.3	106.3
	Pu-240	>200	>200	>200	>200
	Pu-242	>200	>200	>200	>200
	Cm-244	0.55	0.55	0.56	0.57
	U-232	1.09E-03	9.46E-04	3.01E-02	2.70E-02
	Cf-252	2.49E-06	2.54E-06	2.53E-06	2.58E-06
Special Actinide Radionuclides	Am-242m	>0.2	>0.2	>0.2	>0.2
	Cm-243	6.16E-03	5.56E-03	>0.2	>0.2
	Cm-245	>0.2	>0.2	>0.2	>0.2
	Cm-247	>0.2	>0.2	>0.2	>0.2
	Cf-249	1.40E-02	1.28E-02	>0.2	>0.2
	Cf-251	>0.2	>0.2	>0.2	>0.2

a. Mass limits for combinations of radionuclides are to be determined using the provided Sum-of-the-Fractions Methodology, which immediately precedes this table.

b. Table does not show calculated dose mass limits that are higher than criticality mass limits

Section 2 - Non-Fissionable Radionuclides (1 of 4)			
Group	Radionuclide	Mass Limit Criteria (gram)[a]	
		Criticality	Thermal
	Column	[I]	[II]
Actinides	Ac-227	∞ [b]	1.70E+03
	Po-210		0.4
	Ra-226		2.10E+03
	Th-228		2.2
	Th-229		9.30E+03
Group 1	Au-195	∞ [b]	21
	Cd-109		198
	Fe-55		736
	I-125		10.1
	I-129		7.10E+08
	Ni-63		1.00E+04
	Pb-210		3.40E+03
	Sm-145		42
	Ti-44		400
	Tm-170		5
Group 2	Ce-139	∞ [b]	6
	Ce-144		28.7
	Co-57		9.1
	Eu-155		158
	Gd-153		19.5
	Hf-172		63.2
	Hg-203		2.2
	Pm-147		176
	Rh-101		33.3
	Se-75		1.7
	Te-123m		4.6
	Xe-127		1.2
	Yb-169		1
Group 3	Ba-133	∞ [b]	85.5
	Cr-51		3
	Eu-152		43.7
	Ir-192		1.1
	Kr-85		103
	Pa-233		1.1
	Pd-103		6.9
	Sb-125		19
	Sn-113		36.1
	Sr-85		0.8
	Tc-95m		0.7

a. Mass limits for combinations of radionuclides are to be determined using the provided Sum-of-the-Fractions Methodology, which precedes this table.

b. Mass is not limited for criticality.

Section 2 - Non-Fissionable Radionuclides (2 of 4) [a]			
Group	Radionuclide	Mass Limit Criteria (gram)[a]	
		Criticality	Thermal
	Column	[I]	[II]
Group 4	Ag-108m	∞[b]	238.0
	Ag-110m		0.8
	Co-58		0.3
	Cs-134		4.5
	Cs-137		683.0
	Hf-181		0.8
	Ho-166m		3.2E+03
	Mn-54		1.6
	Nb-95		0.3
	Ra-228		4.0E+03
	Ru-103		0.6
	Ru-106		306.0
	Sb-124		0.3
	Sr-89		0.6
	Tl-204		91.9
	Zr-95		0.6
Group 5	Bi-207	∞ [b]	118.0
	Co-56		0.1
	Co-60		3.5
	Eu-154		25.4
	Fe-59		0.2
	Ge-68		158.0
	K-40		2.5E+09
	Sc-46		0.1
	Ta-182		1.1
	Zn-65		2.1
Group 6	Sr-90	∞ [b]	369.0
	Y-88		0.3

a. Mass limits for combinations of radionuclides are to be determined using the provided Sum-of-the-Fractions Methodology, which precedes this table.

b. Mass is not limited for criticality.

