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Functional Bounding Content Envelope for Gamma and Neutron Emitting Isotopes in the Model 9977 Packaging

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Introduction

The contents approved for shipment in a Type B radioactive material transportation package have historically been descriptions of discrete items, or groupings of well-defined similar items, in the package safety basis documentation. The need for a comprehensive functional content envelope of both gamma and neutron emitting nuclides compliant with regulatory limits has become necessary as the DOE complex requires shipments of unique mixtures of radionuclides and impurities.

Recent publications [1, 2] have presented a calculational model and a corresponding content envelope intended to be compliant with federal regulatory external radiation limits as well as design decay heat limits based on the Model 9977 Packaging. The methodology used to develop this content envelope consisted of determining the external radiation dose rates based on one gram of a given isotope combined, in the case of actinides, with various levels of light element impurities and determining the allowable mass to the regulatory limits based on these dose rates [1, 2]. The method of ratioing from these calculations to the masses that meet the regulatory limits fails in the case of some combinations of actinides and light element impurities because of the effect of subcritical multiplication [3], resulting in non-conservative and non-compliant dose rates in some cases. This is particularly true for many actinides combined with beryllium, boron, fluorine, lithium, and sodium.

In this study, the source was modeled as a sphere with the appropriate dimensions based on the actinide or gamma source density and placed at the bottom of the containment vessel for maximum conservatism. The results presented in this report rectify the above-noted deficiencies by adjusting the previously determined mass limits so that the resulting dose rates are compliant with regulatory limits. Some amount of iteration was required in some instances to adjust the masses for dose compliance. In some instances the masses were increased since they were too conservative. In addition, the method of ratioing the masses when applied to several gamma emitting isotopes also resulted in either non-conservative or overly conservative data. The mass limits presented here are for bare sources and are complaint with the design decay heat limit of 19W. The masses are based on package surface dose rates (the limiting dose rate) that fall in the range 185-195 mrem/h, thus giving an additional margin of between 7.5% and 2.5% to the regulatory limit of 200 mrem/h.

This report presents a revised set of mass limits (i.e., content envelope) for several neutron emitting actinides with varying levels of light element impurities compliant with both external radiation and design decay heat limits. In addition, revised limits for gamma sources are also presented. The neutron emitter mass limits are in Tables 1 through 9 and the gamma emitter mass limits are in Table 10.

The revised content envelope covering a wide range of materials present in the DOE complex, was developed for the Model 9977 Packaging, providing conservative limits for other commonly-used Type B Packagings such as the Models 9975 and 9978. It should be noted that for the Model 9977 package, shipment is also possible with three shielded containers – lead or tungsten for gamma sources and polyethylene for neutron emitters. The design decay heat limits for these are as follows: 19W for tungsten, 6W for lead and 3W for polyethylene. The limits presented in this report would need to be checked against the lower decay heat limits for the lead and polyethylene and adjusted as required for compliance.

Criticality safety is not factored into these limits and should be evaluated on a case by case basis.

Discussion of the Results

The Tables 1, 2a-9a, and 10 contain the new mass limits for the various isotopes and sources. The **orange** highlighted data represent limits restricted by decay heat. The changes shown (Table 1, Tables 2b-9b, and Table 10) are the ratio of current mass limit to the corresponding one in Ref. 2. Ratios equal to one are highlighted in **green.** The light element impurity content shown in the various tables denotes the mass fraction of the light element based on the mass of the mixture. For example, an impurity content of 30pc would be a mixture containing 70w% of actinide and 30w% of the light element. The following paragraphs provide brief comments on features of the data contained in each of the tables.

Pure Actinides

The mass limits for the two curium and the californium isotopes were reduced by approximately 33% compared to the mass limits presented in Reference 2. These three isotopes have large spontaneous fission sources and their limits are very small. Thus, the sources are points in space as opposed to a distributed source (2.5cm x 4cm cylinder) as modeled in Ref. 2. While ^{248}Cm and ^{252}Cf are unaffected by light element impurities, ^{244}Cm has a reasonable (α, n) source when mixed with light elements. The impact of this for ^{244}Cm will be discussed later in this report. ^{242}Pu, which has a shorter half-life for spontaneous fission than ^{240}Pu, also shows a drop in the mass limit, though to a lesser extent than the curium and californium isotopes. The remainder of the actinides all show increases in the mass limits to varying degrees depending on the strength of the spontaneous fission source. Here the larger masses tend to offer self-shielding that more than compensates for the subcritical multiplication effects both of which were not accounted for in the limits set forth in Ref. 2. At the lower end of increase are ^{238}Pu and ^{240}Pu both of which have reasonable spontaneous fission source terms. At the high end of increase are isotopes like ^{243}Am and ^{237}Np with dominant gamma sources. The ^{239}Pu mass limit has been set at 5000 g and could be further reduced because of criticality concerns. ^{238}Pu, ^{240}Pu, and ^{241}Pu+^{241}Am are limited by the design decay heat limit of 19W for unshielded contents in the Model 9977 Packaging. Table 1 presents these results.

Pu Isotopes

The mass limits for ^{238}Pu were restricted by the design decay heat limits for several of the light elements that have low (α, n) cross sections. In the case of C, O, and Si, decay heat considerations limited the mass over the entire range of impurity levels that were studied. Even in the case of the typically strong (α, n) producing isotopes B, F, and Li, decay heat limits dictated the allowable mass at very low concentrations of these impurities. Table 2 presents these results.

In the case of ^{239}Pu combined with beryllium all combinations of the two except 1000ppm had to be reduced for compliance. Boron and fluorine mixtures up to a lower limit of 5% were reduced for compliance. For light elements with low (α, n) cross sections, the mass limits were restricted to its subcritical mass limit of 5000 g. In these cases the dose rates will have large margins to the regulatory limits. However, criticality safety considerations have not been factored in and need to be evaluated before applying this limit. Table 3 presents these results.

^{240}Pu had mass limits dictated by decay heat considerations for some of the weaker (α, n) light elements though to a lesser extent than ^{238}Pu. ^{240}Pu has a neutron source from spontaneous fissions that is an important contributor to the dose rates for the weaker (α, n) light elements. Table 4 presents the content envelope.

Mass limits for ^{241}Pu are not presented separately and are shown in combination with ^{241}Am.

^{242}Pu generally has a weaker dependence on light element (α, n) source of neutrons than ^{240}Pu. However, it has a stronger spontaneous fission source than ^{240}Pu since its half-life for this process is shorter than that of ^{240}Pu. Examining the content envelope for ^{242}Pu and beryllium in Table 5 with that for ^{240}Pu (see Table 4), it can be seen that the mass limits for the latter are smaller than for the former for each concentration. This is due to the fact ^{240}Pu has a higher source from (α, n) reactions in beryllium than ^{242}Pu. On the other hand, for weaker (α, n) sources from oxygen or chlorine, the spontaneous fission source tends to dominate, making the dependence on the light element content almost negligible. In these cases ^{240}Pu has higher mass limits than ^{242}Pu. Both these isotopes as well as ^{239}Pu have mass limits at the kilogram levels for combinations with most light elements barring beryllium, boron, fluorine, and, to a lesser extent, lithium.

Am Isotopes

Since ^{241}Pu beta decays with a half-life of 14.35 years to its daughter ^{241}Am and the latter is the dominant source of the external dose rates, it is more useful to present a combined content envelope for these two isotopes. The peak neutron source as a result of the decay of ^{241}Pu occurs in little over 73 years at which time 89% of the original ^{241}Pu has been converted to ^{241}Am. ^{241}Am combined with light elements is a good source of neutrons produced via the (α, n) reaction. Table 6 presents the envelope for this pair of actinides. In several instances the mass limits are restricted over all concentrations of light elements by decay heat considerations. Thus, these mass limits are conservative in terms of the external radiation levels they would produce.