<table>
<tr><th colspan="6">Section 2 - Non-Fissionable Radionuclides (3 of 4)</th></tr>
<tr><th rowspan="3">Group</th><th rowspan="3">Radionuclide</th><th colspan="4">Mass Limit Criteriaa (gram) [a]</th></tr>
<tr><th colspan="2">Dose (without Shielding Pig)</th><th colspan="2">Dose (with Shielding Pig)</th></tr>
<tr><th>Metal</th><th>Oxide</th><th>Metal</th><th>Oxide</th></tr>
<tr><th colspan="2">Column</th><th>[IIIa]</th><th>[IIIb]</th><th>[IVa]</th><th>[IVb]</th></tr>
<tr><td rowspan="5">Actinides</td><td>Ac-227</td><td>7.28E-04</td><td>6.92E-04</td><td>2.18E+00</td><td>1.81E+00</td></tr>
<tr><td>Po-210</td><td>0.36</td><td>0.36</td><td>1.66E+02</td><td>1.79E+00</td></tr>
<tr><td>Ra-226</td><td>8.64E-03</td><td>#N/A</td><td>5.34E-01</td><td>#N/A</td></tr>
<tr><td>Th-228</td><td>1.50E-05</td><td>1.47E-05</td><td>4.68E-04</td><td>4.67E-04</td></tr>
<tr><td>Th-229</td><td>0.38</td><td>0.35</td><td>7.65E+01</td><td>7.58E+01</td></tr>
<tr><td rowspan="10">Group 1</td><td>Au-195</td><td rowspan="10">8.3E-04</td><td rowspan="10">7.95E-04</td><td rowspan="10">71.69</td><td rowspan="10">57.31</td></tr>
<tr><td>Cd-109</td></tr>
<tr><td>Fe-55</td></tr>
<tr><td>I-125</td></tr>
<tr><td>I-129</td></tr>
<tr><td>Ni-63</td></tr>
<tr><td>Pb-210</td></tr>
<tr><td>Sm-145</td></tr>
<tr><td>Ti-44</td></tr>
<tr><td>Tm-170</td></tr>
<tr><td rowspan="13">Group 2</td><td>Ce-139</td><td rowspan="13">7.50E-06</td><td rowspan="13">7.99E-06</td><td rowspan="13">37.56</td><td rowspan="13">73.43</td></tr>
<tr><td>Ce-144</td></tr>
<tr><td>Co-57</td></tr>
<tr><td>Eu-155</td></tr>
<tr><td>Gd-153</td></tr>
<tr><td>Hf-172</td></tr>
<tr><td>Hg-203</td></tr>
<tr><td>Pm-147</td></tr>
<tr><td>Rh-101</td></tr>
<tr><td>Se-75</td></tr>
<tr><td>Te-123m</td></tr>
<tr><td>Xe-127</td></tr>
<tr><td>Yb-169</td></tr>
<tr><td rowspan="11">Group 3</td><td>Ba-133</td><td rowspan="11">6.24E-06</td><td rowspan="11">5.25E-06</td><td rowspan="11">2.27E+02</td><td rowspan="11">9.46E+02</td></tr>
<tr><td>Cr-51</td></tr>
<tr><td>Eu-152</td></tr>
<tr><td>Ir-192</td></tr>
<tr><td>Kr-85</td></tr>
<tr><td>Pa-233</td></tr>
<tr><td>Pd-103</td></tr>
<tr><td>Sb-125</td></tr>
<tr><td>Sn-113</td></tr>
<tr><td>Sr-85</td></tr>
<tr><td>Tc-95m</td></tr>
</table>

a. Mass limits for combinations of radionuclides are to be determined using the provided Sum-of-the-Fractions Methodology, which precedes this table.

Section 2 - Non-Fissionable Radionuclides (4 of 4) [a]					
Group	Radionuclide	Mass Limit Criteriaa (gram)			
		Dose (without Shielding Pig)		Dose (with Shielding Pig)	
		Metal	Oxide	Metal	Oxide
	Column	[IIIa]	[IIIb]	[IVa]	[IVb]
Group 4	Ag-108m Ag-110m Co-58 Cs-134 Cs-137 Hf-181 Ho-166m Mn-54 Nb-95 Ra-228 Ru−103 Ru-106 Sb-124 Sr-89 Tl-204 Zr-95	6.03E-06	6.09E-06	5.73E-03	9.46E+02
Group 5	Bi-207 Co-56 Co-60 Eu-154 Fe-59 Ge-68 K-40 Sc-46 Ta-182 Zn-65	1.71E-04	1.70E-04	2.48E-02	2.46E-02
Group 6	Sr-90 Y-88	3.87E-07	3.90E-07	1.55E-05	1.57E-05