^{243}Am is a strong gamma emitter and other than in combination with the larger concentrations of beryllium or boron, where the mass limit is 1 g, the mass limit remains constant at 1.32 g for every other light element. The dominant source of gammas is its short lived daughter ^{239}Np (half-life of 2.36 days) with which it is in secular equilibrium. Table 7 presents the mass limits for this actinide.

^{237}Np

This isotope is predominantly a gamma emitter and other than for some higher concentrations of beryllium, the mass limits are constant as shown in Table 8.

^{244}Cm

This isotope of curium has strong neutron sources from both spontaneous fission and (α, n) reactions with light elements. Thus the neutron dose rate is the dominant factor in contributing to external radiation. The mass limits across all light elements and concentrations are in the milligram range. Table 9 presents the mass limits. The mass limits for the weaker (α, n) light elements at lower concentrations are identical to that of the pure isotope.

Gamma Sources

Gamma emitters are mostly lower for isotopes with harder gamma spectra compared to the previous set because the sources are virtually points in space though the material is modeled at the correct density. This compares to a voided distributed source (2.5cm x 4cm cylinder) in the old set of calculations. For the actinides with predominantly soft spectra, the limiting masses are fairly large as a result of self-shielding by the source itself. In these cases, the old set was of masses was conservative. The entire set of limits is presented in Table 10.

Mixtures of Isotopes

For mixtures of isotopes, the sum of the fraction of each isotope to its individual limit should be less than or equal to 1 for compliance with the regulatory limits, i.e.

$$\sum_{i=1}^{n} \frac{M_i}{M_{Li}} \leq 1$$

where,

M_i is the mass of the ith isotope in the mixture containing n isotopes, and

M_{Li} is the maximum allowed mass for that isotope with the appropriate impurity fraction.

Conclusions

This report presents a comprehensive set of mass limits for a large number of actinides in combination with several light elements as well as a set of gamma sources that are compliant with external radiation limits set forth in 10 CFR Part 71 as well as the IAEA regulations TS-R-1. The content envelope presented in this report based on the Model 9977 can be applied to and are conservative for both the Model 9975 and the Model 9978 Packagings. The Model 9975 Packaging has double containment (inner and outer containment vessels) and a gamma shield. The Model 9978 Packaging has a 5-inch containment vessel compared to a 6-inch containment vessel for the Model 9977 Packaging, making the source to dose measurement point distance larger.

References

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Table 1. Mass Limits in grams for Pure Actinides

Isotope	Mass limit (g)	Change from Ref 2
^{238}Pu	33.46	1.05
^{239}Pu	5000.0	1.50
^{240}Pu	2687.03	1.05
^{242}Pu	2003.19	0.84
$^{241}Am+^{241}Pu$	165.94	7.94
^{243}Am	1.32	4.34
^{237}Np	2982.00	56.05
^{244}Cm	0.26	0.69
^{248}Cm	0.07	0.68
^{252}Cf	0.0000012	0.66

Note: ^{239}Pu mass limit is set to the ANSI/ANS-8.1-1998 subcritical limit and will reduce due to criticality safety considerations

Table 2a. ^{238}Pu Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	14.13	33.46	33.46	33.46	33.46	33.46	33.46	33.46	33.46	33.46	33.46
5000ppm	2.99	11.88	33.46	30.99	33.46	33.46	33.46	33.46	33.46	33.46	33.46
10000ppm	1.49	6.10	33.46	15.98	33.46	33.46	33.46	33.46	33.46	33.46	33.46
50000ppm	0.33	1.35	14.99	3.50	33.46	33.46	24.63	19.66	33.46	33.46	33.46
10pc	0.18	0.75	8.48	1.91	33.46	31.25	13.55	10.87	33.46	33.46	33.46
30pc	0.08	0.35	3.95	0.84	33.46	16.62	6.02	4.80	33.46	33.46	33.46
50pc	0.06	0.27	3.05	0.63	33.46	10.23	4.50	3.63	33.46	33.46	33.46
70pc	0.06	0.23	2.66	0.54	33.46	8.70	3.84	3.04	33.46	33.46	33.46
90pc	0.05	0.21	2.44	0.48	33.46	7.83	3.46	2.75	33.46	33.46	30.90

Table 2b. ^{238}Pu Mass Limits— Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	0.77	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000ppm	0.69	0.76	1.00	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000ppm	0.67	0.72	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000ppm	0.66	0.67	0.77	0.70	1.00	1.00	0.87	0.82	1.00	1.00	1.00
10pc	0.66	0.67	0.73	0.68	1.00	0.93	0.78	0.75	1.00	1.00	1.00
30pc	0.66	0.66	0.69	0.67	1.00	0.94	0.72	0.70	1.00	1.00	1.00
50pc	0.66	0.66	0.68	0.67	1.00	0.75	0.70	0.71	1.00	1.00	1.00
70pc	0.66	0.66	0.67	0.67	1.00	0.74	0.70	0.69	1.00	1.00	1.00
90pc	0.66	0.66	0.67	0.67	1.00	0.73	0.69	0.69	1.00	1.00	0.93

Table 3a. ^{239}Pu Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	2321.3	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
5000ppm	900.0	2774.2	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
10000ppm	476.0	1649.2	5000.0	3589.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
50000ppm	111.0	417.7	3629.0	1127.4	5000.0	5000.0	5000.0	4409.0	5000.0	5000.0	5000.0
10pc	62.5	240.0	2618.0	658.8	5000.0	5000.0	5000.0	3133.0	5000.0	5000.0	5000.0
30pc	29.0	114.3	1482.8	309.7	5000.0	3591.0	3431.0	1803.0	5000.0	5000.0	5000.0
50pc	22.0	88.9	1232.0	236.6	5000.0	3052.7	2850.0	1420.0	5000.0	5000.0	5000.0
70pc	19.5	77.7	1104.0	203.7	5000.0	2785.9	2521.0	1240.1	5000.0	5000.0	5000.0
90pc	17.0	71.5	1030.0	183.7	5000.0	2582.6	2372.0	1159.0	5000.0	5000.0	5000.0

Table 3b. ^{239}Pu Mass Limits— Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.00	1.67	1.51	1.56	1.50	1.51	1.51	1.51	1.50	1.50	1.50
5000ppm	0.85	1.29	1.54	1.76	1.51	1.51	1.54	1.54	1.51	1.51	1.50
10000ppm	0.75	1.04	1.58	1.45	1.51	1.53	1.57	1.57	1.51	1.51	1.51
50000ppm	0.68	0.75	1.34	0.88	1.54	1.61	1.81	1.60	1.53	1.53	1.52
10pc	0.67	0.72	1.11	0.78	1.57	1.71	2.07	1.31	1.56	1.54	1.53
30pc	0.67	0.70	0.84	0.71	1.64	1.42	1.92	1.02	1.63	1.59	1.57
50pc	0.65	0.69	0.79	0.70	1.68	1.31	1.84	0.93	1.67	1.62	1.59
70pc	0.67	0.69	0.77	0.70	1.71	1.26	1.78	0.89	1.70	1.64	1.61
90pc	0.63	0.69	0.75	0.69	1.73	1.21	1.78	0.88	1.72	1.65	1.62

Table 4a. ^{240}Pu Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	945.69	1913.58	2687.03	2489.43	2687.03	2687.03	2687.03	2687.03	2687.03	2687.03	2687.03
5000ppm	260.14	821.78	2635.11	1630.63	2687.03	2687.03	2687.03	2660.12	2687.03	2687.03	2687.03
10000ppm	138.48	486.47	2452.92	1144.40	2687.03	2687.03	2559.09	2416.46	2687.03	2687.03	2687.03
50000ppm	31.31	121.18	1480.99	353.53	2643.10	2182.29	1813.50	1522.38	2646.92	2687.03	2687.03
10pc	17.47	68.38	1059.22	204.55	2404.85	1810.94	1377.10	1082.87	2486.80	2622.05	2687.03
30pc	8.02	31.87	602.18	93.30	2024.80	1218.44	826.66	596.43	2121.93	2273.61	2500.80
50pc	6.18	24.75	486.60	69.98	1865.01	1011.35	663.16	463.98	1943.63	2127.24	2321.88
70pc	5.38	21.64	432.33	59.93	1772.82	904.31	586.69	405.29	1837.12	2044.80	2241.51
90pc	4.98	19.92	410.02	54.06	1705.51	842.44	540.36	369.62	1768.56	1991.12	2179.19

Table 4b. ^{240}Pu Mass Limits— Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	0.79	0.91	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000ppm	0.71	0.79	1.00	0.89	1.00	1.00	1.01	1.00	1.00	1.00	1.00
10000ppm	0.70	0.76	1.00	0.84	1.00	1.00	1.02	0.97	1.00	1.00	1.00
50000ppm	0.69	0.72	0.90	0.75	1.00	0.94	1.05	0.89	0.99	1.00	1.00
10pc	0.68	0.71	0.87	0.74	0.96	0.91	1.06	0.85	0.97	1.00	1.00
30pc	0.67	0.69	0.82	0.72	0.92	0.86	1.08	0.80	0.94	0.95	1.00
50pc	0.67	0.69	0.80	0.72	0.90	0.84	1.09	0.78	0.92	0.93	0.97
70pc	0.67	0.69	0.80	0.71	0.89	0.82	1.09	0.77	0.91	0.92	0.97
90pc	0.68	0.69	0.81	0.71	0.88	0.82	1.09	0.77	0.91	0.92	0.96

Table 5a. ^{242}Pu Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1964.95	1989.97	2001.99	1999.15	2002.51	2001.66	2002.41	2002.39	2002.37	2002.38	2002.39
5000ppm	1827.12	1954.34	2001.19	1986.56	2002.30	2001.47	1999.97	2001.88	1999.66	2000.01	2002.37
10000ppm	1672.06	1908.40	2001.21	1973.13	2001.91	2000.79	2000.70	2000.01	1999.51	1999.60	2002.33
50000ppm	1070.12	1639.68	1995.09	1885.87	2000.65	1998.06	1995.13	1987.21	1998.20	1998.99	2001.95
10pc	783.49	1442.66	1988.24	1805.78	1998.76	1993.47	1986.87	1976.50	1997.08	1998.29	2001.71
30pc	460.39	1094.11	1971.55	1605.70	1995.10	1984.56	1970.58	1954.49	1993.95	1994.69	2000.82
50pc	372.18	963.75	1969.98	1503.98	1992.76	1978.17	1950.70	1942.72	1992.40	1993.44	2000.26
70pc	332.43	901.47	1964.50	1433.04	1991.48	1974.41	1941.47	1924.83	1990.71	1992.77	1999.76
90pc	309.07	858.50	1962.34	1396.96	1990.54	1973.68	1937.97	1925.34	1991.37	1992.55	2001.59

Table 5b. ^{242}Pu Mass Limits– Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	0.82	0.82	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
5000ppm	0.82	0.82	0.83	0.82	0.83	0.83	0.83	0.83	0.82	0.82	0.83
10000ppm	0.80	0.82	0.83	0.82	0.83	0.83	0.83	0.83	0.82	0.82	0.83
50000ppm	0.77	0.81	0.83	0.82	0.83	0.83	0.83	0.82	0.82	0.82	0.83
10pc	0.76	0.80	0.82	0.82	0.83	0.83	0.83	0.82	0.82	0.82	0.83
30pc	0.74	0.79	0.82	0.81	0.83	0.83	0.83	0.82	0.82	0.82	0.83
50pc	0.73	0.78	0.83	0.81	0.83	0.83	0.83	0.83	0.82	0.82	0.83
70pc	0.72	0.78	0.83	0.80	0.83	0.83	0.83	0.82	0.82	0.82	0.83
90pc	0.72	0.78	0.83	0.80	0.83	0.83	0.84	0.82	0.82	0.82	0.83

Table 6a. $^{241}Am + ^{241}Pu$ Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	68.82	165.94	165.94	165.94	165.94	165.94	165.94	165.94	165.94	165.94	165.94
5000ppm	14.66	59.07	165.94	149.78	165.94	165.94	165.94	165.94	165.94	165.94	165.94
10000ppm	7.35	29.75	165.94	79.98	165.94	165.94	165.94	165.94	165.94	165.94	165.94
50000ppm	1.66	6.83	81.88	17.77	165.94	165.94	165.94	104.76	165.94	165.94	165.94
10pc	0.92	3.80	46.21	9.73	165.94	157.00	102.68	56.45	165.94	165.94	165.94
30pc	0.42	1.77	21.60	4.32	165.94	70.86	46.05	24.63	165.94	165.94	165.94
50pc	0.32	1.36	16.32	3.23	165.94	52.97	34.41	18.53	165.94	165.94	165.94
70pc	0.28	1.19	14.23	2.76	165.94	45.35	29.36	15.81	165.94	165.94	165.94
90pc	0.26	1.09	13.11	2.50	165.94	40.87	17.47	14.24	165.94	165.94	165.94

Table 6b. $^{241}Am + ^{241}Pu$ Mass Limits— Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	3.92	8.32	7.99	8.09	7.96	7.96	7.98	7.98	7.96	7.96	7.96
5000ppm	1.35	3.47	8.11	7.79	7.97	8.00	8.05	8.07	7.97	7.96	7.97
10000ppm	1.00	2.07	8.26	4.48	7.98	8.03	8.14	8.19	7.97	7.97	7.97
50000ppm	0.75	1.00	4.61	1.52	8.05	8.32	8.82	5.70	8.04	8.01	8.04
10pc	0.71	0.86	2.91	1.14	8.12	8.16	5.90	3.38	8.10	8.05	8.11
30pc	0.68	0.76	1.74	0.89	8.31	4.06	3.21	1.85	8.30	8.17	8.32
50pc	0.68	0.74	1.47	0.84	8.42	3.21	2.66	1.57	8.42	8.24	8.46
70pc	0.68	0.73	1.37	0.81	8.48	2.85	2.41	1.44	8.50	8.28	8.55
90pc	0.67	0.73	1.32	0.80	8.53	2.64	1.50	1.36	8.56	8.31	8.63

Table 7a. ^{243}Am Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
5000ppm	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
10000ppm	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
50000ppm	1.00	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
10pc	1.00	1.00	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
30pc	1.00	1.00	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
50pc	1.00	1.00	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
70pc	1.00	1.00	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
90pc	1.00	1.00	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32

Table 7b. ^{243}Am Mass Limits— Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39
5000ppm	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39
10000ppm	4.40	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39
50000ppm	3.34	4.40	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39
10pc	3.36	3.33	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39
30pc	3.40	3.34	4.39	4.40	4.39	4.39	4.39	4.39	4.39	4.39	4.39
50pc	3.42	3.35	4.39	4.40	4.39	4.39	4.39	4.39	4.39	4.39	4.39
70pc	3.44	3.35	4.39	4.40	4.39	4.39	4.39	4.39	4.39	4.39	4.39
90pc	3.45	3.35	4.39	4.41	4.39	4.39	4.39	4.39	4.39	4.39	4.39

Table 8a. ^{237}Np Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
5000ppm	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
10000ppm	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
50000ppm	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
10pc	1005.79	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
30pc	1005.79	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
50pc	1005.79	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
70pc	1005.79	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62
90pc	1005.79	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62	2912.62

Table 8b. ^{237}Np Mass Limits— Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73
5000ppm	54.74	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73
10000ppm	54.76	54.74	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73	54.73
50000ppm	54.87	54.76	54.73	54.74	54.73	54.73	54.73	54.73	54.73	54.73	54.73
10pc	18.99	54.80	54.73	54.75	54.73	54.73	54.73	54.73	54.73	54.73	54.73
30pc	19.09	54.87	54.73	54.77	54.73	54.73	54.73	54.73	54.73	54.73	54.73
50pc	19.15	54.92	54.73	54.78	54.73	54.73	54.73	54.73	54.73	54.73	54.73
70pc	19.19	54.94	54.73	54.79	54.73	54.73	54.73	54.73	54.73	54.73	54.73
90pc	19.22	54.96	54.73	54.80	54.73	54.73	54.74	54.73	54.73	54.73	54.73

Table 9a. ^{244}Cm Mass Limits in grams

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	0.23	0.25	0.26	0.25	0.26	0.26	0.26	0.26	0.26	0.26	0.26
5000ppm	0.17	0.23	0.25	0.25	0.26	0.26	0.26	0.25	0.26	0.26	0.26
10000ppm	0.13	0.21	0.25	0.23	0.26	0.25	0.25	0.25	0.26	0.26	0.26
50000ppm	0.05	0.13	0.23	0.18	0.25	0.25	0.25	0.23	0.26	0.26	0.26
10pc	0.03	0.09	0.21	0.14	0.25	0.24	0.24	0.22	0.25	0.26	0.25
30pc	0.01	0.05	0.17	0.09	0.25	0.23	0.21	0.18	0.25	0.25	0.25
50pc	0.01	0.04	0.15	0.07	0.25	0.22	0.20	0.17	0.25	0.25	0.24
70pc	0.01	0.04	0.15	0.06	0.25	0.21	0.20	0.16	0.25	0.25	0.24
90pc	0.01	0.03	0.14	0.06	0.25	0.21	0.19	0.15	0.24	0.25	0.24

Table 9b. ^{244}Cm Mass Limits— Change from Ref 2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
5000ppm	0.67	0.68	0.67	0.68	0.68	0.67	0.68	0.67	0.68	0.68	0.68
10000ppm	0.67	0.67	0.67	0.68	0.67	0.67	0.68	0.67	0.68	0.68	0.68
50000ppm	0.66	0.67	0.67	0.67	0.67	0.67	0.69	0.67	0.68	0.68	0.68
10pc	0.66	0.67	0.67	0.67	0.67	0.67	0.70	0.67	0.68	0.68	0.68
30pc	0.66	0.66	0.67	0.67	0.67	0.67	0.72	0.67	0.68	0.68	0.68
50pc	0.66	0.66	0.67	0.67	0.67	0.67	0.73	0.67	0.68	0.68	0.68
70pc	0.66	0.66	0.67	0.67	0.67	0.67	0.74	0.67	0.68	0.68	0.68
90pc	0.66	0.66	0.67	0.67	0.68	0.67	0.75	0.67	0.68	0.68	0.68

Table 10. Gamma Source Mass Limits

Isotope	Mass Limit (g)	Change from Ref 2
Ac-227	4.14E-04	1.01
Cd-109	5.34E-02	9.37
Co-60	2.47E-06	0.75
Cs-137	1.29E-04	0.80
Eu-152	3.41E-05	0.78
Fe-59	1.18E-07	0.74
Gd-153	3.49E-04	2.49
Hf-181	7.14E-07	0.78
Ho-166m	2.13E-03	0.82
Ir-192	8.26E-07	0.83
Mn-54	9.84E-07	0.76
Pb-210	1.71E-02	0.61
Pm-147	3.09E+00	11.46
Po-210	1.32E-01	1.00
Ra-226	4.23E-03	0.80
Ru-106	5.98E-06	0.64
Sc-46	9.78E-08	0.75
Se-75	1.39E-06	0.92
Sm-145	1.62E-01	11.54
Sr-90	9.94E-04	0.34
Tm-170	4.70E-04	1.74
Yb-169	2.10E-06	1.00
Zn-65	1.43E-06	0.75
Zr-95	3.57E-07	0.78